A DEVELOPMENT PERSPECTIVE FOR BIOMASS-FUELLED ELECTRICITY GENERATION TECHNOLOGIES

Economic technology assessment in view of sustainability

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Roland Siemons (1958) studied engineering at the University of Twente (the Netherlands). He has been working for more than 15 years with the Biomass Technology Group (BTG) on biomass fuelled energy conversion technologies. His activities have included R&D, project appraisal and project implementation, for applications both in Europe and in developing countries.

The foundations of the analysis framework that has been developed in this thesis were laid while he was working on numerous assignments in SE-Asia and Africa. In these assignments, Roland Siemons participated in multi-disciplinary project teams involving a number of donors: DGIS (Netherlands development cooperation), EC, FAO, UNIDO, and the World Bank. Further elaboration of the framework took place during a period of sabbatical leave, and was supervised by Prof. dr. C.J. Jepma (University of Amsterdam, Faculty of Economics and Econometrics) and Prof. dr. ir. W.P.M. van Swaaij (University of Twente, Faculty of Chemical Technology).
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Academisch proefschrift

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. mr. P.F. van der Heijden
ten overstaan van een door het college voor promoties ingestelde commissie, in het openbaar te verdedigen in de Aula der Universiteit

op dinsdag 15 oktober 2002, te 12:00 uur
door Roland Vincent Siemons
geboren te De Bilt
Promotiecommissie

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Faculteit der Economische Wetenschappen en Econometrie
## CONTENTS

**FOREWORD** 7  
**ACRONYMS AND ABBREVIATIONS** 9  
**SYMBOLS** 10  
**UNITS** 10  
**INTRODUCTION** 13  
**OUTLINE** 17  

### PART A: METHODOLOGICAL FRAMEWORK 25

1 **THE PROBLEM OF SUSTAINABLE TECHNOLOGY DEVELOPMENT** 27  
   1.1 CONSIDERING THE ENVIRONMENT 27  
      1.1.1 A definition 27  
      1.1.2 Economic theory and the environment 34  
   1.2 DEFINING SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT 39  
      1.2.1 A physical approach to sustainability 40  
      1.2.2 An economic approach to sustainability, with an exogenous view of technology 43  
      1.2.3 An economic approach to sustainability, with an endogenous view of technology 49  
   1.3 TECHNOLOGY DEVELOPMENT FOR A SUSTAINABLE ECONOMY 52  
      1.3.1 Sustainable technology development as in the Dutch STD programme 53  
      1.3.2 Economic focus for the current analysis 54  
2 **EXISTING EX ANTE TECHNOLOGY ASSESSMENT METHODS** 59  
   2.1 LIFE-CYCLE ASSESSMENT 60  
      2.1.1 LCA description 61  
      2.1.2 How LCA’s deal with the dimension of time 68  
   2.2 COST-BENEFIT ANALYSIS 72  
      2.2.1 CBA description 73  
      2.2.2 How CBA’s deal with the dimension of time 76  
      2.2.3 CBA and environmental issues 77  
   2.3 MAIN DIFFERENCES BETWEEN LCA AND CBA 85  
3 **INTEGRATING LCA AND CBA FOR THE EVALUATION OF MUTUALLY EXCLUSIVE TECHNOLOGY DEVELOPMENT PROJECTS** 89  
   3.1 SYSTEM DEFINITION 90  
      3.1.1 The countries’ system 92  
      3.1.2 The producer’s system 95  
      3.1.3 Matching the two system approaches 96  
   3.2 INDICATORS 97  
      3.2.1 Indicators for the countries’ system 98  
      3.2.2 Indicators for the producer’s system 100
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.3 Integration of the three indicators</td>
<td>102</td>
</tr>
<tr>
<td>3.2.4 Parameters and uncertainty</td>
<td>107</td>
</tr>
<tr>
<td>3.3 CALCULATION PROCEDURES</td>
<td>109</td>
</tr>
<tr>
<td>PART B: APPLICATIONS TO BIOMASS BASED RENEWABLE ENERGY CONCEPTS</td>
<td>111</td>
</tr>
<tr>
<td>INTRODUCTION TO PART B</td>
<td>113</td>
</tr>
<tr>
<td>4 BIOMASS FUEL MARKETS</td>
<td>123</td>
</tr>
<tr>
<td>4.1 THE EXISTING SITUATION</td>
<td>123</td>
</tr>
<tr>
<td>4.2 A GROWING DEMAND FOR BIOMASS FUELS</td>
<td>127</td>
</tr>
<tr>
<td>4.3 SUPPLYING A GROWING DEMAND FOR BIOMASS FUELS</td>
<td>138</td>
</tr>
<tr>
<td>4.3.1 Production costs of biomass fuels</td>
<td>142</td>
</tr>
<tr>
<td>4.3.2 Biomass transportation costs</td>
<td>149</td>
</tr>
<tr>
<td>4.4 MATCHING SUPPLY AND DEMAND</td>
<td>153</td>
</tr>
<tr>
<td>5 A CONCISE EXPLORATION INTO TECHNOLOGIES FOR CENTRALISED BIOMASS-FUELLED ELECTRICITY GENERATION</td>
<td>157</td>
</tr>
<tr>
<td>5.1 IDENTIFICATION OF THE ELECTRICITY GENERATION TECHNIQUES</td>
<td>157</td>
</tr>
<tr>
<td>5.2 TECHNICAL FEASIBILITY AND CONVERSION EFFICIENCY</td>
<td>162</td>
</tr>
<tr>
<td>5.2.1 Efficiencies of biomass-fuelled Combustion-Steam cycles</td>
<td>165</td>
</tr>
<tr>
<td>5.2.2 Efficiencies of biomass-fuelled Gasification-Combined cycles</td>
<td>167</td>
</tr>
<tr>
<td>5.2.3 Efficiency of biomass-fuelled Liquefaction-Combined cycles</td>
<td>170</td>
</tr>
<tr>
<td>5.2.4 Summary</td>
<td>175</td>
</tr>
<tr>
<td>6 AN ECONOMIC ASSESSMENT OF CONCEPTS FOR CENTRALISED BIOMASS-FUELLED ELECTRICITY GENERATION</td>
<td>179</td>
</tr>
<tr>
<td>6.1 SITE PARAMETERS</td>
<td>179</td>
</tr>
<tr>
<td>6.2 GASIFICATION - COMBINED CYCLE CONCEPTS</td>
<td>182</td>
</tr>
<tr>
<td>6.2.1 GCC technology parameter values</td>
<td>182</td>
</tr>
<tr>
<td>6.2.2 Feasibility conditions for biomass-fuelled GCC</td>
<td>185</td>
</tr>
<tr>
<td>6.2.3 Targeting investment costs for biomass-fuelled GCC</td>
<td>192</td>
</tr>
<tr>
<td>6.3 THE SINGLE-SITE LIQUEFACTION - COMBINED CYCLE CONCEPT</td>
<td>197</td>
</tr>
<tr>
<td>6.3.1 Parameter values for single-site LCC technology</td>
<td>197</td>
</tr>
<tr>
<td>6.3.2 Feasibility conditions for biomass-fuelled single-site LCC plants</td>
<td>198</td>
</tr>
<tr>
<td>6.4 THE MULTIPLE-SITE LIQUEFACTION - COMBINED CYCLE CONCEPT</td>
<td>202</td>
</tr>
<tr>
<td>6.4.1 Parameter values for multiple-site LCC plants</td>
<td>206</td>
</tr>
<tr>
<td>6.4.2 Feasibility conditions for biomass-fuelled multiple-site LCC plants</td>
<td>211</td>
</tr>
<tr>
<td>6.4.3 Research and development targets for multiple-site LCC</td>
<td>213</td>
</tr>
<tr>
<td>6.5 PUTTING THE RESULTS INTO PERSPECTIVE</td>
<td>218</td>
</tr>
<tr>
<td>6.5.1 Comparison with co-firing</td>
<td>218</td>
</tr>
<tr>
<td>6.5.2 Market niches for the reviewed technologies</td>
<td>218</td>
</tr>
<tr>
<td>6.5.3 Some elements of a view on the development of biomass</td>
<td>218</td>
</tr>
</tbody>
</table>
FOREWORD

The research reported in this thesis was carried out after 15 years of working in the field of technology development, investment appraisal and implementation of technologies for biomass-fuelled energy conversion. On the one hand, that experience provided a broad set of materials for further elaboration; but on the other hand, it was also necessary to identify and investigate a range of literature about, for me, still remote themes. Themes that concerned questions which arose during those years, but which had to be put aside since there was no time for further reflection. They concerned the principles of financial and economic project analysis, and of ways in which such analyses could be consolidated with environmental concerns. Above all, my participation in project teams, together with economists, assigned to project appraisal for the World Bank, provided a challenging intellectual environment. I gratefully acknowledge the inspiration of Jaap Jansen and Wolfgang Mostert, two economists who were regular members of those teams.

For me, some time for dedicated reflection became a need after the said 15 years of project-oriented work. That labour was carried out within the Biomass Technology Group b.v. (BTG). Hubert Stassen, then director of BTG, was kind enough to grant me the facilities to carry out the research reported here, during a one and a half year sabbatical leave. In addition to this, the countless discussions about technology and economics should be mentioned. Hubert always provided an original and challenging viewpoint. Other BTG colleagues who deserve my gratitude for their contribution to my research investigations include Henk Kolk and Paul Onaji.

During the preparation of this thesis, Christiaan Boudri was a critical reviewer of the more philosophically-oriented first two chapters. Christiaan is an engineer, a historian, and also a philosopher. I am also grateful for the trust shown by Catrinus Jepma and Wim van Swaaij, respectively promoter and co-promoter, who accepted my research proposal and gave me their valuable supervisory time.

As it turned out, a sabbatical leave provided by far not enough space for bringing this research to PhD standards. And a considerable proportion had to be taken from daily family life. For making this possible, I thank my wife and friend Anneke, who made up the balance so well.

The relationships of the research reported here and BTG, hinted at above, go a lot further than simply shared personal interests, and a common past experience. BTG has vested commercial interests in some of the technologies addressed. Such a fact cannot harm a scientific treatise, since only valid arguments are allowed to count. One implication of this very assessment is that opposition to the analysis should not ultimately be attributed to any alleged confusion of interests. By definition of the scientific debate, there is no such confusion, and any such suggestion is unworthy.

The role of knowledge goes far beyond mere understanding, knowledge is power. Technological research particularly yields more than scientific insights alone, it also contributes to technology development. In accordance with this, I hope that the knowledge contained in this thesis will become an effective impetus towards proper action in the development of biomass-based energy conversion technologies. Such intention is naturally the attitude of the consultant, the life which I had, and hope to resume. A consultant’s
career is more complicated than that of a scientist in so far as conflicting interests are concerned. Involvement often leads to doubts about integrity. However, the experts’ best advice is the advice which they themselves would follow. Since the proof of a pudding is in the eating, the integrity of experts is therefore properly tested by demanding that the experts act according to their own advice. If consultants recommend investing in a specific technology, then better they also do it themselves. That should not make the advice less reliable; rather the contrary. It would seem therefore that the political debate, just like the scientific debate, does not gain at all by a reference to, and rejection of, involvement. Let this be an invitation to a critical reading.

Roland Siemons, Enschede, 5 August, 2002
<table>
<thead>
<tr>
<th>ACRONYMS AND ABBREVIATIONS</th>
<th>EXPLANATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIJ</td>
<td>Activities Implemented Jointly</td>
</tr>
<tr>
<td>BDI</td>
<td>Baltic Dry Index</td>
</tr>
<tr>
<td>CBA</td>
<td>cost-benefit analysis</td>
</tr>
<tr>
<td>CC</td>
<td>combined cycle of a gas turbine with a steam cycle</td>
</tr>
<tr>
<td>CDM</td>
<td>Clean Development Mechanism</td>
</tr>
<tr>
<td>CFCs</td>
<td>chlorofluorocarbon compounds</td>
</tr>
<tr>
<td>CHP</td>
<td>combined heat and power</td>
</tr>
<tr>
<td>CS</td>
<td>combustion and steam cycle</td>
</tr>
<tr>
<td>CTA</td>
<td>constructive technology assessment</td>
</tr>
<tr>
<td>EIA</td>
<td>environmental impact assessment</td>
</tr>
<tr>
<td>EU15</td>
<td>the 15 member states of the European Union since the year 1995</td>
</tr>
<tr>
<td>EWB</td>
<td>exempted waste biomass (waste biomass fuels legally treated as non-waste fuels)</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organisation of the United Nations</td>
</tr>
<tr>
<td>FAOSTAT</td>
<td>FAO Statistical Database</td>
</tr>
<tr>
<td>GAST</td>
<td>gas turbine and steam turbine configuration of GCC</td>
</tr>
<tr>
<td>GAVE</td>
<td>the Dutch programme of climate-neutral liquid and gaseous fuels</td>
</tr>
<tr>
<td>GCC</td>
<td>gasifier coupled combined Brayton and Rankine cycle</td>
</tr>
<tr>
<td>GEF</td>
<td>Global Environment Facility</td>
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<tr>
<td>GHG</td>
<td>greenhouse gas</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IFI</td>
<td>international finance institution</td>
</tr>
<tr>
<td>IMF</td>
<td>International Monetary Fund</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>JI</td>
<td>Joint Implementation</td>
</tr>
<tr>
<td>LCA</td>
<td>life-cycle assessment</td>
</tr>
<tr>
<td>LCC</td>
<td>liquefier coupled to a combined Brayton and Rankine cycle</td>
</tr>
<tr>
<td>NG-CC</td>
<td>Natural gas fuelled combined cycle of a gas turbine with a steam cycle</td>
</tr>
<tr>
<td>NWB</td>
<td>non-waste biomass fuels legally treated as other non-waste fuels</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
</tr>
<tr>
<td>PCCC</td>
<td>Pressurised combustion combined cycle for solid fuels</td>
</tr>
<tr>
<td>REB</td>
<td>Dutch regulatory energy tax</td>
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<tr>
<td>RMNO</td>
<td>the Dutch Raad voor Ruimtelijk, Milieu- en Natuuronderzoek (Advisory council for research on spatial planning, nature and the environment)</td>
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<tr>
<td>SEA</td>
<td>strategic environmental assessment</td>
</tr>
<tr>
<td>SETAC</td>
<td>Society of Environmental Toxicology and Chemistry</td>
</tr>
<tr>
<td>SRC</td>
<td>short-rotation coppice</td>
</tr>
<tr>
<td>STD</td>
<td>the Dutch sustainable technology development programme</td>
</tr>
<tr>
<td>STIG</td>
<td>steam injected gas turbine configuration of GCC</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
</tr>
<tr>
<td>WB</td>
<td>waste biomass fuels legally treated as wastes</td>
</tr>
<tr>
<td>w.b. on a wet basis</td>
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</tr>
</tbody>
</table>
WEC  World Energy Council

SYMBOLS

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<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>per capita consumption</td>
</tr>
<tr>
<td>c</td>
<td>specific heat (J/(g.K))</td>
</tr>
<tr>
<td>DR</td>
<td>discount rate (-)</td>
</tr>
<tr>
<td>ERU</td>
<td>emission reduction unit (t GHG/yr)</td>
</tr>
<tr>
<td>GCV</td>
<td>gross calorific value (GJ/t, MJ/kg, MJ/Nm³)</td>
</tr>
<tr>
<td>GDP</td>
<td>gross domestic product (€/yr)</td>
</tr>
<tr>
<td>H</td>
<td>enthalpy (J)</td>
</tr>
<tr>
<td>h</td>
<td>specific enthalpy (J/g)</td>
</tr>
<tr>
<td>I</td>
<td>environmental disruption or environmental pressure</td>
</tr>
<tr>
<td>IRR</td>
<td>internal rate of return (-)</td>
</tr>
<tr>
<td>MC</td>
<td>moisture content (-)</td>
</tr>
<tr>
<td>m</td>
<td>mass (g, t)</td>
</tr>
<tr>
<td>NCV</td>
<td>net calorific value (GJ/t, MJ/kg, MJ/Nm³)</td>
</tr>
<tr>
<td>NPV</td>
<td>net present value (€)</td>
</tr>
<tr>
<td>P</td>
<td>population (-)</td>
</tr>
<tr>
<td>PVC</td>
<td>present value of cost (€)</td>
</tr>
<tr>
<td>S</td>
<td>entropy (J/K)</td>
</tr>
<tr>
<td>s</td>
<td>specific entropy (J/(g.K))</td>
</tr>
<tr>
<td>SGMₘₐ</td>
<td>standard gross margin on a ha basis (€/(ha.yr))</td>
</tr>
<tr>
<td>T</td>
<td>temperature (°C, K)</td>
</tr>
<tr>
<td>t</td>
<td>time (s, h, d, yr)</td>
</tr>
<tr>
<td>TEV</td>
<td>total economic value (€)</td>
</tr>
<tr>
<td>UMC</td>
<td>unit manufacturing cost (€/unit)</td>
</tr>
<tr>
<td>UPC</td>
<td>unit product cost (€/unit)</td>
</tr>
<tr>
<td>W</td>
<td>physical work (J/s)</td>
</tr>
<tr>
<td>α</td>
<td>ash content (-)</td>
</tr>
<tr>
<td>Δ</td>
<td>increase</td>
</tr>
<tr>
<td>η</td>
<td>energy efficiency (-)</td>
</tr>
<tr>
<td>μ</td>
<td>moisture content (-)</td>
</tr>
<tr>
<td>ρ</td>
<td>unit-specific GHG emission coefficient (t GHG/MWhₘₐ)</td>
</tr>
</tbody>
</table>

UNITS

Area
ha  hectare (10,000 m²)

Distance
m  metre
Energy
 J Joule
toe tonne oil equivalent (41,868 TJ)
W Watt (=J/s)
Wh Watt-hour (3600 J)

Mass
 g gram
 g_x gram of matter at a reference moisture content (MC_w) of x %m
 t tonne (1000 kg)
t_x tonne of matter at a reference moisture content (MC_w) of x %m

Pressure
bara absolute pressure in bar (1 bar = 10,000 N/m²)
barg gauge pressure, i.e. pressure relative to the ambient pressure

Temperature
°C degrees Celsius
K Kelvin

Time
d day (24 hours)
h hour
s second
yr standard year (365 days, 8760 h)

Volume
l litre
Nm³ cubic metre gas under normal conditions: 273.15°C and 101325 Pa

Prefixes
m milli (10⁻³)
c centi (10⁻²)
k kilo (10³)
M Mega (10⁶)
G Giga (10⁹)
T Tera (10¹²)
P Peta (10¹⁵)
E Exa (10¹⁸)

Subscripts
 1 with energy units: primary energy
 2 with energy units: secondary energy
b with m³: bulk volume (equal to the specific volume times [1-porosity])
d on a dry basis
daf on a dry and ash-free basis
e electric
G gross
M mechanical
m with %: mass percent
N net
p at constant pressure
S isentropic
s with m³: specific (or true) volume of solid material
th thermal
v at constant volume
v with %: volume percent
w on a wet basis

Currencies

The dominant currency used is the €. The reason is that the focus of this thesis is on European markets for electricity and biomass fuels. Currency conversions from $ to € were occasionally required. In such cases the average interbank exchange rates applicable in the reference year involved were employed. For the period before 1 January 1999, when the € was established, the exchange rate pertaining to the ECU was taken.
INTRODUCTION

This thesis, about the feasibility of technology developments for electricity generation from biomass, starts with an investigation into the multitude of views on the relationships between technology, the economy and the environment. This is because environmental concerns have typically been a major instigator of biomass technology development for energy production. Such concerns have long existed. T.R. Malthus, for example, analysed the environment’s potential inability to provide sufficient food as early as 1803. And long before him, Francis of Assisi (1182 - 1226) wrote about his care of nature. Both aspects, of dependence and care, have over time characterized the human relationship with the environment. However, it is only during approximately the past 40 years that a new element in society’s attitude to the environment has emerged, namely the conviction that people can actually do something about reducing agricultural yields, diminishing amenity, and other environmental matters. Supported by the increased possibilities for worldwide communication, the development of new technologies for a more sustainable economy has become an objective of many researchers, engineers, firms, and governments. The first part of this thesis is about how such sustainable technologies can be identified, and how the development of these technologies can be guided so that their objective is achieved more effectively and more efficiently.

The new assessment method developed in this thesis is based on a review and the integration of existing methods found in economic, technological, and sociological literature. Keywords denoting those existing methods are: economic cost-benefit analysis, environmental life-cycle assessment, and constructive technology assessment. Fundamental inconsistencies between the various analysis and evaluation frameworks are highlighted, along with shortcomings in the individual methods. Some examples of the methodological findings are as follows:

• The fundamentally process-oriented approach of environmental life-cycle assessment reveals environmental issues which are ignored by economists who essentially investigate systems of economic actors like firms and countries.

• The results of environmental life-cycle assessment - usually a weighted total of environmental effects - are often viewed as if complementary to economic cost-benefit analysis. But this view is inconsistent with the fact that some environmental effects, such as emissions of sulphur and nitrogen oxides, have already been absorbed within the monetary economic reality as addressed by cost-benefit analysis. Weighting those effects within an isolated field of environmental issues ignores the valuations already given within the latter framework.

If one shares a concern about the environment within which we are organizing and developing society, these fundamental inconsistencies and shortcomings must be overcome and replaced by more adequate analytical methods.

The focal environmental point in the second part of this thesis is global climate change as ascribed to the anthropogenic emission of greenhouse gases. These gases are emitted by energy conversion processes, as well as by a number of other human activities such as land use change and the production and use of materials. The technological focus is on those
technologies that employ biomass as a fuel for central electricity generation. An attempt is made to establish development targets for these technologies in view of the societal objective to reduce the emissions of greenhouse gases. Biomass is a well-known, potentially greenhouse gas neutral, energy carrier. Only potentially, since biomass fuels can only be greenhouse gas neutral if produced in parallel with their utilisation: only then is the carbon cycle closed. The EU and its member states, the USA and also the UN Global Environment Facility have all been spending considerable resources on the development of specific biomass-fuelled energy conversion technologies. This has also been intellectually supported by the IEA, the OECD, and the IPCC. Within its Framework Four Programme (1995-1998), the European Commission, for example, spent € 100 Million on R&D into various aspects of biomass conversion into electricity and heat. An important question for public administrations and governments is into which technology developments these budgets should be channelled. Unavoidably, in addressing this question, they have to rely on expert opinions. However, only persons who are directly involved in this type of R&D can be experts and thus the very experts advising on R&D budget allocation are the ones subsequently executing the selected R&D. It is therefore only fair to ask technology developers precisely what they intend to achieve with their efforts. To facilitate this public responsibility, it is the objective of this thesis to develop a framework by means of which the technology development targets can be clarified in terms of costs, energy conversion efficiency, and environmental performance.

The second part of this thesis produces some unexpected and perhaps controversial results with regard to the development potential of particular biomass fuelled concepts. For example, for the popular concept of large-scale gasification, integrated with combined cycles of gas and steam turbines, it is shown that no capital cost targets can be defined, which would lead to widespread implementation in EU-type economies. In other words, the availability of the technology will not result in a substantial reduction of greenhouse gas emissions. Despite this, the development of this technology receives considerable financial support from public funds, such as provided by the Department of Energy (USA), the Global Environment Facility (UN) and the Framework Programmes (European Commission). Moreover, the IPCC characterized this particular technology as the exemplary concept in modern biomass-based electricity generation technology. The basic reason why this strategy cannot be sustained, as is elaborated in this thesis, is that the energy conversion efficiencies anticipated by the R&D community are not sufficiently high to create a feasible match between plant investments, commonly projected biomass fuel costs and projected market value of greenhouse gas emission reductions. An alternative concept is identified, which does seem able to make the desired cost-efficient and cost-effective impact on greenhouse gas emission reduction. This alternative is liquefaction through which biomass is converted into high-density oils for subsequent transport and use in gas turbines. Technology development targets, in terms of technically feasible scales, costs, energy conversion efficiencies, and environmental performance are subsequently established.

The fundamental reasons behind the potential offered by liquefaction are the possibility of employing low-cost biomass resources and the use of low-cost means of distribution. Economy of scale analyses show that the lower capacity boundary, above which the technology may become attractive, is 20-30 MWth. Such capacities match well with agri-industries, such as cane sugar manufacture, producing currently underutilised biomass residues. This provides fascinating opportunities for third world countries as suppliers of biomass derived fuels. One conclusion of the assessment made here is that none of the technologies reviewed offers sufficient development potential for the application of biomass fuels produced locally within EU-type economies. In addressing climate change, developing countries might therefore become the indispensable partners of industrialised countries.
OUTLINE

In the following pages an outline of the argument is presented. This outline is not intended to act as an executive summary in which the main findings are reviewed. There are many results, and what readers will consider most important will depend on their personal interests. Some may be more interested in the results of the methodological considerations; others in policy implications, and others in technical matters. These different types of readers might all find something to match their taste. Hopefully, however, there are also many to whom the multi-disciplinary approach of integrating environmental and economic considerations with engineering, appeals the most. The basic purpose of the following pages is to indicate the relationships between the inquiries made and the results found in the subsequent chapters.

Part A: Methodological framework

In Chapters 1-3 the methodology for assessing the development of biomass based energy technologies for reducing greenhouse gas (GHG) emissions is brought into focus. The development of this methodology begins with a chapter on existing views regarding the environment, sustainability and the role of technology.

Chapter 1: The problem of sustainable technology development

Two types of environment are distinguished: buffer environments which are resilient, and exhaustible environments which are vulnerable. A buffer environment, in so far as accessible on an equitable basis, has no economic value, as it continuously provides resources and accepts waste without being affected. However, the exhaustible environment, being characterised by scarcity, does have an economic value. This also includes non-monetised items. How economic science deals with this value is discussed.

Environmental concerns led to the introduction of the concept of sustainable development, which ultimately aims to change society’s interactions with the environment from exhaustive into buffering relationships. There are several approaches used to analyse and define sustainable development, including:

- Physical approaches, in which valuations and trade-offs are based on physical assessments, and in which social issues such as fairness and equity are left as implicit in prejudiced, but not necessarily mistaken, positions.
- Economic approaches in which technology is considered exogenous. These approaches are economic since choices with regard to intra-generational and inter-generational equity, as well as with regard to other environmental valuation matters, are explicit and hence subject to decision making. Technology is considered as given, available for use or abandonment. Often, this type of approach appeals for consumer temperance and calls for the development of renewable technologies which are merely assessed on the basis of physical criteria for their sustainability.
• Economic approaches in which technology is considered endogenous. Here the development of technologies that could contribute to sustainability is explained as the result of targeted investment behaviour and policies.

The final position is adopted in the further analyses, assuming that an accountable society cannot afford to act under the assumption that technological change is accidental. The need to direct sustainable technology development is considered to be a logical consequence of the primordial concern for the environment. With this assumption, and in view of the various criteria for sustainable development (regarding social equity, economic efficiency and environmental exhaustion), the role of economic science includes:

• To analyse investment behaviour with regard to sustainable technology development; and
• To identify performance parameters - such as technical efficiency and costs - of pursued technological innovations, taking into account the future economic conditions under which new sustainable technologies could be economically viable.

Part B of this thesis (Chapters 4-7) concerns the latter of these two issues.

Chapter 2: Existing ex ante technology assessment methods

Two major methods used for the assessment of technology development are identified. These are life-cycle assessment (LCA) and cost-benefit analysis (CBA). Both methods usually conclude with an evaluation of indicators concerning economic and environmental impacts of new technologies. But they differ considerably with respect to the systems in which the technologies are projected. LCA investigates production chains, from raw material to final disposal, and thus places system boundaries at the borders of the exhaustible environment (or of the buffer environment in the case of a sustainable operation). CBA, on the other hand, draws system boundaries around economic actors such as firms or countries. This leaves certain environmental issues outside a CBA, so that LCA-type analyses may be required to identify system-external matters for subsequent incorporation into the CBA framework. Another major difference between LCA and CBA concerns the weighting of asynchronous events. CBA makes use of the discounting method. This approach could also be applied in LCA, but according to internationally agreed standards this is apparently not seen as necessary by its practitioners. For the weighting and evaluation of indicators, LCA, unlike CBA, does not provide generally accepted procedures. And in fact, many LCA evaluations are inconsistent with the existing evaluations that take place in the everyday economic reality of internalised environmental matters.

The elements considered useful for an assessment method for technology development, offered in a complementary manner by the respective methods, are further integrated in Chapter 3.
Chapter 3: Integrating LCA and CBA for the evaluation of mutually exclusive technology development projects

Many different technologies can be conceived for sustainable development. But society does not need all of these technologies at the same time and the same place. And it may even be unable, due to financial constraints, to develop these technologies simultaneously. The conceivable technologies will not be equally attractive, particularly if social equity, economic efficiency, and environmental exhaustion, are requisites for sustainability. So, in reality, one faces a technology selection problem.

In this thesis, the development of sustainable technologies, for central electricity production, is the main topic through which this technology selection problem is further elaborated. The major environmental issue considered is global climate change ascribed to the net emissions of GHGs. CBA serves as the main analysis framework, in a manner though which incorporates the economic value of GHG emissions and their reduction. This is made possible as a result of the UN Framework Convention on Climate Change, and its further development into the Kyoto Protocol. By adopting the Protocol’s approach to global climate change, especially in as far as Joint Implementation and the Clean Development Mechanism are concerned, an important feature of LCA is preserved, namely the placement of system boundaries at the level of the exhaustible environment, where applicable extended beyond the borders of individual countries and firms.

However, CBA ultimately allocates costs and benefits, even of environmental goods, to systems which are identical to economic actors, in this case countries or electricity producers. An analysis of these systems shows that the appropriate indicators for economically feasible technologies are:
- Unit production costs of biomass fuels ($UPC_{\text{raw material}}$).
- Unit production costs of electricity and GHG emission reduction units ($UPC_{\text{product}}$).
- Internal rate of return on investments in production equipment for electricity and emission reduction units (IRR).

Technologies are economically feasible if they can be operational within a balanced system of UPCs and IRR which reflect market prices of goods and of capital cost.

Following this, the position of competing technological concepts in terms of the above indicators is investigated. Market niches, defined in terms of UPCs and IRR, are identified where individual technologies are economically feasible. The mutual relationship between these ‘feasibility niches’ is investigated if multiple technologies are considered. To this end, two new concepts are introduced: the iso-IRR function and the equi-IRR function, both in the field of UPCs. Using these concepts, it is illustrated how feasibility niches can be affected by technology-related parameters which are subject to specific R&D efforts.

Finally, in this part, it is observed that there are several possible reasons why the development of one sustainable technology concept is preferred over another. These include:
• The development of a concept may result in an increase in the affordable biomass fuel price.
• The development may lead to decreased emission reduction costs.
• The development may result in more profitable investments.

Whichever reason is decisive will depend on market prices, the market position of actors, and on their objectives. Technology assessments must therefore be founded in these market realities. Part B of this thesis, about biomass-fuelled central electricity production technologies, starts with an investigation of these items.

Part B: Applications to biomass-based renewable energy concepts

In the second part of this thesis, the newly established methodology is applied to biomass-fuelled central electricity production. First the scope for application in the EU is considered. Following this, the assessment focusses on rural electrification in developing countries. Where biomass, in addition to being grown purposefully as an energy crop, may become available as residues and waste, developments in legislation with regard to waste biomass can be critical. This is discussed in a special introduction to Part B. Here also, the methodological differences between technology assessments for waste processing and for sustainable electricity generation are discussed.

Chapter 4: Biomass fuel markets

The worldwide potential of biomass for sustainable energy production is reviewed and the implementation policies of the industrialised world are identified. The EU is the most pronounced with regard to its implementation targets for sustainable energy. The European case is analysed through a broad investigation of supply and demand issues.

Demand side: Although in the EU expectations with regard to biomass energy are high, it is shown that:
• There is a considerable discrepancy between the politically agreed targets (‘Energy for the future’, 1995) and the scientific results of the Shared Analysis Project (1999) (a project initiated in 1998 by the Directorate General for Energy of the European Commission with the aim of integrating the potential for energy policy analysis that was present within the member states of the EU).
• Analyses of biomass fuel markets are not reported in an integrated manner in the reviewed studies, and the possibility of importing biomass fuels, or biomass-derived fuels, is ignored.
• The implementation plans of the EU, in so far as electricity is concerned, are mainly focussed on applications and on technologies which are expected to become obsolete by 2010-2020.

By this time, alternative technologies for the electricity sector should have been developed, so that policies initiated can be sustained and developed further. These may include innovative technologies for dedicated biomass-fuelled power plants, and new co-firing technologies applied in future state-of-the-art electricity plants fuelled by coal, oil or gas.
Supply side: Existing analyses show that sustainable biomass fuel supplies for large-scale implementation of biomass-based electricity generation technologies are technically feasible. The review of available studies suggests that fuel supply studies have given insufficient attention to quality issues. It is proposed to distinguish between:

- Dry (ligno-)cellulosic residues and waste as well as (ligno-)cellulosic energy crops.
- Wet cellulosic residues, waste and energy crops (e.g. algae).
- Other energy crops, such as oil seeds for methyl ester, sugar/starch crops for ethanol.

Cost indications for fuels in the first category are given and the costs of imported biomass fuels are estimated. From the existing studies it is concluded that cost estimates of energy crop cultivation are often unrealistically low. An improved costing method is therefore proposed. Since existing scenarios do not provide sufficient detail for a projection of future supply and demand behaviour for biomass fuels, a range of biomass fuel costs is used in the further analyses.

Chapter 5: A concise exploration into technologies for central biomass-fuelled electricity generation

Four different technical concepts for central biomass-fuelled electricity generation are identified. These are:

- **CS**: Combustion followed by a steam cycle.
- **GCC**: Gasification followed by a combined Brayton-Rankine cycle.
- **Single-site LCC**: Liquefaction followed by a combined Brayton-Rankine cycle for further on-site conversion of the liquefaction products: bio-oil and pyrolysis gas.
- **Multiple-site LCC**: Liquefaction at various sites, followed by transportation of the bio-oil and the subsequent electricity generation in a combined Brayton-Rankine cycle at a central site where various streams of bio-oil come together.

Technical issues, including typical efficiencies and scales, are critically reviewed.

From the above list, only CS is a mature technology. Biomass-fuelled GCC technology is strongly promoted by technology developers and also by policy makers and developers such as the Intergovernmental Panel on Climate Change (IPCC). The two LCC technologies are barely recognised as concepts eventually capable of providing sustainable electricity. The further analysis in Chapter 6 focusses on the development scope of these last three technologies. Given its maturity, the CS concept serves as the benchmark in the comparative technology analysis.

Chapter 6: An economic comparison of concepts for central biomass-fuelled electricity generation

From the complete set of site-related and technology-related parameters needed for the assessment, a number of market data (biomass fuels) and technology data (technical feasibility, energy conversion efficiencies) have already been reviewed in the preceding chapters. The full data set required for the final assessment is now completed with demand side expectations (such as electricity costs, and values of GHG emission reduction units.
For the GCC and the single-site LCC concepts, appropriate technology development targets cannot be identified. The fundamental reason is that, given the market expectations for biomass fuels, electricity, and ERUs, the projected energy conversion efficiencies are not sufficiently high, especially with large-scale applications. In contrast, for the multiple-site LCC concept, feasible technology developments can be identified and expressed in terms of minimum scales required for economic feasibility, and costs relative to scale.

In a final summing up, these results are contrasted with the strategies expressed by the IPCC with regard to making the energy supply sector more GHG neutral. The point is made that the IPCC’s approach is contingent upon an optimistic view of future biomass fuel prices - much more optimistic than can be reasonably sustained for the EU. Additionally, whereas the current analysis is made from the perspective of purely societal objectives applicable to EU-type economies, the results in this thesis are also considered from alternative angles:

- A technology developer’s viewpoint. Irrespective of any associated environmental benefit, technology developers seek a market for their products. It is shown that the analysis made in this thesis leaves the question of their future market basically unanswered.
- The electricity sector in developing countries. Here, the long-run marginal cost projections of biomass-based electricity generation, in comparison with other electricity generation technologies, determine the potential role of innovative biomass-fuelled concepts. An investigation of this potential also requires a different type of analysis.

Chapter 7: Rural electrification

The long-run marginal cost approach is followed in an assessment of biomass gasification for rural electrification in developing countries. Two cases are distinguished: one in which ERUs are ignored, and one in which these are valued. In the latter case, a relatively low value projection is taken. These cases are in accordance with the scenarios distinguished by researchers of the future market for ERUs. R&D targets in terms of investment costs are derived. The question as to whether these are realistically achievable by equipment manufacturers is deliberately left open to be answered by technology developers.
Conclusion

The insights gained in this thesis are not what one might have predicted, and to some extent are also controversial. This applies equally to the methodology established as to the results of the technology assessments. For example, an economic approach to sustainability is not the most popular position one could have, and the technology developments recommended here differ from those usually met in the arena of sustainable energy technology development. Of those, the most challenging one might very well be the hint to a potentially decisive role of developing countries in achieving a sustainable future.
PART A: METHODOLOGICAL FRAMEWORK
1 THE PROBLEM OF SUSTAINABLE TECHNOLOGY DEVELOPMENT

1.1 CONSIDERING THE ENVIRONMENT

Nowadays, the quality of the environment, and our relationship to the environment, both care of and dependence on, are ubiquitous subject matters in the public debate, in politics and in governments. Scientific and popular journals are dedicated to the environment, as are laws and treaties, as well as national ministries and even entire international organisations. ‘Nowadays’, indeed, since it has not always been like that. Perhaps, because the environment was once in a better shape, or perhaps we behave in a more fashionable manner now. Or has anything changed in our perception?

1.1.1 A definition

For many of today, the Report to the Club of Rome\textsuperscript{3} and Silent Spring\textsuperscript{4} are a milestone in the public debate, warning that economic development was straining against the finiteness of resources and nature’s resilience. Up to the late 1960s, the environment was widely considered to be an infinite supplier of resources and an infinite absorber of wastes. This was in full accordance with the traditional concept of the environment as understood in physical sciences such as chemistry and physics. For these sciences the environment has a very precise meaning, i.e. that which is external to the considered systems, and with which the considered systems interact. Although the principal dependence of systems on their environment is thus recognized, it is also a first principle of these sciences not to investigate the environment. After all, the environment is placed externally. Moreover, in this approach, such an investigation is not even needed, due to the specific characteristics of the environment: it is invariable. Its properties do not change if something is taken from it or put into it. In chemistry, this characteristic defines a buffer.\textsuperscript{5} With reference to this attribute I call this type of environment a ‘buffer environment’. Graphically, this type of environment, external to the economy, is illustrated in Figure 1. Because of the unchanging nature of the environment, thus understood, its investigation has not been of any interest.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{An economy interacting with a buffer environment (Arrows denote material and energy flows).}
\end{figure}

\textsuperscript{3} Meadows, Meadows, Randers \textit{et al.} (1972).
\textsuperscript{4} Carson (1962).
\textsuperscript{5} Compare with the concepts of sink and source. Examples: (1) a heat source, in thermodynamics, is something which can provide heat while its temperature remains the same; (2) a CO\textsubscript{2} sink is something into which CO\textsubscript{2} can be absorbed without resulting in an increased CO\textsubscript{2} concentration in the sink.
Today, we have discovered that human interaction with the surroundings does result in clearly visible changes to these surroundings. Our surroundings, at least at a local level, appear incapable of infinitely absorbing our wastes, and of infinitely supplying raw materials. Since it is no longer able to support human economies infinitely, the environment also needs consideration. We still call these surroundings the ‘environment’, but not anymore in the classical sense of a given and giving constant, but rather as a vulnerable living condition. In many instances, the meaning of the word ‘environment’ has thus changed into its opposite. In contrast with a buffer environment, I call this the ‘exhaustible environment’. However, as far as we are aware, our surroundings are not exhaustible in all respects, since still quite a number of classical sinks and sources can be identified. Everyday usage of the word ‘environment’, therefore, generally carries the two notions of both a buffering capacity and exhaustibility at the same time. Weterings and Opschoor, for example, defined the concept of environmental utilisation space in a study for the Dutch Advisory Council for Research on Nature and the Environment (RMNO), in an attempt to prepare a quantified basis for the Dutch sustainable technology development programme (STD). Their definition is somewhat loose, but can be paraphrased as follows:

Environmental space is the maximum claim which economies may place on the environment. Its size is determined by the maximum level of human activity above which nature and environment are no longer able to absorb its pressure or to repair its damage in a reversible manner.

We can immediately recognise the dualistic character of the environment pointed out above: the environment may act as a buffering sink or source, or it may become an exhaustible system.

The ‘environment’ has two distinct characteristics:
- It is a buffer which does not change (buffer environment)
- It is an exhaustible resource carrier (exhaustible environment)

The environment, as a subject of national and international policies, encompasses a large variety of issues, ranging from abstract concepts such as biodiversity, through quite intangible things such as climate stability, to concrete items such as smog. Any listing of environmental issues appears to be somewhat arbitrary, rather than the result of a systematic analysis. One might expect that official sources, such as policy reports and laws, could help to yield a systematic understanding of the environment and environmental matters. However, on close inspection, clear definitions of the environment cannot be found there. Perhaps the non-systematic character of any listing of environmental issues is an essential feature of our relationship with the environment, which after all is situated, at least partially, outside the boundaries of our systematic knowledge. As society develops, its interactions with the environment change both in qualitative and quantitative terms. As a result, environmental issues present themselves in an unpredictable manner. What has not been an issue until today, may suddenly become problematic without prior notice.
tomorrow or later. This has clearly happened with the ozone layer (affected by the
emission of CFCs) and climate change (caused by the emission of GHGs). The first
expectation of global climate change due to anthropogenic CO₂ emissions were formulated
in 1896,⁸ recognition of agricultural losses as a result of damage done to the protective
ozone layer dates back to 1982.⁹ To better grasp what is incorporated in the novel
definition of the exhaustible environment, one can look into what is actually reported in
studies and policy papers. Below, some examples are taken from studies by the Dutch
Advisory Council for Research on Nature and the Environment (RMNO) and reports by
the OECD, several Life-Cycle Assessments (LCA) into biomass energy systems, and the
EU’s Fifth Action Programme on the Environment.

RMNO and OECD: In participating within the sustainable development project of the
OECD,¹⁰ the Dutch Ministry of Housing, Spatial Planning and the Environment
commissioned a study by the Dutch Advisory Council for Research on Nature and the
Environment (RMNO).¹¹ Among other things, the study investigated the environmental
issues considered relevant in order to identify suitable environmental performance
indicators. The authors distinguished three dimensions to the environment:¹²
• Pollution,
• Depletion of natural resources,¹³
• Loss of naturalness.

These three dimensions do fit with the systematics agreed within the OECD. Rather than
a comprehensive set of complementary categories, in its core set of indicators for
environmental performance reviews,¹⁴ the OECD presents (and reiterated in its progress
report on sustainable development)¹⁵ a politically negotiated list of issues to be dealt with.
They are listed in Table 1. The table also provides an interpretation in terms of the
dimensions proposed by Weterings and Opschoor.

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10/ Reported by OECD (1999b).
11/ Weterings and Opschoor (1994). This study builds on previous work carried out by the same
authors (Weterings and Opschoor (1992)).
13/ With respect to the second dimension, the authors recognised that national and international
policy fora consider resource depletion an economic issue rather than an environmental one (Weterings
and Opschoor (1994), p.46). The argument for it being economic refers to two fundamental response
options to depletion:
• Interchanging resources, which is possible if alternative resources for the same service exist in
  sufficient amounts,
• Decreasing utilisation rates by increasing utilisation efficiencies in balance with continued
depletion.
However, even if considered economic, the issue can still be classified among the environmental matters,
particularly if understood within the framework elaborated later in this section. There need not be a
fundamental contradiction between economy and environment.
14/ OECD (1993b).
15/ OECD (1999b).
It is observed that the general issue of resource depletion is adopted by the OECD only in as far as it concerns the use of renewable resources. Neither non-renewable material resources (considered relevant by the Dutch STD programme)\textsuperscript{16} nor fossil fuel resources (held relevant by Weterings and Opschoor (1994)) were recognised as being threatened by depletion. In a study preceding publication of the ‘core list’ of environmental indicators, fossil fuel depletion had been considered but implicitly rejected.\textsuperscript{17} The conclusion was drawn that fossil fuel depletion may be relevant, but that its conceptual base, data availability, quality and comparability all need development work, and that definitions need standardisation.

**LCA:** Issues often encountered in environmental life cycle analyses of bio-energy projects are the following:\textsuperscript{18} global warming, resource depletion, acidification, ozone depletion, human and eco-toxicity. These are further elaborated in Table 2.

**EU:** An interesting formulation of environmental issues is found in the EU’s fifth environmental action plan, EU (1993). Seven themes were selected for priority actions, i.e. climate change, acidification and air pollution, depletion of natural resources and biodiversity, depletion and pollution of water resources, deterioration of the urban environment, deterioration of coastal zones, and waste. The anthropocentric rationale which partially justifies the choice of these themes is most remarkable. A review is given in Table 3.

\begin{table}
\centering
\begin{tabular}{|l|c|c|c|}
\hline
\textbf{Issue identified by OECD (1993b)} & \multicolumn{3}{c|}{\textbf{Dimensions proposed by Weterings and Opschoor (1994)}} \\
& \textbf{Pollution} & \textbf{Depletion of natural resources} & \textbf{Loss of naturalness} \\
\hline
Climate change & x & & \\
Ozone layer depletion & x & & \\
Eutrophication & x & & \\
Acidification & x & & \\
Toxic contamination & x & & \\
Urban environmental quality & x & & \\
Biological diversity & & x & \\
Landscape & x & & \\
Waste & x & & \\
Water resources & x & & \\
Forest resources & x & x & \\
Fish resources & x & & \\
Soil degradation (desertification and erosion) & x & x & \\
\hline
\end{tabular}
\caption{Environmental issues agreed within the OECD (dimensional interpretation by the author based on the elaborations in the cited sources).}
\end{table}

\textsuperscript{17} OECD (1993a), p. 10-11.
\textsuperscript{18} Compare for example Kaltschmitt and Reinhardt (1997). Biewinga and Van der Bijl (1996) additionally include: emissions of nutrients and minerals to soil and water, ground water depletion, erosion, waste production, landscape values.
Table 2. Environmental issues encountered in LCA of biomass energy projects.

<table>
<thead>
<tr>
<th>Resource depletion</th>
<th>Oil</th>
<th>Natural gas</th>
<th>Coal</th>
<th>Uranium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-renewable energy resources</td>
<td>Hydro electricity</td>
<td>Biomass</td>
<td>Other (e.g. wind)</td>
<td></td>
</tr>
<tr>
<td>Renewable energy resources</td>
<td>CO$_2$</td>
<td>N$_2$O</td>
<td>CH$_4$</td>
<td></td>
</tr>
<tr>
<td>Global warming</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ozone depletion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acidification</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human and eco-toxicity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a/ According to Kaltschmitt and Reinhardt (1997).</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Selected anthropocentric justifications behind the environmental themes chosen in the fifth environmental action plan of the EU.

<table>
<thead>
<tr>
<th>Theme</th>
<th>Anthropocentric rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change</td>
<td>Serious problems for the Community itself (frequency of extreme meteorological events, sea level rise, heat and drought spells, etc.)</td>
</tr>
<tr>
<td>Acidification and Air Quality</td>
<td>Damaging effects on ……. lakes, other surface and ground waters and soils. (Partially anthropocentric)</td>
</tr>
<tr>
<td>Protection of nature and Bio-Diversity</td>
<td>(Damage to nature and biodiversity ) is in contradiction to mankind’s fundamental desire to live in harmony with nature and to enjoy and derive pleasure from it. Nature provides an invaluable genetic bank which is essential to medical, biological, agricultural and other scientific progress.</td>
</tr>
<tr>
<td>Management of Water Resources</td>
<td>Without water, a harmonious and sustainable maintenance or development of socio-economic activities is not possible. (One action is ) To restore contaminated groundwater to a quality required for drinking water production purposes. Manufacturing industry (processing), the energy sector (cooling), the agricultural sector (irrigation) and the tourism sector (drinking and bathing) are very dependent on the availability of good quality and sufficient quantities of water.</td>
</tr>
<tr>
<td>Urban Environment</td>
<td>The urban areas are the places where the problems of the environment touch most the quality of life of citizens.</td>
</tr>
<tr>
<td>Coastal Zones</td>
<td>The Community’s coastal zones constitute a unique environmental heritage, with irreplaceable ..., cultural and economic resources.</td>
</tr>
<tr>
<td>Waste Management</td>
<td>Waste ……. can also constitute secondary raw materials.</td>
</tr>
<tr>
<td>a/ Cited from EU (1993).</td>
<td></td>
</tr>
</tbody>
</table>
Admittedly, the EU’s approach to environmental issues is broader than this suggests, but in a number of occasions a reference to the economy is apparent:

- Fresh air is required for human health, clean air is needed with regard to soil acidification,
- Clean surface and ground water are required to provide drinking water,
- Clean surface water is also needed for productive fisheries,
- Clean soils are needed for the production of good quality agricultural products,
- Clean soils are also needed with regard to healthy living areas.

In many of the above examples of environmental concern, on closer inspection, care is expressed about the consequences of one human activity on another: for example smoke emissions may affect human health, sewage water spillage may affect the cost of providing clean drinking water. Hence the definition of environmental management given by J.W. Kroon, substitute chairman of the Dutch Commission on Environmental Impact Assessment, “Environmental management is how one deals with one’s neighbours". The environment, and the relevant environmental impacts, are understood here in an economic manner - interpreting, admittedly, the economy in a broad sense, i.e. as the total arrangement of the human household. I call this type of environment the economic exhaustible environment, since the Kaldor-Hicks principle of welfare economics is applicable here. After all, it is conceivable that compensating payments are made by perpetrators to victims (although this is not to suggest that compensation would be preferable over prevention).

Future human generations constitute a particular expression of the economic exhaustible environment - a view strongly articulated in the well-known Brundtland report. Our dealing with these fellow men is elaborated further when discussing sustainability below, where the dimension of time is introduced into the relationship between present day society and the environment.

In other instances, such as in the case of biodiversity, and also when considering the creation of nature reserves, forest protection, habitat protection, etc., we come across another understanding of the exhaustible environment, i.e. one in which it is felt that specific aspects of nature need protection for their own sake. The environment, using this definition, deserves our absolute respect, - ‘absolute’ since there is no reference to the human economy. Any interference of our economies with this type of environment should be prevented and, as a consequence, specific areas are turned into nature reserves and fenced in. This has a cost, since fences and other types of protection cost money, and the resources available at those locations, such as wood, oil and minerals, can no longer be utilised. So, also in this case, as soon as we become aware of it as an issue, we deal with this type of environment in an economic way, but no longer by a transaction in which a cash transfer is made to the victim. In reality, in this situation, compensating payments are available at those locations, such as wood, oil and minerals, can no longer be utilised. So, also in this case, as soon as we become aware of it as an issue, we deal with this type of environment in an economic way, but no longer by a transaction in which a cash transfer is made to the victim. In reality, in this situation, compensating payments are


20/ "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (World Commission on Environment and Development (1987), p. 43).
not even conceivable. I call this type of environment the *theoretical exhaustible environment*, using the word ‘theoretical’ in its antique Greek meaning of contemplative or speculative. The theoretical, or speculative, attitude was already discussed by Aristotle, and after him by the mystics and other philosophers from the Romans through into the so-called Dark Ages. It concerns a disinterested desire for knowledge (truth) and beauty for their own sake. At this point one is forced to note the fundamental contradiction within the concept of a ‘disinterested desire’ - a contradiction which I suggest should be regarded as a driving force towards more knowledge and beauty, rather than a force into the silence of the meaningless (as the positivist reader might conclude). This driving force towards more knowledge and beauty can, perhaps, be illustrated with the following quotation about contemplation from Aristotle:

> “And this activity alone would seem to be loved for its own sake; for nothing arises from it apart from the contemplating, while from practical activities we gain more or less apart from the action.”

The concept of the disinterested desire for truth and beauty plays its role again, later in history, in the aesthetics of the German idealism, and, apparently, also in the way people experience the environment today. In this respect, the environment is the object of this particular type of contemplation, and it cannot be avoided because even contemplation which yields nothing more than itself needs an object. Speculations about environmental matters concern a reality of values that is independent of society. A tempting alternative descriptor, instead of theoretical exhaustible environment, is ‘intrinsic exhaustible environment’, since the type of values implicated here are often called intrinsic values. However, it is hard to understand how that which is intrinsic to a thing can be known. In practice, the term ‘intrinsic’ distracts from our interpretation and our needs of these environmental values.

Dealing with theoretical environmental issues is, just as with economic environmental issues, in the end a political decision, although these decisions are based on different grounds. Vested rights do not play a role, for example. Making the distinction is therefore of some importance. It is worth noting that often our national and international policies, regarding the exhaustible environment, do not adopt a position (let alone make a choice) with regard to the intended type of evaluation (economic or theoretical) of environmental impacts. The Dutch law on environmental impact assessment, for example, remains all-embracing by defining environmental impacts as “the consequences of an activity for the physical environment, as observed from the interest of protecting people, animals, plants, goods, water, soil, air and their mutual relationships, as well as observed from the interest of protecting ethical, natural scientific and cultural-historical values”.

No evaluation framework, as to the interest of animal or plant life etc. is provided. Yet it is us, the

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21/ Nicomachean Ethics, Bk. X: Ch. 7. Translation: W.D. Ross, in: McKeon (1941).
22/ The contradiction noted here was also recognised by Aldred (1994) (p. 383). Aldred attempts to “resolve the paradox”, as he puts it, “by decoupling two notions of value which are conventionally linked - welfare and utility ...”. For the purpose of the above analysis, there is no real need to resolve a paradox.
23/ Dutch law on management of the environment (Wet Milieubeheer).
people, on behalf of animals or plants, who have to make such an evaluation. How could one proceed? It is therefore to be welcomed that economic science has discovered the environment as one of its subject matters.

1.1.2 Economic theory and the environment

The changed attitude within society with respect to the exhaustible environment has become the subject of economic theory and the development of economic appraisal tools. In an analysis of sustainability concepts prepared for the World Bank, Pezzey\(^{24}\) showed that neoclassical economic growth models applied up to the 1960s assume a system which disregards the environment as one of the production factors. The economic system (Figure 2, with value flows connecting production factors), is thus placed within a schedule of material and energy flows such as shown in Figure 1, however with the assumption that the environment is inexhaustible, or, which is the same thing, that material and energy flows from and into exhaustible environments are zero or negligible. The postulated production factors are capital, technology and labour. ‘Environmental economics’, on the other hand, has recognized that actually the economy’s interaction with the exhaustible environment may not be that small, and therefore incorporates the exhaustible environment as one of the production factors within its analysis model (Figure 3).\(^{25}\) Note that the economic system encompasses the exhaustible environment but does not consider buffer environments.

![Diagram of the neo-classical model economy interacting with its environment](image)

**Figure 2.** The neo-classical model economy interacting with its environment (Dotted arrows denote value flows, continuous arrows denote material and energy flows).


Obviously, placing the buffer environment outside the analysis system is a mere conceptual operation. The difficulty is to identify those environmental matters which need to be incorporated within the analysis framework. Pezzey (1992) deliberately includes renewable resources. Although, at first sight, this appears to be superfluous in view of the buffer characteristic of renewable sources, it does, for two reasons, make sense:

- Renewability of a resource is a potential rather than a given fact. Biomass, for example, can be grown sustainably, but it can also be ‘mined’.
- Renewable resource characteristics of specific locations may compete with each other (for example, the fishery service potential of a lake may conflict with its habitat services for endangered species).

With the introduction of the environment as a production factor, several huge problems have entered economic science, including:

- The physical understanding of the environment: concrete distinction between, and identification of, environmental buffers and exhaustive environmental issues; and
- The valuation of environmental stocks (environmental capital) and services (including environmental impacts).

Whereas the first should necessarily be left to physicists, the latter is a particularly economic matter. Economists face the least difficulties with the valuation of economic environmental services. Valuation of theoretical environmental services is a lot more difficult, let alone a valuation of environmental capital.

A difficulty, common to all these matters of environmental valuation, is the quantification of the discount rate. This rate is not only required for cost-benefit analyses of projects and sectoral policies - balancing current and future costs and benefits, including environmental services and impacts, on a single scale in support of decision-making - but also for
As long as the environment was a mere buffer in economic science, the discount rate could be measured in the market. For economists who consider the environment as a production factor, this is clearly impossible since at least some environmental interactions are involved for which no monetary markets exist. Yet, the discount rate is determined in a coherent total of all the interactions together. Establishing the discount rate has therefore become a complicated and controversial issue. Scientific economic literature about the applicable discount rate suggests that the extended time frame applicable to some environmental matters, across generations, is the reason for the debate about the discount rate, and that a final solution should result from a proper analysis of inter-generational responsibility for equity. It is also apparent that in justifying a concrete discount rate, many economists ultimately appeal to ethical arguments. Thereby, the position in favour of a low discount rate is presented as morally superior, basically stating that only in that way is a proper account given of the damage to the environment that the present generation will bequeath to its descendants. This claim on an ethical exclusiveness appears to be flawed because discounting acts, ambiguously, like a double-edged sword: a low discount rate does not only place a heavier weight on future damage (costs), it also effectively supports investment projects and policies with low future benefits. Whereas the former claims to be morally right as an expression of care for future generations, the latter obviously does not. For a complete interpretation of the ongoing debate it is necessary to recognise the dualistic position of economic science: it is both descriptive and prescriptive. Descriptive, in the sense that it investigates - and we limit the argument here to the discount rate and its consequences - the value that people attach to future events, including environmental matters, and how people compare such values to current values. Prescriptive in the sense that the results of that investigation influence future economic behaviour, including the development of policies and the appraisal of projects. Although ethical considerations are not excluded here, the term ‘prescriptive’ is thus coined in a much more comprehensive manner than merely ethical. The role of economic science is structured in this manner because, as a social science, its practitioners are part of its subject of investigation - namely society. Selecting the appropriate discount rate is a public social decision, and

26/ How otherwise could available resources be capitalised? Simply valuing the available reserves of crude oil against current oil prices is inadequate in view of the much lower exploitation and consumption rates. Proportional to the discount rate, future sales value represents a lower present value.

27/ It should be noted that ‘inter-generational’ responsibility is an imprecise term, because it suggests, but does not actually denote, a mutuality. It merely reflects the responsibility of today’s generation of economic actors for those of generations to come (rather than the other way round). It is therefore measurable in principle.

28/ According to Hanley and Spash (1993) (p. 127), they all do: “After reviewing this literature, we argue that in choosing the discount rate, economists take an ethical view about the claims of future generations.” Arrow, Cline, Maler et al. (1995), (p. 131), on the other hand, observe a distinct descriptive approach in addition to an ethically-motivated prescriptive approach in the establishment of a discount rate.

29/ From an exposé by Schelling (1995), about the prevention of global warming, another argument may be derived on why a low discount rate is not necessarily morally just. It would result in appraisals of investments by the current rich in favour of benefits for the descendants of the current poor in developing countries (whereas those descendants are supposed to be richer than their poor predecessors). Schelling, however, does not interpret this circumstance as an argument against a low discount rate, but rather as an argument against discounting per se.

30/ This view of economic science corresponds with the vision articulated by Max Weber, which (continued...)
it may be presumed that when economists employ non-economic arguments to justify their choice of a discount rate, their vote is as worthwhile as that of any other representative of society. In everyday society, the debate is not precisely about the scientific notion of a discount rate, but in the end the outcomes of the public debate about concrete particular environmental values, together with observable behaviour, do determine the actually applied discount rate.

The controversy about the applicable discount rate has not remotely been resolved. This is illustrated by the fact that scientific journals continue to publish contributions to the debate. Even the principal question, as to whether a discount rate is at all adequate for an analysis of inter-generational distribution, has been put forward strongly. Schelling argues that the theoretical foundation of the discount rate (in a pure time preference and a changing marginal rate of consumption) refers to properties belonging to the subject making the evaluation, i.e. his own current and future consumption. In other words, discounting is not about valuing current savings in view of costs or benefits falling to not yet existent persons. His argument either calls for an extension of the theory (to keep discounting as a valuable tool), or for an alternative means to express inter-generational accounting. As to the latter, Schelling does make some serious suggestions but these are not further analysed here. For the time being, discounting as such is still broadly accepted among economists. In any case, this seems not entirely unjustified, since inter-generational responsibility is not completely a new phenomenon which for the first time became apparent in the debate on environmental issues. Although demonstrable time frames are an order of magnitude shorter, examples are visible in long-lived organisations such as countries and firms, and the investment funds for pensions. Here there does exist a general interest, transcending the individual interests of the current stakeholders. Perhaps the growth rates held necessary here to preserve continuity could be a genuine indication of an inter-generational discount rate.

Of course, the direct valuation of environmental services and impacts is as important as the more abstract selection of the discount rate. As explained above, environmental issues range from economic ones to theoretical ones. Economic environmental issues can be valued with regard to their economic impact on other economic activities, whereas theoretical environmental issues must be regarded on their own merits. Since markets do not yield the necessary information on theoretical environmental values, economists have to fall back on more vague valuation techniques based on the sounded willingness to pay or to accept. Alternative, and sometimes complementary valuation methods, include the

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30/(...continued)
was further commented upon and interpreted by De Boer: “Economic science, ..., concerns the behaviour of actors pursuing objectives in a situation of scarcity. It attempts to discover the rational calculations of (actors) .... As an attitude this type of understanding is similar to the mutual attitude among colleagues in the scientific discourse. Hence, the attitude towards the researched is equal to the attitude towards colleague researchers.” (translation: R.V. Siemons) (De Boer (1980), p. 128).


32/ Whereas “eternity is an unrealistic assumption for an individual, it provides a meaningful representation of long-lived organisations” (Toth (1995)). In his paper about discounting and the issue of global warming, Manne explicitly assumed “a single agent acting as a trustee on behalf of both the present and future generations” (Manne (1995), p. 392).
contingent valuation method, the hedonistic pricing method and the travel cost method.\textsuperscript{33} For the successful application of these methods, the various value components of goods must be distinguished. In the following discussion on this matter, it should be kept in mind that economic value is defined as the value which constitutes utility. The previous analysis suggests that the economic value (of any good, not only of environmental goods) consists of three components: traditional or pre-environmental economic values, economic environmental values and theoretical environmental values. Pearce,\textsuperscript{34} however, supposes that the total economic value (TEV) of environmental goods is broken down into the following four components:

\[ TEV = \text{Use Value} + \text{Non-Use Value}, \]

with:

\[ \text{Use Value} = \text{Direct Use Value} + \text{Option Value} + \text{Indirect Use Value}, \]

and:

\[ \text{Non-Use Value} = \text{Existence Value}. \]

Of these components, the Direct Use Value corresponds to the pre-environmental values irrespective of any environmental component. Indirect Use Values are non-marketed but economically valuable functions of the environment. These correspond to the economic environmental issues defined previously. For Existence Values, Pearce, in his ‘Economic valuation and the natural world’, merely provides a negative definition: they are values which are not reflected in any other value.\textsuperscript{35} Also Aldred, in a subtle and relevant analysis, presents a negative definition of Existence Value, i.e.: it is “the value assigned by the agent in addition to any expected changes in the welfare of the agent dependent on the good’s continued existence”.\textsuperscript{36} Without further reflections on Existence Values, it can be concluded that they correspond to the theoretical environmental issues previously identified. Option Values are not covered in the schedule implied earlier, of traditional or pre-environmental economic values complemented with economic environmental values and theoretical environmental values. According to Pearce (1992) (p. 9), Option Values concern the reservation of certain assets for potential future direct or indirect use. One might wonder whether Option Values cannot be assigned to future useless things of which we do not know the existence yet. For, what would be the willingness to pay, as expressed by a dyed-in-the-wool environmentalist, for the preservation of a forest which might be a habitat of a yet undiscovered and evermore useless species? (The possibility of ever discovering such species cannot be excluded). Whereas for some this may make sense - certainly for the imagined environmentalist - for others this is simply bizarre.\textsuperscript{37} But this should not matter to a descriptive economist. Munasinghe,\textsuperscript{38} with reference to work by Markandya and by Freeman,\textsuperscript{39} reports that doubts have been shed on whether Option Values can be meaningfully distinguished from Use Values. The bottom-line is, as

\textsuperscript{33} For a review and comparison of the fundamentals of these methods, see Hanley and Spash (1993).
\textsuperscript{34} Pearce (1992), p. 8-11.
\textsuperscript{35} Pearce (1992), p. 8.
\textsuperscript{36} Aldred (1994), p. 394.
\textsuperscript{37} In fact, this example was seriously proposed by Attfield (1998).
\textsuperscript{38} Munasinghe (1993), p. 38.
\textsuperscript{39} For secondary references see Appendix C.
indicated above, that economic actors should be capable, with or without assistance by analysts, of distinguishing between the value components of goods.

With these conclusions it is shown, somewhat detachedly, in which manner environmental values are being discovered in society as well as in economic science. The incorporation of the environment into economic science also provides an impulse to a better understanding of sustainable development, as discussed in the next section.

1.2 DEFINING SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT

The notion of the buffer environment, as defined above, is indispensable in an analysis of sustainability and the concept of sustainable development. There is a difference between the two, sustainability being a state, and sustainable development indicating a change.

Sustainability, understood as a constraint to society’s relationship with its exhaustible environment, is a characteristic which one desires to be applied to human economic activities in the broadest sense. At best, it is an ideal which is aimed for. Its actual achievement is difficult, if not impossible to demonstrate. In fact, it carries the notion of eternity, of something lasting for ever, supported by its surroundings: a buffer environment. In identifying options for making human activities more sustainable, it is attempted to turn impacts to the exhaustible environment into a long (or ever) lasting interaction. The quest for sustainability, which we recognize in a range of policies (e.g. the OECD project on sustainable development, the EU environmental action programme, the Kyoto protocol), is actually a movement to restore the classical relationship with the environment, from an exhaustible one back to a buffer environment.

For those who are interested in the development of Third World countries, the term ‘sustainable development’ does not merely refer to the change of an unsustainable economy into a sustainable one. For them, it reaches beyond that by including the pursuit of economic equity and growth. It is useful to provide a few details here, because in parallel to developments in economic science, some influential physicists have maintained their own stance in the discussion about sustainability and sustainable development without any interaction with economists. In terms of analysis tools, the main difference between an economic and a physical approach is that economists consider economic values whereas physicists consider physical quantities. It is perhaps therefore inevitable that physicists tend to define sustainability as a state, whereas economists are more disposed to look beyond the state towards economic development. This review starts with a purely physical interpretation of sustainability, continues with an interpretation of sustainable development which is both physical and economic in nature but which shows an exogenous view of technology, and concludes with an interpretation of sustainable development which integrates physical, technical and economic analysis in a dynamic manner.

1.2.1 A physical approach to sustainability

Fava, Consoli et al., representing the Society of Environmental Toxicology and Chemistry (SETAC) as well as the SETAC Foundation for Environmental Education, are involved in the development of life-cycle assessment tools (a topic discussed in Chapter 2). Their sustainability considerations are mainly about resource depletion. This issue is important to them out of a concern for intra-generational equity and for inter-generational equity. The first theme induces an expanded spatial horizon in their analyses, and the latter gives rise to an expanded time horizon. They distinguish flow resources and stock resources. In the first group they include:

- Air and wind
- Water
- Solar radiation
- Ocean currents
- Living resources

Stock resources would encompass:

- Land including space
- Primary fossil energy sources
- Minerals

The essential characteristic of flow resources, in contrast to stock resources, is that they are not only consumed but also replenished. It is therefore slightly puzzling why land is not classified as a flow resource. After all, although soils can become depleted of their fertility, land is never used up. Fava, Consoli et al. mathematise their findings into quantifiable sustainability indicators. For flow resources they give:

\[
\text{Depletion indicator} = \frac{\text{Consumption rate}}{\text{Rate of replenishment}},
\]

and for stock resources:

\[
\text{Depletion indicator} = \frac{\text{Remaining use years}}{\text{Stock}} = \frac{\text{Stock}}{\text{Consumption rate}}. \tag{44}
\]

Remaining use years can also be calculated for flow resources which are not sustainably consumed:

\[
\text{Remaining use years} = \frac{\text{Stock}}{(\text{Rate of replenishment} - \text{Consumption rate})}.
\]

It must however be doubted whether these are truly indicators of depletion. Critical counter arguments include:

- *Quantification:* Reliable quantification of resources is difficult, and in some cases (e.g. mineral fuel resources) it must be doubted whether it is possible at all.

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41/ Fava, Consoli, Denison et al. (1993), pp. 65.
42/ "... a resource may be relatively plentiful and sustainable in the country of manufacture, but may be near depletion in the country supplying the resource." (Fava, Consoli, Denison et al. (1993), p. 66).
44/ Remaining use years is sometimes also referred to by the 'resource-production ratio'.
• **Material conservation**: Material resources are never used up, but rather transformed into different shapes.

• **Substitution**: Options may exist for resource substitution.

By acknowledging that estimates of reserves are contingent upon commodity prices, technology innovations, and willingness to share information, the quantification difficulty is also recognized by Fava, Consoli et al.\(^{45}\) With respect to material conservation, they question whether the resource stock should be limited to the raw stock, or should also include the historical quantity processed.\(^{46}\) Their example is copper ore deposits and copper plumbing pipes. If the quantities processed are included, then consumption does not result in reduced stocks, and consequently the ratio of stock and consumption does not indicate remaining use years but rather a recycling rate of which it is unclear what it has to do with depletion and sustainability (unless, of course, an increased residence time during the utilisation phase can be identified). This particular observation is not made by the cited authors. Fava, Consoli et al. also observe substitutability as a principal characteristic of the economy.\(^{47}\) As an example, they mention the substitution of glass fibre for copper in telecommunications networks. The substitution option is paradoxical because, although a specific resource may become depleted, the service rendered by that resource may continue on the basis of its substitute. Or in other words: depletion may occur, but it need not necessarily matter. These questions make resource depletion less tangible as a sustainability issue, also in the opinion of Fava, Consoli et al. Yet, they stick to proposing the above indicators for sustainability analysis. This seems acceptable where quantification difficulties and recycling opportunities are small, and where substitution options are unknown.

Secondly, mention is made here of purely thermodynamic approaches to sustainability. These are especially applied to stock conservation and pollution. Their essence can be summarised by three points of departure (although it should be recognised that several variants of thermodynamic approaches exist):

• The considered system encompasses the Earth, i.e. all economic activities as well as their entire worldwide environment;

• Energy is conserved (the First Law of thermodynamics);

• The potential for an energy carrier to cause a change, reduces with the performance of that action (the Second Law of thermodynamics).

Given the assumed system boundaries, a buffer environment is provided by outer space. From there, scarce materials could be obtained,\(^{48}\) but no references in the literature about sustainability were found where this is speculated upon. Outer space also provides solar radiation, and this in turn is a source of renewable energy in the shape of sustainably grown biomass, photovoltaics, wind and hydro-energy. Likewise, tidal energy is provided from outside, by solar and lunar gravity. Used materials can be recycled by employing a

\(^{45}\) Fava, Consoli, Denison et al. (1993), p. 76.

\(^{46}\) Fava, Consoli, Denison et al. (1993), p. 70.

\(^{47}\) "... one major issue influencing the accuracy and utility of resource depletion analysis is the potential for greatly reducing overall demand for some reserves through substitutions." (Fava, Consoli, Denison et al. (1993), p. 73).

\(^{48}\) Incidentally, the equitable division of such goods is covered by Article 1 of the Outer Space Treaty (1966), signed by 123 and ratified by 96 countries (as per February 2001).
transformation process fed with energy, but the Second Law states that this necessarily results in increased entropy of the environment surrounding the recycling process. Managed non-sustainably, this entropy increase ends up somewhere within the system of the Earth, but it could be removed to outer space by employing the energy flow supplied from there. In this manner entropy production can be associated with all uses of stock resources, including mineral fuels, and it has been proposed as a measure for depletion.

In view of the Second Law, performance qualities can be attributed to an energy carrier. They are ultimately lost during its use. A simple example of a performance quality of an energy carrier is the ability of a hot material (say steam) to provide energy to something cooler. In some elaborations of the thermodynamic approach to sustainability, a particular performance quality is proposed: exergy. This is the ability of an energy carrier to provide work. As with the ability to provide energy by cooling, exergy is not an intrinsic property of any energy carrier per se, but it is rather a combined property of the energy carrier and the immediate surroundings of the process in which the energy carrier is employed, i.e. the lowest available cooling temperature together with the chemical composition of the immediate surroundings.\footnote{Accordingly, the exergy of a body differs from place to place. Sometimes the exergy is normalised by defining standardised surroundings, such as those proposed by Szargut, Morris and Steward (1988).} Note, however, that the exergy lost during the action of an energy carrier is independent of the chemical composition of the immediate surroundings. The lowest available cooling temperature remains, however, determinative for the energy loss of sustained processes.\footnote{In 1986, I gave a general proof of this insight (Siemons (1986)).}

The associated indicator for depletion of mineral energy carriers and raw materials is $T^* \Delta S$, where $T^*$ denotes the lowest available cooling temperature of the surroundings, and $\Delta S$ the entropy production of the process considered. Its use as a measure for contamination phenomena is also claimed\footnote{Cornelissen (1997).} - indirectly, by determining the entropy production required for emission removal - but in reality such a measure is not about contamination but about contamination prevention. A thorough review of the potential use of the exergy loss occurring in processes as an indicator for sustainability is given by Boudri, Cornelissen, Hendriks et al. (2000).

The depletion indicators proposed by Fava, Consoli et al., and discussed at the beginning of this section, are less comprehensive than the entropy-related indicators of the thermodynamic approach. Whereas the first are merely governed by the principle of material conservation, the development of the second is additionally inspired by the Second Law of thermodynamics. The comparative strength of the thermodynamic approach, is the ability to measure all depletion issues with the single yardstick of entropy production. However, since the thermodynamic approach effectively includes the material-balance approach, the objections against the indicators of Fava, Consoli et al. also apply to entropy-related indicators. At the same time, it is observed that these approaches are limited to material depletion and, as acknowledged by some, to pollution prevention. Several issues, such as biodiversity, landscape values (see Tables 1 and 2) are not covered.
Some economists, mainly grouped around the journal on Ecological Economics (published since 1989), have dedicated themselves to founding their science on the principles outlined above. An acknowledged pioneer in this respect is Georgescu-Roegen (1971) to whom the introduction of entropy production into economics is attributed. Söllner (1997), in his well-disposed review of the potential role for thermodynamics in economics, in Ecological Economics, concludes however that these approaches do not provide guidance into matters of valuation and social equity.

1.2.2 An economic approach to sustainability, with an exogenous view of technology

In this section, we turn to a wider perspective. Intra-generational equity (particularly North-South issues), inter-generational equity, and also technology, are held to be important here. The concern for sustainability in the approach discussed, leads to a plea for an alternative technology which is less polluting, less wasteful, and more equitable. Technology is thus interpreted in the broadest sense, as a lifestyle.

Together with Holdren, P.R. Ehrlich produced a number of publications which particularly focussed on the impact of population growth on the environment and the economy. They made use of the following equation:

\[ I = P \times C \times T, \]

where:
- \( I \) = environmental disruption,
- \( P \) = population,
- \( C \) = per capita consumption,
- \( T \) = environmental damage per unit consumption.

The equation expresses a linear relationship between population size, its per capita consumption, and the impacts caused to the exhaustible environment. An independent parameter \( T \) (with \( T \) for technology) is also postulated. Ehrlich and Holdren applied this equation to a number of different environmental issues, and redefined the parameters \( I \), \( C \) and \( T \) from case to case. For example, when considering air pollution from lead emissions (\( I \)), they defined \( C \) by the annual distance travelled per person, and \( T \) by the distance-specific lead emissions from cars. With their analyses, Ehrlich and Holdren demonstrated that marginal improvements in technology may be easily annulled by a growing population. Hence, for specific environmental issues, a radical technological change might be required, although migration and population policies could equally serve to do the job. There is a strong resemblance between the analysis of Ehrlich and Holdren, and the classic analysis of Malthus (1803), which was mainly restricted to food provision.

Although originally applied in a one-dimensional manner, the reach of the equation cited above has actually been interpreted in a broad manner so as to represent the interaction

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53/ The symbolic expression is taken from Ehrlich, Ehrlich and Holdren (1977).
between population size, consumption, the entire exhaustible environment, and the prevailing lifestyle (in short: technology). The appealing ‘Ehrlich equation’, as it is occasionally known now, has since served many analysts and policy advisors to support their message that we need radically new sustainable technologies, to replace the existing ones.\(^{54}\) One relevant example of a technology development programme where this was done, is the Dutch inter-ministerial Sustainable Technology Development programme (STD). The results of the first 5-year term (1993-8) of the STD programme were reported by Weaver, Jansen, Grootveld \textit{et al.} (2000). One of the roots of the programme was a study of the ‘size’ of the exhaustible environment (Weterings and Opschoor (1992)),\(^{55}\) namely the environmental utilisation space defined in Section 1.1, above. The objective was to project quantification, over time, of the source and sink characteristics of the exhaustible environment. In this manner the future environmental context within which innovative sustainable technology is expected to be functional, could be anticipated.

Weterings and Opschoor, similar to the definitions given by Ehrlich, Ehrlich and Holdren (1977), defined the parameters as follows:\(^{56}\)

\begin{align*}
I &= \text{ environmental pressure}, \\
P &= \text{ population size}, \\
C &= \text{ per capita wellbeing}, \\
T &= \text{ environmental claim per unit wellbeing}.
\end{align*}

The authors concurred that environmental pressure, \(I\), is built up of a large number of variables, some of which are interdependent and some are not.\(^{57}\) For this reason it would perhaps be better to interpret the original ‘Ehrlich equation’ as a vector expression, as follows:

\[ I \cdot P \times C \times T, \]

where \(I\) denotes the multidimensional space of the exhaustible environment, \(P\) and \(C\) are scalars, and \(T\) represents the multidimensional environmental claim or metabolism per unit of wellbeing. Although setting out with this broad interpretation, Weterings and Opschoor did not adapt their analysis accordingly, but made use of the original scalar equation and applied it to individual environmental issues. In any case, whether scalar or not, for this representation of environmental space to make sense, the parameters should be independent. Once we have reviewed how Weterings and Opschoor utilised the equation in their analysis, we will return to this issue.

\(^{54}\) E.g. in addition to Ehrlich, Harper (2000) refers to Commoner, Meadows and Goldsmith.


\(^{56}\) Symbols are adapted to the original source (Ehrlich, Ehrlich and Holdren (1977)), also provided by Weaver, Jansen, Grootveld \textit{et al.} (2000) (p. 21) in their report about the Dutch STD programme.

\(^{57}\) Weterings and Opschoor (1992), p. 31.
Applying the equation as a normative instrument for sustainable environmental management

Weterings and Opschoor employed the ‘Ehrlich equation’ to investigate the required technology response to a number of cases representing depletion of renewable and non-renewable resources, and pollution. These are listed in the first column of Table 4. The authors started by setting particular requisites to the environmental claims, $T$, which society is supposed to make in a sustainable economy. Their approach is illustrated here with regard to the use of non-renewable resources, such as oil and natural gas. They interpreted parameter $I$ as the remaining reserves, and $P \times C$ as the annual worldwide consumption. Both are a function of time in a projected future. $T$ is the duration of continued supplies at the current utilisation rate, i.e. the so-called ‘resource-production ratio’ (its unit is year). Crucial to the analysis of Weterings and Opschoor is their postulate that sustainable management maintains the specific impact parameter, $T$, at a level of at least 50 years: $^{58}$

\[
\frac{I}{P \times C} \geq 50
\]

Initially, they did not justify this figure. One would expect that the establishment of such a criterion is contingent upon the time required for technology renewal, that is the development of techniques (technologies in a limited sense: the equipment) augmented by the time needed for their worldwide dissemination.$^{59}$ As a result of the proposed resource management, consumption would steadily decrease with time. Fifty years on, the resource would still be able to provide for another 50 years, ad infinitum. Although it might seem that any non-renewable resource dealt with in this manner achieves an infinite lifetime, and that consequently a radical technology change would never be required, this is an illusion. After all, there are physical limits to technology improvements, so that for any given resource, a moment will come beyond which it is no longer physically possible to maintain the proposed sustainable management strategy. After that moment, the available technology transition period would still be 50 years, but from then onwards, full resource substitution would be a necessity. With this view, it appears that an analysis based on the ‘Ehrlich equation’ does not automatically place an emphasis on radical technology renewal, and that it may also show the relevance of optimisation and process improvement. Where exactly the points of impact for a radical change are identified depends on the selection of the time frame (do we expect to need 20, 50 or 100 years for technology renewal?) and on the value obtained for the parameter $T$ (how many remaining use years are actually left?).

Maintaining the specific impact parameter at one value, while the population increases and the reserves decrease, makes a continued reduction in the consumption rate necessary. For the specific example of mineral oil, taking into account projected population dynamics,


$^{59}$ In a later study Weterings and Opschoor postulated $T$ again as a constant of 50 years, justified, this time, as the expected time required for radical technological change from a fossil fuel economy to a solar energy economy (Weterings and Opschoor (1994), p. 30). Coincidentally, this is precisely the term considered critical by Georgescu-Roegen during the 1970s and 1980s (cited by Daly (1997), p. 271).
they concluded that, by the year 2040, oil consumption should be reduced by 85% compared to a business-as-usual scenario. For other depletable resources, the results of their analysis, expressed as worldwide levels of desired utilisation reductions, are listed in Table 4. An equitable division of environmental utilisation space among the various economic entities, identified as the industrialised and the developing countries - based on population size: a per capita division - makes the desired reduction levels in industrialised countries yet more rigorous. In this manner, sustainable technology development was given a target, thus establishing the margins for an equitable development of the world economy.

Table 4. Desired worldwide consumption levels adopted by the Dutch STD programme (Source: Weterings and Opschoor (1992)).

<table>
<thead>
<tr>
<th>Impact /a</th>
<th>Desired utilisation reduction by the year 2040, w.r.t. business-as-usual scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Depletion of non-renewable resources:</strong></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>85%</td>
</tr>
<tr>
<td>Natural gas</td>
<td>70%</td>
</tr>
<tr>
<td>Coal</td>
<td>20%</td>
</tr>
<tr>
<td>Aluminium</td>
<td>None</td>
</tr>
<tr>
<td>Copper</td>
<td>80%</td>
</tr>
<tr>
<td>Uranium</td>
<td>Unknown</td>
</tr>
<tr>
<td><strong>Depletion of renewable resources:</strong></td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td>60%</td>
</tr>
<tr>
<td>Biodiversity (extinction of species)</td>
<td>99%</td>
</tr>
<tr>
<td><strong>Pollution:</strong></td>
<td></td>
</tr>
<tr>
<td>CO₂ emission</td>
<td>80%</td>
</tr>
</tbody>
</table>

/a/ This categorisation by the referred source.

The recommendations are sweeping. The topic of sustainable biomass utilisation (about which rigorous advice is given by Weterings and Opschoor: a 60% reduced consumption) is discussed in more detail in Chapter 4. In principle, it would be possible to achieve the recommended reductions in a number of ways, characterised by a reduced consumption or by radical new technologies providing equal or even larger services based on alternative resources.

Before accepting the suggested way forward, there are a number of methodical difficulties associated with the analysis by Weterings and Opschoor which are worth considering. It is not surprising of course - this type of analysis being a straightforward further development of the depletion indicators quoted by Fava, Consoli et al. - that their analysis of depletion phenomena is hampered by the same principal difficulties as those encountered in Section 1.2.1: quantification, material conservation, and the substitution paradox.

Quantification difficulties: For the example of oil depletion, quantification difficulties become apparent when confronting the data of Weterings and Opschoor with current estimates, roughly a decade newer. In retrospect we know that in 1990 the resource
was much larger than the assumed 6,000 EJ.\textsuperscript{60} This is due to the fact “that technological advances in exploration technologies are enabling oil finds to be made with less risk and lower technical costs”\textsuperscript{61}. In 1999 Odell reported a conventional oil reserve of 16,000 EJ, plus a non-conventional oil reserve of another 16,000 EJ. Thus, in retrospect, the resource-production ratio in 1990 was much larger than the assumed 50 years, in fact about 250 years. Weterings and Opschoor could not possibly have known the underlying data already in 1990. But the phenomenon of increasing exploitable reserves has been known since much earlier times. Meyer, for example, shows that proven oil reserves had increased by about 70% during the period 1970-1990.\textsuperscript{62}

**Substitution:** In addition, I argue, had they appreciated the interchangeability of mineral fuel types (oil, gas, coal), they would have concluded - on the basis of the then prevailing data - that there is no need at all for a reduced consumption of those fuels within the time frame of their study.\textsuperscript{63} (With the presumed 50 years criterion for sustainable resource management). This touches upon the substitution paradox, already encountered when discussing the physical approach to sustainability (Section 1.2.1). It is not that an analysis using the ‘Ehrlich equation’ would suffer from a fundamental shortcoming with respect to the option of substitution. On the contrary, substitution of one resource for another yielding the same service, is one of the possible response options to depletion. And therefore, from an analysis based on the ‘Ehrlich equation’, an investigation into potential substitutions within the prevailing technology paradigm may be demanded. A radically renewed technology, such as a ‘solar society’, is not the only possible answer. It was nevertheless a deliberate choice of Weterings and Opschoor to disregard substitution options. This becomes apparent from their second report to the Dutch RNMO,\textsuperscript{64} in which they advocate what they call ‘strong’ sustainable management with regard to stock resources, as opposed to a ‘weak’ one.\textsuperscript{65} Strong sustainable management means that each of these resources is employed in such a manner that it is never completely exhausted. Sustainability would thus imply that what has once been a resource, should remain a resource for ever. Weterings and Opschoor actually present this approach as a political choice,\textsuperscript{66} but what is their justification? Substitution can be shown to exist in both economic and technological development. And if a resource is fully substitutable it is no longer a singular resource for a particular useful function. Part of it may continue to exist or it may be consumed altogether - that does not matter to anyone. Evidently, inter-generational equity is not necessarily served by insisting on strong sustainability. One has to admit that in cases where substitution cannot be foreseen, there is no certainty as to the timely occurrence of technical and economically feasible

\textsuperscript{60}/ Weterings and Opschoor (1992), p. 9.
\textsuperscript{61}/ Odell (1999), p. 737.
\textsuperscript{63}/ Without precisely repeating their calculations with an assumed full compatibility of oil, coal and gas, this speculation is based on the following: economic exploitable reserves of coal, oil and gas were estimated at 26,000, 6,000 and 4,500 EJ respectively, and their respective annual consumption at 90, 125 and 60 EJ. Hence, in 1990, the aggregate resource-production ratio was 133 years. (Data are quoted from Weterings and Opschoor (1992), p. 9).
\textsuperscript{64}/ Weterings and Opschoor (1994).
\textsuperscript{66}/ “... we basically assume that a fairly strong position will be preferred ...”, Weterings and Opschoor (1994), p. 15.
alternatives for current uses of stock resources. But in such cases there is no such thing as a choice between strong or weak sustainability.

Material conservation: Unfortunately, Weterings and Opschoor also walk into the trap of disregarding material conservation. This can be illustrated with an example: their analysis of the worldwide copper ore resource and its utilisation. The position was taken that the size of the resource is known, and that the use of copper over time should be limited in accordance with this availability, taking into account population dynamics and the presumed 50 years criterion of sustainable resource management. Conversely, however, it can be argued that material resources generally are not limited by their current form of availability (e.g. in the form of ores). After all, previously used materials can be recycled. The conclusion regarding the desired reduction of worldwide copper utilisation (not that of ore but that of copper), is therefore unjustified.

One further difficulty concerning this type of analysis should also be mentioned. Above, it was shown that when managing resources according to the proposed method, the physical limits to technology optimisation ultimately make it necessary to abstain from the further use of the resources which are to be conserved. This contradiction proves that the ‘Ehrlich equation’ can ultimately not be maintained as a generally applicable theorem in a model of a sustainable economy. It might, however, have a limited validity, applicable during specific periods of economic history. In this manner, this type of analysis can help to formulate an appeal for revolutionary innovative techniques and even changes in lifestyles.

In the approach to sustainability discussed here, given the general state-of-the-art (of techniques and behaviour: of technology), each additional unit of consumption results in one extra unit of depletion, pollution, etc. (along the entire gamut of environmental issues). The existing technology can therefore be associated with the consumption-specific claim on the environment. The presumption made in drafting the ‘Ehrlich equation’ is that technology is an independent parameter. Otherwise such an equation would not make sense. In a meaningful scientific equation, parameters do not just mutually define each other. They represent existing properties and the equation shows their relationship. It might appear superfluous to state this simple insight here. But particularly with regard to the ‘Ehrlich equation’ some extraordinary philosophical remarks have been made by those employing it. Harper stated (in an otherwise very readable paper): “Ehrlich and Holdren’s equation ... can potentially be used in a more quantitative way if we redefine the factors more carefully to ensure consistency and measurability. ... In this reformulation C is effectively GDP per capita (GDP/P) in a given community of population P. T is a factor sometimes called environmental intensity, i.e., environmental impact per unit of GDP or I/GDP. Therefore I=P(GDP/P)(I/GDP) and simple cancelling shows the equation to be true by definition.” Likewise, Weterings and Opschoor wrote: “This equation is actually a generalisation of an identity” and subsequently, paraphrasing.

67/ Harper (2000), p. 366. In this citation symbols are adapted to those employed here.
68/ Weterings and Opschoor (1992), p. 5. The parameter Y is not further defined by the authors.
\[ I' = P \times C \times T, \]

and with \( T' = \frac{I'}{Y}; C' = \frac{Y}{P} \), it follows that:

\[ I' = P \times \frac{Y}{P} \times \frac{I}{Y} \]

\[ I' \rightarrow I. \]

Unfortunately, equations which are true by definition do not yield any insight beyond the definition itself - something which is clearly not intended by the referred to analysts. Therefore, I argue that technology is *de facto*, though apparently unwillingly, treated here as an independent parameter. That is to say, technology is understood as a given state-of-the-art rather than as a result of investments in R&D, financed from savings (equalling production minus consumption). This is why this method of analysis is categorised here with those economic approaches where technology is considered exogenous. In contrast, the model of neo-classical environmental economics (Figure 3) shows technology as a dynamic production factor. The relevance of this view for better understanding sustainable development is discussed in the following subsection.

### 1.2.3 An economic approach to sustainability, with an endogenous view of technology

Turning theoretical considerations on sustainable development into an operational approach, official reports and economic guide books from economic development organisations, such as the OECD and the World Bank, address the exhaustible environment *in addition* to social issues (such as health, living and working conditions, and income distribution) and economic issues (such as growth, efficiency, and financial stability). The aim of making our economies more sustainable goes hand in hand with making them more equitable and more prosperous. On behalf of the World Bank, Munasinghe (1993) illustrates this with the diagram reproduced in Figure 4, but similar illustrations (and hence conceptual understandings) can be found in, for example, the documentation of the OECD’s project on sustainable development.
Munasinghe identifies the maximisation of net economic and social benefits as the overall development objective, also of sustainable development. Notice that sustainability is not merely presented as an alternative next to economic development, let alone economic growth, but is put forward as placing additional requirements on desired growth or development. He summarises these additional requisites as follows.\footnote{Munasinghe (1993), p. 4.}

- Services from, and stock, of natural resources are to be maintained, whereby
  - Renewable resources should be used at rates below or at their natural rate of regeneration,
  - Non-renewable resources should be utilised at an efficiency\footnote{One might suggest: at a ‘rate’ rather than an ‘efficiency’.} which is determined by the substitutability between these resources and the progress of technology development.
- Wastes are to be generated at rates below, or at, the assimilation capacity of the environment.
- Efforts should be made to protect intra- and inter-generational equity.
- The implementation requires a pluralistic and consultative social framework.

Particularly since they are presented as additional to development objectives, one wonders why the requisites of intra- and inter-generational equity, and of pluralism, are mentioned at all. Are these not already the objectives of development? Further, the demanded effort to protect equity seems premature as long as equity is an objective that needs pursuing. Leaving these details aside, with sustainability being considered additional to development, the most prominent issues are the management of resources and wastes, and the role of technology.
Making use of the environmentally extended neoclassical paradigm (Figure 3), Pezzey (1992), again for the World Bank, mathematises a wide range of the verbally-expressed sustainable development concepts found in literature dating back to 1977, and prepared by environmental scientists as well as by academic economists and representatives of international development organisations. In his review, Pezzey shows that substitution is not the only solution to the potential depletion of non-renewable resources.73 If considerations are limited to the value flows in a model economy with a principally non-substitutable non-renewable resource at its disposal (a ‘cake-eating’ model), technical progress may be fast enough to ensure steadily increasing utility. On the other hand, Pezzey74 also recognizes that physical laws, such as the first and second law of thermodynamics, ultimately place limits on technical progress and thus on economic development in the considered ‘cake-eating’ model. But technical progress does more than enable the exploitation of non-renewable resources at ever decreasing rates up to a physically determined minimum, it also provides the means for resource substitution. In the past, the availability of mining technology was a condition for substituting fossil fuels for wood. Perhaps, in the future, innovative energy conversion technology will result in changes in the opposite direction. It would seem that the physical determination of environmental stocks and services can change contingent upon technology development. Technology, and investment into its development, deserve their own position, along side the environmental stock and environmental services, in the environmentally-extended neoclassical model of the economy, presented in Figure 3. In his contribution to an OECD workshop on frameworks to measure sustainable development, Atkinson (1999) shows that if technological change is the result of coincidental discoveries, of which the impacts on productivity bear no relationship to the society’s investments in R&D (i.e. if technological change is exogenous to the economy), then any concern about society’s sustainable development is in vain, not because coincidental discoveries cannot be steered in desirable directions, but because “the future will be taken care of by improvements in technology which could more than offset any collateral liquidation of resource and environmental assets”.75 To support this argument he provides some striking estimates of productivity increases relative to ‘green’ accounting indicators such as green Net National Product gNNP and genuine savings $S_g$. On the other hand, Atkinson argues, that if technical progress is endogenous instead, then properly designed economic policies will be able to influence its rate and direction, so as to contribute to sustainable development.

Is technical progress exogenous or endogenous? An answer to this question might seem to be the philosopher’s stone. The point is that this cannot be known. By definition, exogenous technology change is unpredictable. If such change existed in the past, a fact which might be revealed by historical research, than nobody can know if it will turn up again when we need it. An accountable society simply cannot afford to act under the presumption that technology change is exogenous.

74/ Pezzey (1992), p. 35.
With this presumption, and in view of the various criteria of sustainable development (regarding equity, efficiency and exhaustion), it belongs to the role of economic science:

- To analyse the quantities of savings directed towards sustainable technology development, in view of the total of value flows, and
- To identify performance parameters - such as technical efficiency and cost - of pursued technological innovations taking into account the future economic conditions under which new technology is supposed to be operational.

The first issue is not further addressed here, but in the second part of this thesis, an attempt is made to show the principal possibilities of the latter, albeit in the very limited area of energy technologies. A necessary activity within this approach is an assessment of the damage to the exhaustible environment, expressed in monetary terms rather than just physically. An available tool is cost-benefit analysis (CBA), discussed in more detail in Chapter 2. There, it is also shown the extent to which CBA falls short of the required consistency, that is to say, at least as regards the assessment of energy technologies.

1.3 TECHNOLOGY DEVELOPMENT FOR A SUSTAINABLE ECONOMY

From the preceding section, it appears that controversies with respect to how sustainable development trajectories are to be identified, are still very strong. That technology, and its development, plays an important role is generally agreed, but which techniques we will need, and when, is far from clear.

In accordance with the conclusion of Section 1.2.3, the basic presumption made in this thesis is that sustainable technologies should not only serve development which is more equitable and in balance with the exhaustible environment, but one which is also efficient. In this respect, the question as to whether photovoltaic solar electricity serves sustainable development more efficiently than wind turbines or biomass should be seen as very relevant. This is just one of the many relevant technology topics, which include dilemmas such as:

- Decentralised or centralised electricity production?
- Natural gas or renewable alternatives?
- Renewable fuels (energy carriers) or renewable electricity?
- CO₂ storage or mineral fuel substitution?

A mere technical adjustment of technologies to match the exhaustible environment is considered insufficient. It is unavoidable, therefore, that the question on how sustainable technologies will fit within future market frameworks has to be addressed. This approach to technology development is fully receptive to environmental issues as such. The critical remarks made in the preceding sections - particularly about the discount rate and about the results of the founding analyses of the Dutch STD programme - might give the impression to some dedicated environmentalists that their problems are put aside too easily, but that would be an unfair reading. On the contrary, the approach attempts to give a fair voice to all the relevant considerations. Proceeding differently would carry large risks, with regard
to success and actually with regard to sustainability. This is illustrated with a further elaboration on the Dutch STD programme which, in the previous section, was classified as a programme founded on an exogenous economic framework. Following this, the economic focus of the current analysis is explained in more detail.

1.3.1 Sustainable technology development as in the Dutch STD programme

Based on the analysis provided by Weterings and Opschoor (1992), the STD programme concluded that the scale of the required changes necessitates a break in existing trends in current technology development processes. “A prudent working hypothesis is for the North to target ten- to fifty-fold reductions over the anticipated claims on eco-capacity by the middle of the 21st century.” With this recommendation, the STD programme set out to initiate a national programme in collaboration with a team of stakeholders in technology. A broad set of technology clusters was selected:

- Nutrition;
- Transport and mobility;
- Buildings and urban spaces;
- Services provided by water;
- Services provided by materials and chemicals (This includes the production and use of organic materials and liquid fuels from biomass, a topic which is analysed in the second part of this thesis).

The implementation methodology of the STD programme is rooted in social network theory and is called ‘constructive technology assessment’ (CTA). CTA is “a deliberate procedure in technology design to introduce an iterative feedback loop from users to designers.” The underlying idea is that social networks are decisive in technology development, and that the outcome of this development can be controlled by a politically agreed programme (such as STD). As it appears, STD is the first attempt to apply this management technique to long-term technology developments. The social networks in this approach would generally include stakeholders in the activity of technology development, and also those affected by the technology (directly or indirectly). A broad definition, but in practice amounting to:

- A consortium of ministries (the Dutch Government),
- Businesses and industries, and
- A consultative forum of societal organisations and stakeholder groups.

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77/ Weaver, Jansen, Grootveld et al. (2000), p. 44.
78/ Further strength is claimed to be the back-casting methodology (Weaver, Jansen, Grootveld et al. (2000), p. 73). In my understanding, back-casting is synonymous with designing a development trajectory. Since designing development paths is part of every serious technology development effort - short-, medium- or long-term, - it is a bit puzzling why back-casting appears so prominently as a foundation of STD.
79/ Weaver, Jansen, Grootveld et al. (2000), p. 73.
80/ Past applications of constructive technology assessment have mostly been oriented toward short-term social optimisation of existing technologies ... However, the technique could also be applied in longer-term projects, with the aim of integrating long-term social considerations into technology designs from the outset.” (Weaver, Jansen, Grootveld et al. (2000), p. 73).
81/ Weaver, Jansen, Grootveld et al. (2000), p. 70.
The latter is not further explained by Weaver, Jansen et al., and its selection could be a matter of democratic concern. In fact, the concern about who is to participate goes a lot deeper. After all, in many respects the environment is a worldwide issue and hence cannot be addressed solely by a national collaboration programme. Particularly not within the framework of a programme which pretends to be participatory for methodological reasons. Further, in this era of worldwide communication and trade, technology is rarely developed for single national economies only, and this will occur even less often in the future if globalization trends continue. In view of the global character of some environmental issues, and of many technologies, sustainable technology development needs to be addressed by a worldwide community. When, eventually, the developed technologies become available, they might turn out not to be economically feasible. The STD programme does not routinely analyse this in advance, but rather relies on the beliefs and convictions of the selected participants. Although these participants (as long as they share their convictions) should not necessarily acknowledge this argument as a valid criticism, they should all be worried about the durability (which is a form of sustainability) of their efforts.

1.3.2 Economic focus for the current analysis

Global climate change as a result of the emission of greenhouse gases (GHGs) is the central environmental issue for this thesis. Its technical background is extensively discussed in many reports, especially those of the Intergovernmental Panel on Climate Change (IPCC), and is not summarised here. With the United Nations Framework Convention on Climate Change (UNFCCC), 1992, worldwide climate change was internationally accepted by 36 countries as a phenomenon which needs internationally coordinated action.

Up until its Second Assessment Report in 1995, the IPCC attempted to prepare an integrated assessment of human-induced climate change by drawing up the balance of costs and benefits of such change related to a wide gamut of response options which included both efforts to reduce climate change (emission reduction, increasing sinks) and mitigation of consequences of climate change. Ideally, the result of such analysis would comprise targets of optimal quantities of GHG emission reductions and their values for each moment in time during an established period. A possible outcome of the analysis, which includes the mitigation of consequences as one of the response options, might very
well be that those targets and values would be zero, and that acceptance of climate change, combined with damage mitigation or damage prevention, would be the preferred alternative.

Of all the environmental stressors, GHG emissions are perhaps the most complicated to value. The reasons for this complexity include:

- The general issue of Global Warming covers a very wide range of impacts (Table 5):
  - Market and non-market impacts.
  - Impacts which are expected to affect the entire Earth, although to a different extent from place to place and from time to time.

This requires a broad physical and monetary assessment, the models for which are highly controversial.

- Impacts mainly concern the future of generations to come, which poses a particular valuation difficulty as regards the applicable discount rate.

A review of the attempts to determine the damage costs of human-induced climate change by the emission of GHGs is provided by Pearce, Cline, Achanta et al. (1995). These authors not only provide results of cost estimates up to 1994, but also an extended discussion on the difficulties of physical estimation and subsequent valuation. A summary of their results is provided in Table 6. An assessment of damage costs is only half the job in the valuation of GHG emission reduction. This needs to be balanced with cost estimates for emission reduction and damage mitigation. Table 7 reviews the overall preliminary results, as of 1995, of this analysis. Particularly those of Cline show a very large range, an observation that implies nothing to the detriment of that author.

### Table 5. Overview of climate change impacts and their estimation status. (Source: Pearce, Cline et al. (1995)).

<table>
<thead>
<tr>
<th>Damages</th>
<th>Market Impacts</th>
<th>Nonmarket Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary economic sector damage</td>
<td>Other economic sector damage</td>
</tr>
<tr>
<td>Fully estimated, based on willingness to pay</td>
<td>Agriculture</td>
<td>Dryland loss</td>
</tr>
<tr>
<td>Fully estimated, using approximations</td>
<td>Forestry</td>
<td>Water supply</td>
</tr>
<tr>
<td>Partially estimated</td>
<td>Fisheries /a</td>
<td>Energy demand</td>
</tr>
<tr>
<td>Not estimated</td>
<td>Construction</td>
<td>Transport</td>
</tr>
</tbody>
</table>

*a/ Often included in wetland loss.
*b/ Primarily agricultural damage.
In this thesis, the relevance of these estimates - values of GHG emission reduction and their expected evolution - is in the economic framework which they provide for technologies intended for GHG emission reduction. Methods for GHG-neutral electricity generation are examples of such technologies. Each unit of such electricity produced does not only carry the value of the electricity, but additionally represents a value in view of GHG emission reduction. However, the IPCC has not further refined and improved the estimates of GHG values quoted above. In 1997, the Kyoto Protocol\textsuperscript{85} to the UNFCCC was agreed by the governmental negotiators of 38 countries. The signatories to this Protocol committed themselves to implement specified GHG emission reductions during a first phase which ends in 2012. In view of this political development, the IPCC decided to place more emphasis on options for GHG emission reduction. Effectively, IPCC’s Working Group III, which until 1995 was charged with the economic and social dimensions of climate change in the broadest sense, was given another focus in 1998, i.e.: “to assess the scientific, technical, environmental, economic, and social aspects of the

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
\hline
Nordhaus (1991) & & & & 27 \\
Fankhauser (1994) & 74 & 84 & 93 & 102 \\
\hline
\end{tabular}
\caption{Summary of damage cost estimates for various periods, in 1990 US$/t CO\textsubscript{2} (After Pearce, Cline et al. (1995), p. 215).}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|}
\hline
\hline
Nordhaus (1994) & & & & \\
Best guess & 19 & 25 & 32 & 37 \\
Expected value & 44 & 66 & 97 & \\
\hline
\end{tabular}
\caption{Summary of estimates of optimum CO\textsubscript{2} emission prevention cost, in 1990 US$/t CO\textsubscript{2} (After Pearce, Cline et al. (1995), p. 215).}
\end{table}

\textsuperscript{85} UNFCCC (1997).
mitigation of climate change." Thus, the option of mitigating the consequences of climate change was removed from its scope of evaluation.

In any case, the Protocol created a market value for a particular type of sustainability. The market for prevented GHG emissions is not the first market for environmental issues, for example, in several states of the USA nitrous and sulphur oxide emissions are kept under control by means of an emissions trade system. A distinct phenomenon of the Kyoto Protocol, however, is its international character, as it recognises two international market options through which its signatories can fulfil their obligations: the Clean Development Mechanism (CDM) and Joint Implementation (JI). With these options, the Protocol allows its signatories to not only seek GHG emission reductions within their own countries, but also to buy such reductions from other countries. In comparison with an obligation to effectuate GHG emission reductions within each committed country separately, the expected results are that the overall cost of reducing GHG emissions will be lower and will harmonise within a smaller range. The political facts established by the Kyoto Protocol, on the one hand, are promising in that they show that global environmental issues can be given an actual market value. On the other hand, the rapid, and perhaps rash, implementation, prior to a more thorough cost-benefit analysis of global warming, is a cause of concern for those who are developing technologies which could play a role in GHG emission reduction in the longer term. In addition, the implementation of the Protocol is still surrounded by uncertainties.

Nevertheless, the creation of a market for reduced GHG emissions is a revolution for those involved in the development of renewable energy technologies. In the past their drive was to develop these technologies to the extent where unit energy production cost became lower than with conventional non-renewable technology. So far, with exceptions for economic niche conditions (such as solar panels on light buoys in shipping lanes, and solar panels for the electrification of remote villages in developing countries), they have not succeeded. Whether renewable energies will ever become generally cheaper than conventional ones, is doubtful. As long as fossil resources are essentially freely available in sufficient amounts, the costs incurred are principally those of exploration and mining -costs which tend to decline (see Odell (1999), referred to in Section 1.2.2). With this new market development, the energy market is no longer a fossil fuel supplier’s market only. Under these new conditions the selection of targets for renewable energy technology development is a new challenge.
2 EXISTING EX ANTE TECHNOLOGY ASSESSMENT METHODS

Those wanting to establish the characteristics of future technologies have several methods at their disposal. In 1999 a review\(^7\) of such methods was prepared for the Dutch GAVE programme.\(^8\) Whereas Weterings, De Vaan, Siemons \textit{et al.} (1999) proposed an array of assessment activities to be carried out prior to the appraisal of a government policy to support the development of identified technologies, they distinguished four principal evaluations which should be carried out simultaneously after technology options have been identified:

- Life cycle analysis (LCA);
- Cost-benefit analysis (CBA);
- Design assessment; and
- Multi-actor analysis.

The first two methods in this list are discussed in more detail in later sections of this chapter. Also their mutual relationship is investigated, for further consolidation in Chapter 3. The latter two methods, design assessment and multi-actor analysis, are not elaborated upon here. A very brief characterisation, however, is due.

Design assessment concerns the expected technical feasibility of candidate technologies. Technical feasibility on a conceptual level is, obviously, a prerequisite for potentially successful technology development. Its assessment is an isolated activity, which does not need feedback from LCA or CBA. However, it does provide data (physical efficiency, emissions, etc.) which are used in LCA and CBA. Some design assessments are also made in this thesis, in Chapter 5. Multi-actor analysis is understood by Weterings, De Vaan, Siemons \textit{et al.} (1999) as stakeholder modelling, such as carried out by Diepenmaat (2000) and justified in his thesis.\(^9\) It provides an understanding of the societal commitment towards particular technologies by allocating development roles to the business sector, knowledge infrastructures, and the government sector. The potential contribution of multi-actor analysis to the extensive technological changes that may eventually be required to address worldwide environmental issues was however not further elaborated upon by Weterings, De Vaan, Siemons, \textit{et al.} Societal acceptance is an indispensable condition for technological change. Whether creating such acceptance is more than marketing and information provision, and whether the intended type of network analysis can even be employed as an assessment tool in the sense of ‘constructive technology assessment’ (see also the remarks made in Section 1.3.1) is a matter which is not further investigated here.

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\(^7\) Weterings, De Vaan, Siemons \textit{et al.} (1999).

\(^8\) The GAVE programme attempts to introduce new gaseous and liquid energy carriers in view of a sustainable energy provision. It is carried out by NOVEM for the Dutch Ministry of Housing, Spatial Planning and the Environment, as well as the Ministry of Economic Affairs.

\(^9\) Diepenmaat (1997).
2.1 LIFE-CYCLE ASSESSMENT

Why LCA should be discussed here

The Society of Environmental Toxicology and Chemistry (SETAC) defines LCA as follows: “Life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases on the environment; and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity, encompassing extraction and processing raw materials, manufacturing, transportation and distribution; use/re-use/maintenance; recycling, and final disposal”. At first sight, LCA does not appear from this definition to be an ex ante evaluation method for technology development projects. LCA is one of the methods suitable for what is referred to as an Environmental Impact Assessment (EIA). An EIA is an obligatory activity under EU law for specific projects. Rather than an assessment method, an EIA is a prescribed procedure of which specific formalities must be met. These formalities, however, do have a content and this is where the LCA method can play a role. In a particular shape the EIA procedure can be found in ex ante evaluations of policies and programmes. It is then called Strategic Environmental Assessment (SEA). Again LCA is one of the available tools.

Nonetheless, LCA is being employed for the purpose of ex ante evaluation of technology development projects. Examples of such evaluations are the study of energy crops by Biewinga and Van der Bijl, and the one on sustainable fuels by Kaltschmitt and Reinhardt. Also the Dutch STD programme, more extensively addressed in Chapter 1, identified LCA as one of the cornerstones of technology selection and development targeting. Berg, Dutilh et al., in their beginner’s guide to LCA, state that one of the purposes of LCA is to enable new products or services and strategic policy alternatives to be judged. In the preparations for the Dutch GAVE programme, mentioned in the introduction to this chapter, LCA was specifically recommended as one of the methods necessary to evaluate the technology developments to be promoted by the GAVE programme. In accordance with the definition given at the start of this section it may be used for this purpose, since a product, a process, or an activity, to be evaluated need not necessarily exist already. It may be an intended project to manufacture the product, or to develop the process or the activity. Further, LCA is indeed advocated as a method for ex ante assessments, as it is intended “to provide decision-makers with information which

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91/ See e.g. EU (1997b).
93/ Biewinga and Van der Bijl (1996).
94/ Kaltschmitt and Reinhardt (1997).
95/ Weaver, Jansen, Grootveld et al. (2000), p. 74 and pp. 151.
defines the environmental effects of human activities ...” 97 Hence LCA may be used in EIA procedures. Its use is not necessarily restricted to reducing the collateral damage of planned activities, but includes the investigation and comparison of project alternatives.

Several technical scientists collaborating in SETAC have been, and still are, major developers of LCA. Most of these scientists are employed by large industries or by environmental institutes (such as the Dutch Centre for Environmental Studies (CML) in Leiden).

2.1.1 LCA description

A European and ISO standard for LCA was published in 1997. 98 Apparently LCA is considered such an essential and sensitive tool in policy-making that standardization is required. The draft standard describes LCA at the procedural level and does not prescribe the content in terms of the environmental issues to be covered. Four phases are distinguished: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation of results. The procedure may be repeated several times, as indicated by the double arrows in Figure 5. The procedure is iterative: information gained in one stage serves to adapt results of previous phases.

![Figure 5. Phases of an LCA (Source: ISO 14040, 1997).](image)

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97/ Consoli, Allen, Boustead et al. (1993), p. 5: "The prime objectives of carrying out LCA are:
1. to provide as complete a picture as possible of the interactions of an activity with the environment
2. to contribute to the understanding of the overall and independent nature of the environmental consequences of human activities; and
3. to provide decision-makers with information which defines the environmental effects of these activities and identifies opportunities for environmental improvements."

The four phases are distinguished by the activities carried out during, and the targets to be achieved by each phase. Briefly, the goal and scope definition phase should:

- Clarify the goal of the LCA;
- Define the scope of the LCA. This includes:
  - The definition of the system boundaries,
  - The definition of the functional unit,
  - The definition of the data quality requirements.
  - An evaluation of system equivalence (in comparative LCAs), and
  - A description of an optional critical review of the LCA (The iterative nature of LCA is apparent!).

This phase of goal and scope definition is also referred to as scoping. Since the basis of an LCA is laid down during scoping, it makes sense to elaborate further on the precise scoping activities, so as to enable a comparison with other project evaluation methods.

**System definition**

A product brings about more consequences than are immediately evident from its use. Processes interact with the environment at more locations than the single site of a major technical operation, and thus have larger societal impacts than can be observed at the level of the singular operation. The general tendency is for LCAs to be carried out for complete production chains, the links of which are not necessarily part of a single financial entity such as an enterprise or a country. These links are partial processes which may occur in various geographical areas but also at distinct moments in time during the life cycle of a product. For this reason the primary subject (a product or process) of an LCA is placed within a system which incorporates several additional components, e.g. the manufacture of raw materials, and the final disposal of products.

Products, production processes, and human activities in general, are vastly interrelated. The question therefore arises how far a system for analysis should extend, and how a system is bounded. The holistic view on system limitation is that everything is interdependent to such an extent that the deliberate omission of anything results in unacceptable inaccuracies. The ideal system would thus be closed. Interactions would only occur between subsystems encompassed by the ideal total. Fixing system boundaries as something smaller than the entire Earth, and all possible futures, would thus be a matter of convenience or practicality, made necessary by people’s ignorance (lack of understanding and lack of data) as well as by a lack of calculation power. This view is
expressed by Reinhardt and Stelzer.\textsuperscript{102} But then again, unavoidably, LCA is about the provision of desired societal services or functions (why else perform an LCA rather than refrain from providing the service or function?). If, for example, an LCA is about a power plant, or about alternative fuels for electricity production, it is presumed that electricity is needed anyway. In this situation, electricity itself and the results of its use, are not analysed further.\textsuperscript{103} This implies that an LCA system is never closed, but that there is an environment with which it interacts. By necessity this is a buffer environment\textsuperscript{104} as perceived by the LCA analyst, otherwise the system would have to be extended to analyse the environmental effects.

Indeed, the \textit{exhaustible} environmental issues considered by an LCA (downstream water, threatened ecosystems, etc.) are encompassed by the system boundaries. Strangely, LCA practitioners are not always aware of this theoretical background. Usually, only technical components are described as constituting the system evaluated, and the exhaustible environmental subsystems are rarely explicitly included. This attitude is supported by the founders of the LCA methodology: Fava, Denison, Jones \textit{et al.} (1991) (p. xix) define a general system boundary by (among other things) energy and raw materials inputs, as well as by the outputs of water effluents, airborne emissions and solid wastes. This is a cause for some analytical concern as the environmental impacts due to these inputs and outputs may differ from place to place and from time to time - and hence their relevance would require investigation. Up to specific levels, contaminated effluents for instance, may be absorbed by surface waters without harming them. In this situation the waters act as environmental buffer sinks. Above absorbable contamination levels, surface waters become exhaustible environments. Another reservation concerning the sole focus on the technical project component, as if it represents the entire system, is that environmental consequences remain implicit and not understood. After all, without further specification, energy and material consumption have no meaning - they can be of a renewable or a non-renewable character, i.e. relate to a buffer environment or to an exhaustible environment. These simple examples demonstrate that for LCAs to be meaningful, defining the evaluated system by the boundaries of the project technical component is not sufficient. Rather, the system should also include the affected environment. This may be illustrated with the recent example of the discussions as to whether or not gas extraction from below the Waddenzee should be allowed.\textsuperscript{105} At stake was the issue as to whether the sea floor would drop by a substantial amount as a result of such activity. In this particular case the system considered was the industrial activity of gas extraction \textit{combined with} the ecosystem of the Waddenzee. Environmental impacts thus occur within the system, rather than outside it.

This leads us to the following conclusions:

\textsuperscript{102} In Kaltschmitt and Reinhardt (1997), p. 72.
\textsuperscript{103} It is not impossible to include, as a questionable issue, the use of electricity in an LCA. Whether or not it is included depends on the research question: the goal of the LCA, as determined during scoping.
\textsuperscript{104} A buffer environment is the concept of the environment in its classical interpretation: that which is independent of the system under study (Section 1.1.1).
\textsuperscript{105} Debated in the Dutch parliament from June 1998 until December 1999 (Staten Generaal (10 June 1998) and Staten Generaal (14 December 1999)).
- System boundaries separate the system from the classical buffer environment (sinks and sources).
- An LCA is not only about a human activity (a production process, a project, or generally a technical component), but also about the exhaustible environment affected by that activity.
- A division of the system into subsystems (the technical project component and the affected environment) is required, otherwise the analysis will not yield an assessment of any environmental impact.

This view is supported by Heijungs, Guinée, Huppes et al. (1992a)\textsuperscript{106} in so far as they explicitly distinguish between a ‘product system’ and an ‘environmental system’. The concept is illustrated in Figure 6. Clarity as to the precise relationships with the environment (buffer environments, exhaustible environments) can be achieved by insisting that arrows, representing an interaction of a system with something else, should have both a beginning and an end in specified items.\textsuperscript{107}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{system_boundaries.png}
\caption{Generic system boundaries, as employed in LCA.}
\end{figure}

This is enough on the principles of spatial extension of system boundaries. In practice, good LCAs do justify their selection and handling of environmental issues. Even if subsystems of exhaustible environments are not visible in their system definition, they are dealt with explicitly during the phases of scoping and interpretation. It may thus occur that an LCA reports the quantities of GHG emissions from a system, without further investigating the effects of these emissions since they are dealt with adequately in other analyses.

\textsuperscript{106} Heijungs, Guinée, Huppes et al. (1992a), p. 21.
\textsuperscript{107} The options for these items are: another system, an exhaustible environmental sink or source, or, finally, a sink or source buffer environment.
Finally, it should be noted that comparative LCAs, investigating the differences between alternatives for equal services, may be confined to only those subsystems and system interactions which differ. In this context, Kaltschmitt and Reinhardt (1997) introduced the concept of ‘ökologische Bilanzierung’ (ecological balancing). Ignoring subsystems and system interactions, however, comes about only after they have been included in an initial iterative system assessment.

*Indicators and functional units, particularly relevant for biomass energy projects*

LCAs have been applied to evaluate a single project, and also to mutually compare multiple projects concerning the same service. For the LCA of a single bio-energy project, the project is usually compared with a fossil-fuel based energy project which it is supposed to replace. In this manner only the incremental effects (such as increased or avoided emissions with respect to the fossil alternative, the ‘baseline’) are quantified. These are then expressed for the project over its entire duration. In this manner, statements concerning a project’s total avoided GHG emission can be justified - a practice which one comes across in JI project appraisal. Such statements can suffice as an LCA result. If, on the other hand, LCA is utilized to compare multiple projects, the LCA requires the definition of the *functional unit*. The environmental effects are subsequently expressed as indicators of the form:

\[
\text{Environmental indicator } i \cdot \frac{\text{Environmental effect } e}{\text{Functional unit } u}
\]

Examples of functional units found in relevant literature are: secondary energy (J\text{secondary} or Wh\text{secondary}), primary energy of biomass fuel (J\text{primary biomass}), primary energy of substituted fossil fuel (J\text{fossil substituted}), as well as land use (ha). The functional unit of the LCA corresponds to the product unit in the economic analysis (various production processes can be compared by determining the unit production cost (cost/unit), see Section 2.2.1). ISO 14040 states: “A functional unit is a measure of the performance of the functional outputs of the product system.” In the case of comparative LCAs, a functional unit is a particular societal service which the projects compared have in common.

*Secondary bio-energy:* In the case of bio-energy projects the obvious functional unit is secondary bio-energy with a defined quality. Secondary energy is heat or electricity ready for delivery to end-users. This unit, after all, is the product or societal service which it is all about - a form of renewable end-user energy and therefore granted the prefix

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108/ See ISO 14040 (1997): Article 5.1.2.1: “The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed to ensure that such comparisons are made on a common basis.” Article 5.1.2.4: “In comparative studies, the equivalence of the systems being compared shall be evaluated before interpreting the results. Systems shall be compared using the same functional unit.”


111/ If the production of biomass-based transport fuels is being considered, the vehicle-km is a useful functional unit.
‘bio’ (the Dutch product ‘Groene stroom’ is another example of renewable end-user energy).

**Primary bio-energy:** Against the use of the functional unit of the primary energy of the biomass fuel it must be argued that not all biomass fuels can be converted into secondary energy at the same energy efficiency and that, therefore, comparative LCAs of multiple bio-energy projects using this unit as a reference fail to compare the projects under the same prerequisites (i.e. equal energy services to society).

**Substituted primary fossil energy:** The same disadvantage is not attributed to the functional unit of the primary energy of substituted fossil fuel, since by determining the value of indicators based on this unit, energy efficiencies are taken into account. This unit might thus be seen as equally acceptable as the unit of secondary bio-energy. It is less immediate however.

**Land use:** Some authors claim that the occupied land area (ha) for biomass production is a useful functional unit for the comparison of multiple bio-energy projects.\(^{112}\) Certainly, on the basis of this unit, distinctive numbers can be determined. Two bio-energy projects might show a difference in tonnes of avoided GHG emissions per hectare of land where an energy crop is grown. If the evaluation was restricted to GHG emissions, the project with the largest indicator (t avoided GHG emission/ha) would be preferred. This might be a valid argument, but only if the equality of societal services for both projects (i.e. equal quantities and qualities of bio-energy provided) is abandoned. This would contradict the basis of project comparison. As a result, energy-based and area-based indicators, determined for the same project, may also contradict.\(^{113}\) Therefore, land area cannot be a valid functional unit for comparing bio-energy projects. Land, not being a function of energy crops, is an input, not an output. If the objection is raised that land area for the production of energy crops is scarce, and that therefore land use needs to be optimised,\(^{114}\) then land utilisation should be seen as a relevant environmental effect (or impact) and, in its turn be made comparable by dividing it by a selected functional unit, thus yielding a specific environmental indicator (e.g.: ha/J). The functional unit should be determined on the basis of the purpose of the system (i.e. its product) rather than by what LCA practitioners want to find out.

\(^{112}\) ‘A second functional unit is one hectare of agricultural produce during one year’ and ‘A function that energy crops have in common with non-energy crops is that they are both forms of land use’ (Biewinga and Van der Bijl (1996), p. 9). In Kaltschmitt and Reinhardt (1997): “Als funktionale Einheit wird die ‘Verwendung einer Fläche zur Bioenergieträgerproduktion bzw. -bereitstellung bezogen auf ein Durchschnittsjahr’ gewählt.” (p. 71).

\(^{113}\) Biewinga and Van der Bijl do show such contradictions: “When a crop with a high energy production and a high emission per hectare is compared with a crop with a low energy production and a medium emission per hectare, emission per GJ for the first will be lower and emission per hectare will be higher” (Biewinga and Van der Bijl (1996), p.9). A similar contradiction is reported by Kaltschmitt and Reinhardt (1997) (p. 423). They do not see any reason to resolve this contradiction.

\(^{114}\) Kaltschmitt and Reinhardt (1997), p. 71: “Diese Festlegung der funktionalen Einheit, die einen äußerst signifikanten Einfluss auf die Ergebnisse hat ..., wird im wesentlichen mit der Forderung begründet, durch die Bilanzierungsweise die derzeitigen Verhältnisse möglichst realitätsnah abzubilden. In Deutschland stellen die für einen Energiepflanzenanbau real und - selbst bei einer Grenzbetrachtung -potentiell verfügbaren Flächen praktisch den absolut beschränkenden Faktor dar.” Under such conditions it would be worth considering an environmental indicator of land use: ha/functional unit. In the end however it is possible to interpret the approach chosen by Kaltschmitt and Reinhardt in full accordance with the remarks made here, as they employ the indicator ‘fossil fuel substituted per ha’. This indicator can be inverted immediately into the indicator land used per unit of fossil fuel replaced, which is adequate.
Since there are numerous environmental issues, LCAs typically result in listings of multiple indicators. To facilitate the drawing of conclusions it is necessary to give a relative weight to the various indicators. The allocation of weighting factors requires two considerations:

- Comparison of the size of a stressor, relative to the total environmental issue (e.g. the emission of an acid relative to the issue of acidification). After all, a quantified stressor indicates nothing about the contribution of a single project to the related environmental issue. Such a comparison is often called normalisation.\(^{115}\)

- A mutual comparison of normalised environmental indicators of different orders (depletion relative to biodiversity, etc.). This activity is placed within the evaluation phase of an LCA. The LCA standards do not prescribe a particular method for this comparison. Quantitative weighting is just one of the possibilities, but some form of weighting is always required.\(^{116}\)

Whereas a purely scientific approach towards the normalisation activity is conceivable (if sufficient knowledge about the environment is available), the evaluation, inevitably, is highly subjective. A summary of several evaluation methods that take the subjective nature of the activity into account, is given by Heijungs, Guinée, et al.\(^{117}\) In another background report on the LCA methodology, some other methods are presented by Fava, Consoli et al.\(^{118}\)

Such methods are not elaborated upon here. The main point being made is that the cited authors do not propose a preferred method, and that they rather point at the systematic difficulties which still pertain to all these methods. There is one particular difficulty, however, with the evaluation of normalised environmental indicators produced by an LCA, which should be mentioned here: the evaluation is carried out in isolation from the evaluations taking place in the monetised economy. One might be tempted to conclude that both environmental and economic aspects count, and that a decision is ultimately a balance of marginally prevented weighted normalised environmental damage and incremental monetary cost.\(^{119}\) I disagree because environmental matters and the economy are interrelated in a more complex manner. A number of environmental issues, such as those emissions which are regulated in some way or another, are already incorporated within the monetised economy. After all, the requirement to meet specified emission standards results in a cost component. This implies that, up to a certain intensity of certain environmental stressors, some sort of weighting has already taken place in terms of money relative to other monetised goods.\(^{120}\) A well-balanced decision-making process would

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\(^{115}\) e.g. by Heijungs, Guinée, Huppes et al. (1992b), p. 48.

\(^{116}\) Compare Heijungs, Guinée, Huppes et al. (1992b), p. 52.

\(^{117}\) Heijungs, Guinée, Huppes et al. (1992b), p. 106.

\(^{118}\) Fava, Consoli, Denison et al. (1993), p. 87.

\(^{119}\) Or marginal weighted normalised environmental damage and marginal avoided cost.

\(^{120}\) Taking the example of polluting exhaust gas emissions - under the presumption that the emissions are regulated at an optimum level - their value equals the cost made by the emission producer to reduce the emission below a required level, augmented by the cost of the damage caused by the remaining emissions. See Section 2.2.2.3.
require that the LCA weighting process is consistent with the already existing monetary weighting of environmental issues. Limiting the weighting process for normalised environmental indicators within the single context of purely environmental matters is therefore inadequate.

2.1.2 How LCA’s deal with the dimension of time

Although system definition is a matter of space, it also concerns the dimension of time - this is implicit in the concept of life cycle. This is deliberate, since an important reason for the development of LCA has been the understanding that technical goods do not only interact with the environment during their operational life, but also during their construction and destruction. Published LCAs have a particular way of dealing with the time dimension. They pretend that environmental impacts occurring in the future are equally relevant as those occurring today - that is, if they happen at the same moment. This approach is not prescribed by ISO 14040 but the standard does show that its authors are aware of a hidden difficulty; as it says in Article 4.1: “There is no scientific basis for reducing LCA results to a single overall score or number, since trade-offs and complexities exist for the systems analysed at different stages of their life cycle.”121 Do the authors of ISO 14040 intend to state that the simple fact that environmental impacts occur at different moments in time is a reason for not allowing mathematical operations on resulting data? If that is so, one might wonder how annual emissions, or the annual sequestration of a single harmful gas, can be totalled over the lifetime of a production system.122 This matter needs closer consideration, not only because of a lack of clarity in the ISO standard and a possible contradiction with some practices. The focus of LCA development has, so far, mainly been on the analysis of products, rather than on processes (let alone generic technological concepts).123 Hence, perhaps, the time dimension has not received the same attention as it does in cost-benefit analysis. After all, the lifetime of, for example, a milk package is a lot shorter than that of a power plant. It could be suspected that the time dimension, in the LCA concept, has been mainly introduced to enable the coverage of the entire production chain (say from pulp wood, through carton manufacture, milk packaging, distribution, and utilisation, to disposal). Such a chain is at least one order of magnitude shorter than the life cycle of a production system. Whether or not this speculation over the reason for LCA’s failure to deal with time is correct, this thesis is investigating long lasting processes and therefore needs a method that identifies and handles time issues.

According to economic theory, the discount rate is decisive in guiding intertemporal decision-making. It determines the importance of events at different moments in time in the following manner:

122/ The design of the forest plantation projects carried out by the FACE Foundation are a fine illustration. All carbon sequestered over project lifetimes of 99 years is aggregated linearly into a single number for each project. Compare SGS (2000), p. iii.
123/ Three examples as illustrations: electricity (product), a power plant (process), large scale electricity production for feeding distribution grids (generic technological concept).
where \( I_0 \) is the present importance of event \( E_t \) occurring at future moment \( t \); and \( I_t \) is the importance, at moment \( t \) of the event at the moment of its occurrence. Instead of ‘value’, which would be appropriate, albeit in a very broad sense, I use the word ‘importance’ here. This is to get rid of monetary connotations: there is no need to restrict the concept of a discount rate to its meaning in project finance (the opportunity cost of capital). That is just one of the possible interpretations. Discount rate is a much broader social actuality. Note that, however implicitly, the above equation does provide a measurement method for the discount rate. Making it explicit:

\[
\text{discount rate} \ = \ \frac{I_t \ (\text{of } E_t)}{I_0 \ (\text{of } E_t)}
\]

The magnitude of the discount rate is particularly critical for the current evaluation of distant events. This has been recognised by economists involved in the debate about global climate change and future emissions of GHGs (see Section 1.1.2). However, is an economist’s argument valid when talking about the environment? Yes, as we have seen earlier (Section 1.1), many environmental issues are of an economic nature. At least for those issues, compatibility between LCA and economic theory is required, to avoid inconsistencies between the results of LCAs and economic analyses. Concerning those environmental issues which are of a purely theoretical nature, the view could be expressed that the environment does not bother about time effects. Their prevention is equally important, whether they occur today or 20 years hence. This position is untenable, however, since it presumes a human action (or its abandonment) of which the costs are weighted in a broader context. Therefore, in both cases - economic or theoretical environmental impacts - people’s economic dealing with delayed environmental effects cannot be avoided.

It is not necessary here to enter into an investigation into how precisely discount rates are measured. What matters is their meaning for environmental decision-making, and thus their potential relevance for LCA. Generally, with increasing discount rates, a future event becomes less important in comparison with a similar event occurring in the present. An example with realistic figures is as follows: at a discount rate of 5%, an avoided GHG emission of 1000 tonnes ten years hence is equivalent to an avoided emission of 645 tonnes today, or, in other words, it would appear 36% less important than an emission reduction of 1000 tonnes today. An example of a product for which the discount rate is critical in LCA is concrete constructions. The manufacture of concrete structures causes large GHG emissions. Thus, at the beginning of the life cycle of the construction, a large environmental effect occurs. An LCA would need to compare this with the functional unit of for example one square metre building service. This function is sustained over the complete life cycle of the construction. To arrive at an environmental indicator in the shape of the effect per functional unit (here: t GHG/m²), economic theory prescribes that
both the effects and the services are discounted to the present and totalled before their quotient is determined. If the discount rate equals zero then all future events are effectively added immediately, however with positive discount rates this no longer applies, and the environmental indicator increases proportionally. The example of a concrete structure is further illustrated in Figure 7. Note that LCA guide books and standards do not explain how to arrive at an indicator in cases such as this.

A contrasting example is that of a coal fuelled power plant. Such an operation, although constructed and dismantled with distinct environmental impacts too, is an active GHG emitter over its entire operational life. Neglecting the effects of construction and decommissioning in this case, the sensitivity to the value of the discount rate is illustrated in Figure 8. In contrast with the indicator found for the concrete structure discussed above, the calculated indicator is independent of the discount rate.

Figure 7. Sensitivity to the discount rate of an environmental indicator for a concrete structure.

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As a matter of fact, the latter observation is another argument against the view that high discount rates, generally, result in the negligence of environmental matters (see the discussion about the discount rate in Section 1.1.2).

Figure 8, Sensitivity to the discount rate of an environmental indicator for a coal-fuelled power plant. (Data are not exact, and for illustrative purposes only: electricity production = 3,723 GWh/yr for year 1-25, CO₂ emission = 2,420 kt/yr for year 1-25).

It has thus been demonstrated that the discount rate can be employed to account for temporal effects in LCA, and that (See also Table 8):

- The discount rate does not influence environmental indicators for effects which occur simultaneously with, and in proportion to the production of the functional unit. In other cases, the discount rate is influential in the following manner:
  - Effects which occur at the beginning of a life cycle are very important if the discount rate is large. At low discount rates such effects are less important.\textsuperscript{125}

The magnitude of the applicable discount rate is therefore particularly relevant for those environmental effects which are proportional with production of the functional unit.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Rate of time preference & Environmental effect & Simultaneous with and in proportion to production & Mainly in beginning of the life cycle & Mainly far in future of the life cycle \\
\hline
High & Irrelevant & Increased relevance & Reduced relevance \\
Low & Irrelevant & Reduced relevance & Increased relevance \\
\hline
\end{tabular}
\caption{The relevance of environmental effects in LCA as a function of the rate of time preference.}
\end{table}

Finally, it is speculated that discounting may further play a role in the boundary determination of systems. As touched upon briefly in Section 2.1.1, the interdependence of production chains forces the LCA analyst to decide which subsystems to include within the overall system, and which to disregard. Product life cycles are usually interlinked with the life cycle of various production systems. An example based on electricity production

\textsuperscript{125} As a matter of fact, the latter observation is another argument against the view that high discount rates, generally, result in the negligence of environmental matters (see the discussion about the discount rate in Section 1.1.2).
and use is illustrated in Figure 9. The product cycle of energy (System I) is repeated numerous times during the production system’s life cycle (System II). In Figure 9, System I shows a relatively short cycle duration (the order of magnitude being smaller than 1 year), whereas System II may last 20 years or more. Note, that although only two systems are displayed, several other production systems, such as shipbuilding and cable manufacture, are also interlinked with the life cycle of electricity production and utilisation. At this stage in any LCA, whether about products or processes, a decision must be made about which subsystem to include in the overall system to be investigated. The reason why, the discounting procedure of economic analysis might offer a suitable method for subsystem selection, is that production systems generally last much longer than product cycles. By appropriately discounting future events, it may appear that the environmental effects of a production system (System II in Figure 9) are negligible in comparison with effects of a product chain (System I). This would then be a valid reason for restricting the overall system boundary to System I. Elaboration of this potential role for discounting is left for future research. It is presented in this section merely as a fundamental solution to, as yet, unsolved problems with LCA.

Figure 9, Two interlinked systems: a product chain (system boundary I) and a process chain (system boundary II).

### 2.2 COST-BENEFIT ANALYSIS

**General meaning of cost-benefit analysis in R&D targeting**

How cost-benefit analysis (CBA) can be helpful in the selection of technology development projects is not immediately clear. Whereas a straightforward CBA simply
compares expected costs and benefits of a project, and selects the preferred projects on the basis of the highest cost-benefit ratio or some similar criterion, such a procedure is not possible in the case of technologies which do not yet exist, because their costs and benefits are naturally unclear. Nevertheless, CBA can be an important tool in the selection of desirable technology development targets, and the determination of technology development strategies. A first-order approach for CBA consists of three steps:

- Identify a conceivable future economic context (compatible with an economic development scenario).
- Physically characterize (e.g. in terms of processing efficiencies and unit size) those conceivable future technologies which are candidate technologies for further development.
- Determine cost-benefit indicators for those candidate technologies as if they were functional in the considered future economic context.

In reality, future technologies are hard to characterize (their nature being subject to speculation and to the bias of stakeholders) and future economic conditions cannot be foretold with confidence. Precisely under such circumstances this first-order CBA approach may demonstrate its attractive features. By means of the first-order approach, the sensitivities of cost-benefit indicators to assumed technology characteristics and economic conditions can be examined.

After the execution of the first-order approach, a second order step can be taken within the framework of CBA, by not only considering the future technology under conceived future economic conditions but also including the costs and benefits of the anticipated technology development path. The financial feasibility of that development path could thus also be evaluated. Later in this thesis, the first-order approach is further elaborated upon and applied.

2.2.1 CBA description

Unlike LCA, CBA methodology has not been normalized in national or international standards. Rather, if one wants to analyse the CBA methodology, one is referred to student text books, and a rich tradition of applied CBA.

Briefly, the general procedure for a CBA is as follows:

- Definition of the system boundaries of the analysed project. (Through the system boundary all project inputs and outputs are established).
- Quantification of project inputs and outputs for the entire time frame laid down by the system boundary. (The time window is part of the system boundary).
- Determination of the appropriate discount rate for assessing future project inputs and outputs on a consistent basis.
- Calculation of indicators.
- Evaluation.
Below, these issues are further elaborated upon.

**System definition**

Technology development is an investment project. The investor, in the project analysed, constitutes the system as considered by CBA. This investor may be a person, a private or public enterprise or a country. With the issue of Global Warming, even the entire global community may act as the system. At first sight these distinctions seem to denote a spatial distinction in system boundaries. This is correct, but they also refer to the dimension of time: a country’s community or the global community may be considered as including future generations. CBA places particular emphasis on how to deal with this dimension (see Section 2.2.2).

As regards spatial system constraints, systems determined by persons or enterprises are referred to as ‘financial’, in contrast to ‘economic’ systems which are constituted by country boundaries. This terminology originates from CBAs as exercised by those international institutions which are dedicated to the project financing of governments (IFIs) such as the World Bank and the IMF. The ‘economic’ CBA does not consider the project cash flows as perceived by the private investor, but rather as perceived by the country inside the boundaries of which the investment is made. In such ‘economic’ analyses, usually the immediate cashflows, as perceived by the private investor, need to be corrected for taxes and subsidies received or paid by the country involved (some other corrections are usually necessary, for example on labour cost). The difference between ‘financial’ and ‘economic’, as defined by the IFIs, is only instigated by the represented interests (the viewpoint) of this type of evaluator. IFIs need to make this distinction because they bear responsibilities towards governments rather than persons or enterprises. The ‘economic’ approach is neither more realistic, nor more universal, than the ‘financial’ approach. In descriptions of the distinctions between ‘economic’ and ‘financial’ CBA, the terminology used sometimes suggests otherwise: for example ‘economic’ CBA would correct for price distortions (clearly a pejorative expression) prevailing in nonmarket economies. However, such a negative value judgement is fair from the perspective of evaluators who assume national boundaries as system boundaries. Therefore, differentiating between ‘economic’ and ‘financial’ evaluations can be interpreted as merely a matter of selecting different system boundaries for the evaluation.

Incorporating environmental issues in the analysis (further elaborated upon in Section 2.2.3) is a procedure for extending the system such that it includes the exhaustible environment. This makes sense for both the ‘economic’ and the ‘financial’ approaches, especially where environmental effects can be valued in monetary terms. With the

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127/ In Section 2.1.1 it was explained how LCA considers system types of an essentially different nature. See footnote 100.

128/ The notion of taking responsibility for future generations is effectively phrased by Brundtland et al.: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (World Commission on Environment and Development (1987), p. 43).

129/ Quotes are used to indicate that the definition employed by IFIs is being used.

130/ Munasinghe, Meier, Hoel et al. (1995), p 151.
development of the so-called flexible tools (JI and CDM)\textsuperscript{131} this becomes possible for avoided GHG emissions within the framework of ‘economic’ CBA. In so far as the values of avoided emissions can be made payable to the private investor in a project (a form of internalisation), such environmental effects can also be incorporated into a ‘financial’ CBA.

\textit{Indicators and functional units}

A CBA yields a limited number of monetary indicators. These may be distinguished into two types: pure monetary indicators, and unit cost indicators. Unit cost indicators are shaped in a manner similar to the environmental indicators produced in an LCA (see page 65), i.e. as a quantity divided by a functional unit which serves as a common basis through which projects can be compared and judged. Examples of unit cost indicators are:

- Unit production cost (UPC) of energy (\(\text{\euro}/\text{GJ}\) and \(\text{\euro}/\text{kWh}\)),
- UPC of avoided GHG emissions (\(\text{\euro}/\text{t}\) GHG avoided emission).

It could be argued that, strictly speaking, unit cost indicators do not fit a true CBA, as these indicators do not balance benefits with costs. Rather, an analysis resulting in these indicators is about cost effectiveness. However, if in a comparison of multiple projects, production targets in terms of physical quantities produced are equal, then benefits are equal as well, and the distinction between CBA and cost effectiveness analysis vanishes. Examples of pure monetary indicators are:

- Net present value (NPV) (\(\text{\euro}\)), defined as the total of all discounted cash inflows and outflows of a project taking all current and future cash flows into account,
- Net present value ratio (NPVR) (dimensionless), defined as NPV/(present value of the investment),
- Internal rate of return (IRR) (%/yr), defined as the rate at which NPV equals zero.

Whereas unit cost indicators can serve for comparing projects on the basis of equal service provision (which is also the LCA approach, Section 2.1.1), pure monetary indicators are useful for project comparison under other perspectives, for example that of the scarcity of opportunities, the scarcity of capital, or the maximization of cash inflows. First of all, however, both unit cost indicators and pure monetary indicators provide absolute criteria for the appraisal of individual projects, since for project feasibility, it is at least necessary that:

- UPC \#unit sales price,
- NPV \(\geq 0\), or that
- IRR \(\geq\) discount rate.

If various projects are being considered, then it may be impossible to carry them all out. For example, a valley may be the candidate location for a plantation and for an industrial area at the same time. Under these circumstances of scarcity of opportunities, the project with the larger NPV will be preferred by the valley society. An investor, on the other hand, with ample project opportunities, and with a desire to maximize his cash inflow, will prefer the project with the larger IRR. Note, however, that these two indicators do not necessarily point into the same direction: the project with the largest NPV does not

\textsuperscript{131} JI = Joint Implementation, CDM = Clean Development Mechanism. Both project types are defined in the Kyoto protocol, UNFCCC (1997).
automatically have the best IRR (for example if the projects considered require different amounts of capital). This is because the different indicators resulting from CBA do not focus on the same issues, and the use to be made of the indicators is dependent on the perspective of the evaluators, or, in other words, the interest represented by them. This does not render one approach less rational than the other. Therefore, a differentiated view with regard to the use of the various indicators is recommended here, as opposed to the common recommendation of employing only the NPV.\footnote{132}{\vspace{10pt}

\textbf{2.2.2 How CBA’s deal with the dimension of time}

A CBA evaluates a project over its economic lifetime (the project life cycle). Referring to the example given in Figure 9, a CBA would focus on the subsystem ‘Power plant: energy conversion’ during its projected economic lifetime.\footnote{133}{\vspace{10pt}

As discussed, a CBA is fundamentally able to incorporate the environmental matters that occur during this entire period. The tool used in CBA to make future events, whether monetized or not, comparable with a common yardstick is the discount rate, as already discussed in Sections 1.1.2 and 2.1.2.

In the context of a single project evaluation, the applied discount rate has a unique value. However, depending on the viewpoint of the evaluator (global society, national society, private enterprise), large differences in its magnitude may occur. Also whether inter-generational, or just intra-generational responsibilities, (in other words: the extent of the time horizon) are concerned makes a difference. Thus the discount rate is influenced by the applicable system boundaries. Discount rates applied in the debate about global climate change valuation - an inter-generational matter - were briefly touched upon in Section 1.1.2. In their contribution to the considerations of the IPCC, Arrow, Cline, Maler \textit{et al.} (1995) report discount rates of 2-3\% (with a prescriptive approach, based on ethical considerations) up to 26\% (according to a descriptive approach). At the social level of a country, the magnitude of the discount rate is determined by the balancing of two objectives: future consumption (growth) and current consumption.\footnote{134}{\vspace{10pt}Squire and Van der Tak (1975) recommend values in the range of 5\% (growth oriented countries) to 10\% (consumption oriented countries). The discount rates for private enterprises are equal to their perceived opportunity cost of capital, and they differ from enterprise to enterprise. They are, even after correction for anticipated inflation, also strongly determined by the country in which an enterprise is located, mainly due to risk perceptions. Private enterprises in industrialised countries typically apply discount rates of about 12-15\%, in developing countries discount rates as high as 30-40\% may apply.

\textit{Squire and Van der Tak} (1975), p. 109.\footnote{135}{\vspace{10pt}Squire and Van der Tak (1975), p. 110.\vspace{10pt}}


\textit{The economic lifetime is the expected project lifetime. It is distinguished from the technical lifetime of equipment. At the end of technical equipment lifetime, equipment may be replaced. This is repeated until the end of the economic lifetime. If technical lifetime exceeds economic lifetime, equipment may have a positive value at the end of a project.}\footnote{133}{\vspace{10pt}The economic lifetime is the expected project lifetime. It is distinguished from the technical lifetime of equipment. At the end of technical equipment lifetime, equipment may be replaced. This is repeated until the end of the economic lifetime. If technical lifetime exceeds economic lifetime, equipment may have a positive value at the end of a project.\vspace{10pt}}
2.2.3 CBA and environmental issues

Environmental impacts can be incorporated in a CBA of projects, and this is not restricted to those issues covered by the economic definition of environment discussed in Section 1.1. Once society's value perception of theoretical environmental matters are measured, for example by means of the contingent valuation method (Section 1.1.2), those issues can also be incorporated. Where such issues do not fall within a system representing an economic actor, they can be incorporated in the analysis as external costs. Environmental externalities may be encountered in both 'financial' and 'economic' CBA (as distinguished in Section 2.2.1). The inclusion of externalities in CBA requires an extension of the system boundaries such that, in addition to the original project, also its exhaustible environment becomes part of the system considered (a move which we have also encountered with LCA, Section 2.1.1 and Figure 6). For environmental externalities in an economic analysis this is illustrated in Figure 10. The diagram shows the system boundaries of a project, and of its exhaustible environment, with associated externalities to the project. Notice that these externalities are internal to the overall system which encompasses the exhaustible environment. The associated costs are not borne by the primary project actor.

The attractiveness of incorporating externalities in a CBA is that this simplifies the comparison of projects having a completely different range of environmental impacts. This is particularly appealing for evaluating different sustainable energy concepts, since these are often so different in nature. For example, comparing wind power and hydro power, the first has a huge impact on landscape values, and the second can even lead to a complete change in land use. On the other hand, if one looks closely enough, one becomes aware of a multitude of subtle discrepancies between project alternatives, and their relevance may be doubted. This is evident from analyses of the various candidate energy crops. In their analysis of the environmental performance of rape seed, sugar beet, winter wheat, sweet sorghum, silage maize, hemp, miscanthus, poplar, willow, and eucalyptus, Biewinga and Van der Bijl (1996) reported LCA indicators for GHG emissions, acidification, ozone depletion, minerals consumption, pesticide leakage, soil erosion, water utilization, fertilizer utilization, waste water spillage, biodiversity, landscape values, and employment creation. The cited work is by no means unique, and one desires an objective tool to handle such results.
Externality costing is an instrument, provided by economic analysis, which can be used to value exhaustible environmental impacts. ‘External effects’ or ‘externality’ are those impacts of an economic activity or a project which arise beyond the boundaries of the primary system considered, and for which the associated costs are not accounted for by the actors - private or public - within that system. Not all externalities concern the exhaustible environment. Sometimes issues such as employment effects and effects on GDP are also considered externalities. In this sense an ‘economic’ evaluation can also be considered as one that incorporates the effects which remain external in a ‘financial’ evaluation (see Section 2.2.1). Nevertheless, many external effects do appear to be of an exhaustible environmental character since our economies do not internalise all exhaustible environmental costs into the cashflow systems of economic actors on any of the conceivable system levels. Exhaustible environmental externalities include: GHG emissions, and emissions into the air with health impacts such as dust and SO2. Various analysts have attempted to determine the exhaustible environmental externalities of energy systems, including biomass energy projects. Recent examples of such efforts are Holland, Berry, Nocker \textit{et al.} (1995), OECD (1997), Faaij, Meuleman, Turkenburg \textit{et al.} (1998), and Sáez, Linares and Leal (1998).

\textit{The method of costing externalities}

The approach chosen by Holland, Berry, Nocker \textit{et al.} (1995), for conventional as well as renewable energy systems, deserves special mention as it represents, on the one hand, an approach adopted over say the last 10 years by major analysts and government institutions and, on the other hand, the ultimate consequence of particular economic thinking about...
the exhaustible environment. The work of Holland, Berry, Nocker et al. was part of a joint activity by the European Commission and the US Department of Energy, begun in 1991 (the Exteine project), with the objective of developing a commonly shared methodology to evaluate externalities associated with energy production, and, ultimately, to enable the development of internalisation policies. The latter was one of the objectives formulated in the European Union’s ‘Programme of policy and action in relation to the environment and sustainable development’ (EU (1993)). The principles are laid out below, and they have also been proposed in the IPCC reflections with regard to the determination of policies concerning global warming.

The analysis starts from the principle that both the damage to the environment, and the costs of prevention, are functions of environmental stressors. A larger emission, for example, is more harmful than a smaller one. Likewise, does emission prevention cost less

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**Figure 11.** The cost of an externality as a function of the stressor level.

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136/ See Foreword and Executive Summary to Holland, Berry, Nocker et al. (1995).
137/ Munasinghe, Meier, Hoel et al. (1995).
if higher emission levels are allowed. This is shown in Figure 11 for an imaginary production activity. The graph shows conceptual curves for the change of abatement cost (A) and damage cost (D) with changing emission level (E).\textsuperscript{138} Abatement costs are defined here as the cost of reducing the emission from the original level emitted by the production activity to a lower level (for this particular case, this implies that all abatement activities remain external to the production system). Damage costs are equal to the value of the damage caused at an emission level. At any stressor level, two cost types constitute the externality: damage cost and abatement cost. These are simply added. One observes:

- That there exists an optimum emission level (E\textsubscript{o}) (minimized total cost for society as a whole - i.e. including the exhaustible environment). It is determined by the intersection of the marginal cost decrease of emission abatement and the marginal cost increase of damage. These are defined by, respectively, \(\frac{d(-A)}{dE}\) and \(\frac{dD}{dE}\).\textsuperscript{139}

- At the optimum stressor level, the cost of the externality relative to the production project equals the total of abatement and damage costs prevailing at E\textsubscript{o} \((A\textsubscript{o} + D\textsubscript{o})\). The cost of an externality to the production activity is determined as the integral of the total marginal cost function augmented by the cost at E\textsubscript{o} \((\int dA + \int dD + A\textsubscript{o} + D\textsubscript{o})\).

Holland, Berry, Nocker \textit{et al.} (1995)\textsuperscript{140} claim that damages which occur at the optimum stressor level are \textit{irrelevant} externalities - a somewhat unclear expression. If this should be interpreted as that they are not true externalities, then, in my opinion, this is theoretically incorrect since, whether a damage is an externality, or not, does not depend on the stressor level but only on whether its associated costs are accounted for within a system (see definition above). If the authors imply that they are true externalities, but that their costs are irrelevant, then, in my opinion, this is politically unjustifiable, since the costs of such damages are certainly very relevant for an accountable society which aims at dividing costs and benefits in an equitable manner. A precise interpretation should recognize that:

- Externality costs are built up out of two components: damage costs and abatement costs. Fundamentally, external costs are neither equal to environmental damage costs nor to the cost of damage prevention.

- At any stressor level, damage costs are relevant - theoretically, for the determination of external costs; and practically, for the pursuit of equity.

- In a fair society, external costs are paid by the end-users of products as an addition to the non-internalised production price. Whether the cashflow of such payments is further internalised into the production system is a matter of societal management preferences. The adage that ‘the polluter should pay’ ultimately refers to the liability of the end-user of polluting products, not to the liability of the producer of those products.

- The external cost addition should serve two distinct purposes, i.e. damage compensation or repair (D, in the analysis) and, secondly, impact prevention (A).

\begin{itemize}
  \item The damage costs as a function of the stressor, are the dose-response function in the terminology of Holland, Berry, Nocker \textit{et al.} (1995), there: p. 33.
  \item They need not necessarily have the form of a straight line as used in the example.
  \item Holland, Berry, Nocker \textit{et al.} (1995), Volume 1, p. 4-5.
\end{itemize}
Note that for stressor levels below the optimum, external costs increase with decreasing levels. This is due to the application of excessive abatement measures. A rational society attempts to make polluters operate at the optimum stressor level $E_0$. Whether or not a society succeeds in this, the cost of an actual externality can be determined for the prevailing stressor level - provided sufficient information is available. The assessment is based on two things: firstly, on knowledge of the curves of abatement and damage costs, and secondly, on the real situation with regard to environmental stressors such as permitted emission levels. Holland, Berry, Nocker et al. (1995)\textsuperscript{141} rightly remark that it would be a mistake to merely take actual abatement costs as an approximation for the externality costs (referred to by those authors as the ‘control cost method’) - a criticism made by them with regard to Bernow and Marron (1990). Holland, Berry, Nocker et al. argue that the procedure would be correct if allowable stressor levels were set at the optimum, but that this cannot be presumed without further verification. Although such verification is required, their argument also misses the point: abatement costs essentially only represent part of the costs. Similar discrepancies are found in the study by Swezey, Porter and Feher (1995)\textsuperscript{142} who report that it is an issue whether control costs or damage costs should be used in quantifying external costs. In fact, that is not an issue at all.

Rather, the precise understanding of what externalities really are seems to be the issue. A possible explanation for the controversy is that some analysts may fail to see that, under a regulated environmental impact regime, only part of the previously external costs have been internalised (with such costs reflected in production costs) and another part of the external costs related to the same stressor have not. Regulation of the maximum allowable emissions to air are an example of such internalisation - in this case of abatement cost. It is very rare, under such regimes, that air polluters internalise damage costs and manage a fund to assist victims of air pollution (emissions remain, even if they are limited). However, the internalisation of damage costs does exist (e.g. liability insurance policies, compensation for expropriation). From the comments expressed here, one should conclude that a critical review of the existing analyses of externalities concerning energy production is required.

**Externality costing to date**

The most influential environmental costing study on energy, with a focus on Europe, to date, was reported by Holland, Berry, Nocker et al. (1995). Their work formed the basis for a number of other publications, such as OECD (1997), Faaij, Meuleman, Turkenburg et al. (1998), and Sáez, Linares and Leal (1998) (the latter two studies are specifically about biomass energy production). The environmental impacts and stressors covered include:

- Global warming (emissions of $CO_2$ and equivalents),
- Acidification (emissions of $NO_x$ (formation of $NH_4$), $SO_x$),
- Issues of human and eco-toxicity (emissions of $CO$, dust).

\textsuperscript{141} Holland, Berry, Nocker et al. (1995), Volume 1, p. 7.

Lee (1995), and Swezey, Porter and Feher (1995), reported on these issues for energy production in the USA. Not generally included in studies on externalities of energy production, so far, are:

- Resource depletion (fossil fuel utilisation), 143
- Ozone depletion (emission of N₂O).

Externality costing studies also exclude a number of issues seen in LCAs on biomass energy systems, e.g.: transfer of nutrients and minerals to soil and water, ground water depletion, erosion, waste production, landscape values (Biewinga and Van der Bijl (1996)). Occasionally the literature does report the costing of a few additional environmental issues, e.g.: impacts on flora, fauna, buildings, nature, 144 biodiversity, 145 water discharges, land-use impacts, 146 soil erosion. 147 Stirling (1997) provided an extensive review of the theoretical and practical difficulties associated with the method of externality costing. One major methodological difficulty is that for quite a number of environmental impacts there is no market on the basis of which a damage cost function can be drawn up. The ways in which data are collected and interpreted differ a lot among the various researchers. Results prior to 1995 were presented by Stirling. 148 I use his figures 1 and 2, about the externalities of coal power plants and their comparison with alternative power technologies. This shows the enormous variation (for coal power alone several orders of magnitude) of aggregate external cost assessments by major analysts (Figures 12 and 13, below). 149 The reason for the wide discrepancies include differences in:

- System boundaries,
- Scope of impacts considered,
- Physical quantification (data and assessment methods),
- Cost estimation (data and assessment methods).

Stirling is right in his comment that from the results depicted here in Figure 13 a conclusion cannot be drawn as regards a preference among various electricity supply options in view of minimal environmental costs. One might take Stirling’s position that as long as full costing of all externalities is not agreed upon, the method as such should not be applied at all, the reason being that the method will groundlessly result in biases: “... how to avoid a disproportionate emphasis on the more quantifiable aspects ...?” 150 This argument fails to see that 1) the actual existence of externalities depends on the, more or less, arbitrary system boundaries which contain the economic actors, and that 2) by market management, carried out by governments, external costs can be made to shift from outside to within the systems. After all, ‘externality’ does not have an absolute meaning: it is a relative concept as opposed to internality. 151 Therefore, the desire to refrain - for

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143/ This matter is occasionally included, for example in CE (1996) cited in Vollebergh (1997).
144/ Faaij and Meuleman (1998).
146/ Swezey, Porter and Feher (1994).
149/ These two graphs are based on studies listed in Appendix C.
151/ This was rightly recognised in OECD (1997) (p. 7), with the assessment that “The damage values of the U.S. study, which are on average an order of magnitude lower than those estimated in the (continued...
fundamental reasons - from externality costing, obliges one to utilize this very tool in order to externalize currently internalized costs, and thus 'purify' the evaluations. A self-contradictory position and therefore untenable. Internalisation into production systems is already established with regard to a few specific environmental impacts. Further, society is in a situation where agreement has been reached on the costing of some specific environmental externalities, and has made them, or is about to make them, subject to market mechanisms. Examples are:

- The regulation of many environmental stressors (emissions to air, water and soil) in numerous countries. (Admittedly, whether regulations manage remaining emissions at optimum levels may be analysed and disputed - analysed by no other means than proper externality costing. There is no alternative).
- The trading of SO\textsubscript{2} and NO\textsubscript{x} emission rights in several states of the USA:\textsuperscript{152} Oregon, Massachusetts and California. (Whether quota are set at optimum levels can also be evaluated using externality analysis).
- The environmental taxes applied to power plants in the states of California, Iowa, Massachusetts, Nevada, New York, Vermont and Wisconsin,\textsuperscript{153}.
- The emerging market for trading national and international GHG emissions (JI, CDM).

A review of the methods used and results of studies on external environmental costs of energy systems is beyond the scope of this thesis. The fundamental issues that need to be addressed in such a review have been identified above. The unavoidable conclusion is that the practical interpretation of costing externalities is still too limited to enable a sensible general application for generic energy technology assessment, which after all is the purpose of this thesis.

\textsuperscript{151}(...continued)

EC study, also reflect the role of an existing emissions cap with tradable allowances that already significantly internalises the costs from SO\textsubscript{2} emissions. Because of these objective differences, values derived from studies focused on one area cannot be extrapolated to other OECD or Annex I areas where conditions might differ significantly.". On the other hand, taken together, internal and external costs, being brought into a single category (the full costs, which is the subject of the cited report), are in principle comparable.

\textsuperscript{152} Fang and Galen (1994).

\textsuperscript{153} Swezey, Porter and Feher (1994).
Figure 12. Results of externality analysis of new coal power plants as reviewed by Stirling (1997).
2.3 MAIN DIFFERENCES BETWEEN LCA AND CBA

From the above presentations a number of differences between LCA and CBA, but also potential supplements from LCA to CBA, and vice versa, have become apparent. Differences concern the:

• Scope of system types analysed.
• Scope of environmental impacts.
• Type of results.
• Evaluation method.

These are briefly summarized in the table below:

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<thead>
<tr>
<th>Item</th>
<th>LCA</th>
<th>CBA</th>
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<td>System types</td>
<td>• Production cycle</td>
<td>• Economic actor</td>
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<td>Impacts</td>
<td>• Economic environmental impacts</td>
<td>• Economic environmental impacts</td>
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<td></td>
<td>• Theoretical environmental impacts</td>
<td>• Theoretical environmental impacts</td>
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<td>• Temporal issues not differentiated</td>
<td>• Temporal issues qualified</td>
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<tr>
<td>Results</td>
<td>• Physical indicators</td>
<td>• Unit cost indicators</td>
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<td></td>
<td>• Product oriented functional unit only</td>
<td>• Monetary indicators</td>
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<tr>
<td>Evaluation</td>
<td>• Debatable</td>
<td>• Debatable</td>
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<td></td>
<td>• Relative to environmental matters only</td>
<td>• Calculable</td>
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<td>• Relative to an integrated field of utility, including environmental issues</td>
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Although CBA has been developed towards a broader horizon, from its traditional system reference of private firms, to country boundaries and even the exhaustible environment; the most characteristic feature of LCA is probably its focus on complete production cycles. This attribute makes LCA a strong tool in the consideration of environmental issues which cross national borders, such as emissions to air of acidifying gases, greenhouse gases, and ozone depleting substances. The application of LCA-type system analyses in JI baseline studies shows that key environmental issues are revealed if system boundaries go beyond the traditional ones assumed by CBA (private firms, country borders). In its turn, CBA is essentially able to absorb such results, in so far as they are expressible in terms of money, into its analysis procedures.

LCA enables the physical quantification of both economic and theoretical environmental impacts. Further, CBA is, in principle, able to evaluate them using a single yardstick. In reality this fundamental ability of CBA has yet to be proven for quite a range of exhaustible environmental matters. A weakness of LCA is that it assumes that impacts which occur after many years are as important as those which happen at the start of a project. CBA makes use of the discounting instrument to qualify such long-term events. It was shown that LCA might also be able to apply that instrument.

Typically, LCA yields a number of physical data, based on the unit products of the system analysed. Difficulties arise with LCA as soon as more than one physical indicator is determined. Despite the systematic attempts made by, for example, Heijungs, Guinée, Huppes et al. (1992a), it then becomes apparent that physical indicators as such have no meaning (they do not indicate!) and that LCA provides no tool to reconcile them on a common basis. Hence the requirement in an LCA for an ‘interpretation’ stage. CBA converts the LCA physical indicators into unit cost indicators and into pure monetary indicators. It is a weakness of CBA that it has not succeeded with full monetary incorporation. This failure of CBA is more of an impotence with LCA. The interpretation of physical data remains, within LCA, a matter of controversy between the parties involved. Solutions to such controversies may, or may not, be negotiated. A possible approach is to assign weighting factors to the various physical indicators of an LCA. However, in cases where some environmental matters are already internalised in the economic reality, the results are not necessarily consistent with the everyday value system. The weighting of multiple issues is traditionally carried out in a CBA in terms of unit costs. The experience with CBA shows that certain cost types are negligible in comparison with others, and thus, that weight factors can show very large differences across several orders of magnitude. This point is worthy of consideration by LCA interpreters. Interpretation is less a matter of debate and negotiation in cases where CBA offers sufficiently accurate costing results. A CBA can provide the data required for cost internalisation, and thus the instruments for policies which aim at assisting the invisible hand of the market.

Ex ante project evaluation can take advantage of the strengths of both LCA and CBA, reject their flaws, and live with their prevailing paucities. Currently, this can be achieved as follows: \footnote{Practical applications of LCA-type environmental balances, integrated with CBA-type (continued...)}
evaluations, are found already in CDM and JI project identification. On the one hand, the CDM and JI projects are carried out in a single country, so in that sense system boundaries do not cross country borders. On the other hand, the concepts of CDM and JI only exist because of the understanding that country borders do not matter in the prevention of GHG emissions. In the final evaluation of a CDM or a JI project therefore, the overall system encompasses the host and the guest countries involved in the project. Emission reductions under CDM and JI are determined by a comparison of the project results with a so-called ‘baseline’. This comparison involves an LCA, revealing emission additionality, and a CBA which reveals financial additionality.

Additionality indicates whether a project would have occurred in the absence of the CDM or JI mechanism. An anticipated development trajectory should therefore be part of the balancing procedure. Emission additionality is a well understood phenomenon (see for example Gustavsson, Karjalainen, Marland et al. (2000)). The guidelines for national GHG inventories, published by the IPCC, form a widely accepted framework (IPCC (1996)). During the test phase of JI and CDM, known as AIJ (activities implemented jointly), financial additionality only played a role in the programme managed by the USA (Dixon (1999)). For CDM, Mendis (1999) proposed incorporating the criterion of financial additionality.
3 INTEGRATING LCA AND CBA FOR THE EVALUATION OF MUTUALLY EXCLUSIVE TECHNOLOGY DEVELOPMENT PROJECTS

Mutually exclusive technologies yield equal services (that is, services of the same quantity and quality), but they cannot be implemented at the same time and place. In the actual market, the existence of mutually exclusive technologies is immediately evident: they compete. One is implemented here and another elsewhere, depending on site-specific and other parameters. However, information about current markets is not sufficient for the identification and selection of new technological concepts for research and development. Here, the problem arises that the technologies considered do not yet exist and that the market for which they are intended is necessarily a future projection as well. Also, among technologies not-yet-developed, one finds various alternatives which mutually exclude each other. For example, in the case of centralised biomass-fuelled electricity production technology, such alternatives are:

- Biomass gasification integrated with combined Brayton and Rankine cycles, often referred to as BIG/GT.\textsuperscript{156}
- Biomass pyrolysis integrated with combined Brayton and Rankine cycles.

In present day electricity production, the combined Brayton and Rankine cycles are found in modern gas fuelled power plants in which gas turbines are coupled to a steam cycle. The single Rankine cycle is applied in conventional steam power plant (usually coal fuelled).

The development of new technologies is usually advocated with reference to improved efficiencies and other performance advantages, such as reduced environmental impact. These advantages are often expressed solely in physical terms, without appreciation of the economic implications. But performance advantages do bear costs which are not necessarily limited to the cost of the development efforts required. They may well extend to the investment levels required for the implementation of the aimed-at superior technologies. If this is not sufficiently recognized, - as is the situation, according to Radetzki,\textsuperscript{156} in the biomass energy R&D community and its financiers, - technology development may result in technologies which do not comply with economic efficiency criteria, and which therefore will not find substantial employment. This is particularly relevant if there exists more than one alternative to achieve general objectives such as reduced energy or materials consumption. Once new technologies are available, the economically superior ones are likely to prevail. It is therefore apparent that foreseeable

\textsuperscript{155} The acronym BIG/GT (Biomass fuelled Integrated Gasifier and Gas Turbine) was introduced by Williams and Larson (1993). Later on in this thesis, for systematic reasons, I refer to this type of system by the term 'biomass fuelled GCC'. GCC indicates 'Gasifier coupled to a Combined Cycle' (See Section 5.1).

\textsuperscript{156} "The debate on the role of biomass in the OECD countries is dominated by engineers who conceive the equipment and plant for its use; and by true believers in the advantage of this resource, no matter at what cost." (Radetzki (1997), p. 545). An unkind remark, in so far as it suggests that the referred to engineers and other advocates do not bother about costs. Although this might be occasionally true, the general implication is refuted by this thesis (since it is brought forward by one of those very engineers). It is not another attempt at engineering domination, and it hopefully exemplifies that arguments rather than profession are decisive.
economic efficiencies should be evaluated in advance, and that development targets for selected concepts should be set, not only in terms of physical performance but also in terms of economic criteria. In the following sections an outline is presented of a methodology by means of which such evaluations can be made, and economic development targets identified.

3.1 SYSTEM DEFINITION

As discussed earlier (Section 2.2.1), the system boundaries are fundamentally determined by the represented interest. In an attempt to cover a universal interest, it would be an option to include all conceivable actors involved directly or indirectly within the system. For example, concerning electricity production: fuel suppliers, fuel transporters, the electricity producer, and others. Indeed this listing may be extended still further, as can be observed in the field of project appraisal. However, its complete identification is not a prime concern. The questions to be addressed are basically: who are the responsible actors and, then, how can they account for their responsibilities? In reality, nobody is interested in a comprehensive approach which pursues economic and other optimisations for an aggregate actor system, precisely because society is segregated into multiple actors, each with their own responsibility. In the approach followed here, two major perspectives are chosen:

- Of countries,
- Of producers, responsible for sustainable manufacture.

Primarily therefore two systems are distinguished: a ‘countries’ system and a ‘producer’s system’. This selection is not arbitrary, only countries and producers bear the relevant responsibilities or, which is the same thing, are in a position to act. And thus these are the ones who need to consider alternative actions (including technology development). Admittedly, there are some assumptions in this approach. It is assumed that environmental issues are represented by country governments, and that those environmental issues are acknowledged by producers (possibly, but not necessarily, as a result of government policies). The objection that environmental interests are not always represented adequately by a country, or recognised properly by a producer, may be true, but the evaluation methodology developed here is only intended for situations where environmental issues are commonly understood. So, an essential assumption made here, is the idea that, in principle, environmental issues can be represented properly by governments and producers.

Although a producer is always located within a single country, a countries’ system may encompass several countries. This is necessary for the analysis of cases in which environmental issues affect various countries. Examples of such issues are climate change, 

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157/ A recent study for Novem on the sustainability of biomass fuel imports into the Netherlands specifically proposed including current “local users of the considered biomass sources (land, forest, etc.), people that are to be involved in preparation of the biomass, either directly (…) or indirectly (…), local/regional/national government, …... care should be taken to also consider the local stakeholders that do not have the possibilities to express their opinion. They can be identified and involved through participatory techniques …” (Rijssenbeek, van der Vleuten, de Winter et al. (1996), p. 34).
induced by the rapid increase of GHG concentrations in the atmosphere, and the depletion of European fisheries. The systems approach proposed is further illustrated, below, using the example of climate change. Under the United Nations Framework Convention on Climate Change (UNFCCC (1992)) a multitude of countries have committed themselves to reduce the emission of GHGs. Primary responsibilities are placed with the so-called Annex I countries, consisting of the major industrialised economies. Other signatories - non-Annex I countries - are often able to contribute to the reduction targets of the Annex I countries (under the CDM mechanism, for example by providing biomass fuels). In addition to the division into Annex I and non-Annex I countries, a further distinction within the group of Annex I countries is relevant, between those who sell, and those who buy, emission reductions from each other under JI (sellers are mainly those countries that are undergoing the process of transition to a market economy).

The example is further confined to one particular type of technology: the substitution of fossil fuels by biomass fuels for sustainable electricity production. This option includes a wide range of alternatives, so that the technology selection problem is typical. The technologies to be evaluated have several characteristics in common; they produce sustainable electricity of equal quality and quantity. One system boundary is therefore defined by this product outflow.

For establishing the incremental emissions resulting from plant operation in which biomass-based electricity generation differs from conventionally produced electricity, LCA methodology indicates that the entire chain from fuel production up to its conversion to electricity should be taken into account. Therefore, in so far as emissions are concerned, the system includes fuel production, and all fuel transports up to delivery to the power plant. This applies not only to the evaluated technologies, but also to those which they are going to replace (fossil fuel power plant), since the reduced GHG, and other, emissions are quantified by balancing the two. In the example only GHG emissions are included, despite the fact that some studies also hold that other emissions and impacts are of importance. GHGs recognised in the Kyoto Protocol are the following:

- Carbon dioxide (CO$_2$),
- Methane (CH$_4$),
- Nitrous oxide (N$_2$O),
- Hydrofluorocarbons (HFCs),
- Perfluorocarbons (PFCs),
- Sulphur hexafluoride (SF$_6$).

In the time dimension, the system is bounded by the economic lifetime of the project in which the technology is implemented: in this example, an electricity power plant. However, environmental stressors may exist which cause damage over even further extended time periods. Thus, for a fair assessment such damage should be translated into values which are relevant during the project’s duration. That evaluation is done by means of externality costing (see Section 2.2.2).

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158/ The quality of electricity is determined by its power, and its moment of availability.
159/ UNFCCC (1997).
In the previous chapter, the question was raised whether or based on what grounds any item in the World and its future could be omitted from the systems considered. It was shown that at least the so-called functional unit, here: electricity, must be assumed constant; and it was speculated, but not elaborated, that the discounting method might be of assistance in selecting relevant issues. In the example considered here, a decision should be made on whether GHG emissions embodied in capital should be included within the system’s comparison or not. Based on pure LCA grounds, Reinhardt and Stelzer argue, why it is appropriate to neglect those issues: in balancing the two compared cases (biomass vs. fossil fuels) they are negligibly small. This applies to emissions resulting from the construction and decommissioning of the respective energy conversion components (power plants), and also to those resulting from the creation and discarding of infrastructures for fuel production (e.g. roads, mines, refineries). Their approach is adopted here too.

3.1.1 The countries’ system

For the example of fossil fuel substitution by biomass, Figure 14 shows the boundaries of the countries’ system. Notice that countries which do not participate as an actor in the application of the new technology, or in the substituted technology, are not contained by the system. Nevertheless, countries which do not deliver fuels nor produce electricity with the new technology, may still suffer damage from climate change. Their interest should be taken into account by the economic value attached to avoided GHGs.

In the system diagram, both the closed biomass fuel cycle and the substituted fossil fuel utilization system are depicted. Whereas the figure makes the various emissions to air explicit in terms of the location where they occur, other physical inputs and outputs are indicated in an aggregate manner only. The reason for sticking to the overall level here is simply a matter of clarity. It is the intention to also analyse these unspecified inputs and outputs on a country level.

To some extent the systems as shown are simplified and specific to particular situations. For example it is assumed that the country in which the fuels are utilized for electricity production is different from those where the fuels are produced. If fuels were provided locally within one single country, the international sea transport would be omitted, and the countries F and E and/or B and E would coincide. Further, local fuel transports are not indicated separately. Emissions from this activity are implicitly incorporated in an aggregated manner within the subsystem of the fuel providers, Countries F and B (denoted with the subscripts M and BP respectively). If required, local fuel transport within the electricity producer’s country (E) can be dealt with by distinguishing further subsystems within country E (that is, at least two: local fuel transport, and energy conversion).

The emission reduction which occurs if the fuel substitution does take place is the balance of the fossil fuel and the biomass fuel chain (the F and B chains, respectively). This balance can be analysed as shown in Table 9. Note that the reduced emission can be negative, i.e. if there is a real emission increase. The expression ‘reduced’, together with the orientation of arrows, merely determines a sign convention.

Table 9. GHG emission reduction for the countries’ system if the biomass fuel cycle replaces fossil fuel utilisation (if < 0: increase).

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<tbody>
<tr>
<td>GHG&lt;sub&gt;M&lt;/sub&gt;</td>
<td>GHG&lt;sub&gt;EPF&lt;/sub&gt; - GHG&lt;sub&gt;EPB&lt;/sub&gt;</td>
<td>GHG&lt;sub&gt;EPF&lt;/sub&gt; - GHG&lt;sub&gt;EPB&lt;/sub&gt;</td>
<td>GHG&lt;sub&gt;ISTF&lt;/sub&gt; - GHG&lt;sub&gt;ISTB&lt;/sub&gt;</td>
<td>(GHG&lt;sub&gt;M&lt;/sub&gt; - GHG&lt;sub&gt;EPB&lt;/sub&gt;) + (GHG&lt;sub&gt;ISTF&lt;/sub&gt; - GHG&lt;sub&gt;ISTB&lt;/sub&gt;)</td>
</tr>
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</table>

Legend: BP = Biomass provision; FF = Fossil fuel; EP = Electric power; IST = International sea transport; MB = Mining.

Overall emission balance:
- Electricity = equal for both systems
- Reduced GHG emissions = GHG<sub>M</sub> - GHG<sub>EPB</sub> + GHG<sub>ISTF</sub> - GHG<sub>ISTB</sub> + GHG<sub>EPF</sub>

Figure 14. The definition of the countries’ system. (The expression ‘reduced’ together with the orientation of arrows merely determines a sign convention.)
Note that one particular assumption on the balance of GHGs has been only implicit in the discussions so far, i.e. that the biomass fuel is produced sustainably, in the simple sense that it can be continued infinitely. This condition is both a necessary and a sufficient justification for the claim that the biomass fuel cycle is closed, or in other words that the emissions from electricity production are captured by biomass production:

\[
\text{GHG capture in Country B} = \text{GHG}_{\text{EBP}}
\]

This does not imply that the biomass fuel cycle has zero GHG emissions, as can be inferred from the overall balance reviewed in Table 9. Although the reduction in GHG emissions is a result of the avoided utilisation of fossil fuel for electricity production (GHG_{EPF}), there may be some increased GHG emissions at various locations within the system. Evidently, this type of project is only beneficial for the global climate if there is a net reduction in GHGs. Therefore any eventual increase in GHG emissions due to international fuel transport (GHG_{ISTB} - GHG_{ITTF}) and fuel production (GHG_{BP} - GHG_{M}) should be less than the avoided emissions from fossil fuel utilization for electricity production (GHG_{EPF}). Expressed mathematically:

\[
\text{GHG}_{\text{EPF}} > (\text{GHG}_{\text{FP}} \& \text{GHG}_{\text{M}}) \%(\text{GHG}_{\text{ISTB}} \& \text{GHG}_{\text{ITTF}}).
\]

Thus the sustainable electricity produced in the example is not entirely free of GHG emissions. However, if the two above mentioned conditions are satisfied, it is less GHG intensive, so that the output of the project can be viewed as consisting of two components: electricity and avoided GHG emissions.

The overall approach does not reveal how the various countries involved contribute to the overall GHG emission reduction. On a country-by-country basis this can be highlighted as follows:

- **Country B**: The biomass fuel producing country acts as a carbon sink for GHG_{EBP} emitted in the fuel consuming country (Country E). However, the biomass fuel producing country produces increased GHG emissions for the purpose of this very activity.
- **Country F**: The former fossil fuel producing country contributes to reduced GHG emissions by halting the emission of GHGs for the production of fossil fuels.
- **Country E**: The fuel utilizing country (for electricity production) may very well emit more GHGs, i.e. if the emission of GHGs due to biomass fuel utilization is greater than those due to the utilization of fossil fuels (i.e. if GHG_{EPF} < GHG_{EPH}). This is likely, given likely conversion efficiencies, but this does not at all affect the global GHG emission balance of the considered system.

Thus, although for the overall system the emission of GHGs is reduced (under the conditions stipulated above), this does not hold for all country-specific GHG emissions.\(^{161}\)

---

\(^{161}\) This matter is not addressed as long as the distinction between countries is not made. In the framework of the UNFCCC, and the associated mechanisms such as JI and CDM, this clarification is of decisive importance.
### 3.1.2 The producer’s system

The producer’s system (Figure 15), for this example, is a lot simpler than the countries’ system. Figure 15, like Figure 14, highlights the balance of GHG emissions into the air. It is recognized that the system boundaries are also crossed by a number of other flows. For illustrative reasons these are not further specified but indicated with the generic arrow of ‘various capital and operational inputs’.

Under the presumption that he complies locally with pertaining emission regulations (usually with regard to toxic and acidifying emissions), a producer of electricity and avoided GHG emissions is only interested in his own production (i.e. its quantities, costs and benefits). Although the quantity of electricity produced can be measured in a straightforward manner, the quantity of avoided GHG emissions is not immediately clear. A producer of electricity generated from biomass fuels cannot simply claim that he produces electricity with zero GHG emissions. First of all, the two conditions stipulated above should be satisfied. In other words, 1) the biomass fuel cycle should be closed, and 2) on a global level there should be a net reduction in GHG emissions, taking into account the emissions generated during fuel provision (its production and international transport).

![Fossil Fuel Chain](image1)

![Biomass Fuel Chain](image2)

**Figure 15.** The electricity producer’s system (for legend see Figure 14).

Thus, these emissions remain present in the system GHG balance, which is expressed as:

\[
GHG_{\text{avoided}} \cdot GHG_{\text{EPF}} \cdot \% (GHG_{M} \& GHG_{BP}) \cdot \% (GHG_{\text{ISTF}} \& GHG_{\text{ISTB}}).
\]

This equals the total GHG emission reduction reported in Table 9 for the countries’ system. It thus appears that an electricity producer might try to claim the total emission reduction achieved by the replacement of the fossil fuel chain. Whether he succeeds in
doing so depends on a number of political and economic circumstances. This is discussed in the next section.

3.1.3 Matching the two system approaches

The subsystems within the countries’ system, and also the countries’ system and the electricity producer’s system, are closely related by the law of continuity (a physical term taken from fluid mechanics). This applies to emissions, and since the countries’ system encompasses the electricity producer’s system, all emissions related to the latter also cross the boundary of the subsystem of the country in which this producer is located. Therefore, if the electricity producer does indeed claim the entire emission reduction achieved by fossil fuel substitution, the country in which he is located (Country E) is forced to make the same claim. Whether this is politically feasible in the context of the UNFCCC depends on the roles of the countries F, E and B, as well as on their position relative to the UNFCCC. A number of configurations as to the roles of Countries F, E, and B can be devised (Table 10).

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<tr>
<td>1</td>
<td>F, E, and B coincide</td>
<td></td>
<td>F, E, and B coincide</td>
</tr>
<tr>
<td>2</td>
<td>F and E coincide</td>
<td>Separate</td>
<td>E and B coincide</td>
</tr>
<tr>
<td>3</td>
<td>Separate</td>
<td>F and B coincide</td>
<td>F and B coincide</td>
</tr>
<tr>
<td>4</td>
<td>F and B coincide</td>
<td>Separate</td>
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<tr>
<td>5</td>
<td>Separate</td>
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Table 10. Configuration of roles for three types of countries.

Reductions due to avoided fossil fuel production in Country F (GHG\(_{ad}\)): If Country E demands the full emission reduction resulting from the project, the former fossil fuel providing country (F) cannot claim the reductions achieved by his avoided fossil fuel production (GHG\(_{ad}\)), since these would be already accounted for. This is not a problem if the fossil fuel provider and the end-user coincide. It would apply to the Netherlands if biomass replaced Dutch natural gas used in Dutch electricity production. The situation is more complicated if the countries of the fossil fuel provider and the end-user do not coincide. If, in this situation, the former fossil fuel providing country (F) does not belong to Annex I, or is not even committed to the UNFCCC, emission reductions do not form part of its own recognized interests, and then the end-user country (E), including its sustainable electricity producer, could simply also claim the avoided emissions from fossil fuel production. If, in contrast, the former fossil fuel providing country (F) is one of the Annex I countries, the reduced emissions as a result of diminishing fossil fuel production will probably not be transferred, without some financial compensation by the country replacing fossil fuels by biomass (E). As long as Country F does not take the role of biomass fuel supplier there are no further advantages for this country, and therefore JI would not offer a framework for such a transfer. Simple emission trade would, but this is beyond the scope of this investigation. A further complication with regard to this allocation problem is that fossil fuels are traded internationally and that it is probably
impossible to establish from which particular country substituted fossil fuels would originate.

*Reductions due to carbon capture in Country B (GHG_{EPB})*: Countries E and B need to agree on how the emission reductions resulting from CO₂ assimilation in Country B are to be shared. One option is that Country E takes all at the expense of the biomass purchase, and the installation of energy conversion equipment specifically suitable for electricity production from biomass. For Annex I biomass fuel providers (B) (e.g. countries in C&E Europe such as the Baltic states providing biomass fuels to Sweden), JI could provide a framework for negotiation. For developing, non-Annex I, countries CDM could offer the same.

*Increases resulting from increased biomass production (GHG_{BP})*: The biomass fuel providing country (B), has increased GHG emissions (GHG_{BP}) related to its production efforts. This will be of concern to this country if it has obligations under Annex I of the Kyoto protocol. If such a biomass provider and the end-user (E) agreed the transfer of the emission reductions (from B to E) due to carbon capture (GHG_{EPB}) by B, it would not be reasonable, without additional payments, for Country B to accept such increases in its national GHG accounting system. This matter needs to be incorporated in the negotiations under JI suggested above. If the biomass provider is a non-Annex I country, then a straightforward solution would be to allocate the emission increase to the end-user country as a component of its emission savings due to the project.

*Increases resulting from increased international transportation (GHG_{ISTF} - GHG_{ISTB})*: The increased emissions due to increased international transport can be simply included in the emission balance of the end-user country (E). There need be no dispute about these emissions as long as they are fairly accounted for.

The above discussion on emission allocation might be viewed as splitting hairs. Depending on the prevailing parameter values, that qualification may be adequate. However, it is not, in so far as the principle is concerned, and in fact large amounts of money may be involved. The review is given here as an illustration of issues which may arise if an analysis of this type is pursued.

The law of continuity also applies to the cash flows between the subsystems distinguished within the countries’ system: revenues of one are the costs of another. Cashflow continuity also governs the relationship between the electricity producer’s system and the subsystem of the country in which he is located. Note that, for the latter subsystem, the cash flows of the electricity producer need to be corrected for that proportion which remains internal within the implied country (see Section 2.2.1 on ‘financial’ and ‘economic’ system boundaries).

### 3.2 INDICATORS

In this section, indicators are derived for the two different systems identified, the countries’ and the producer’s. Also here, the general approach is applied to the example of climate change and fossil fuel substitution for electricity production.
3.2.1 Indicators for the countries’ system

Countries producing the necessary biomass fuels (type B countries) are interested in fair and effective cost compensation so that the required investments can actually be made. This cost compensation is reflected in the unit production cost of electricity, and GHG emission reductions. Since biomass fuel costs vary from country to country, the end-user (a type E country), interested in overall cost minimisation, will try to select the lowest cost biomass fuel providers. Such providers create a bottom line below which unit production costs of electricity and GHG emission reductions cannot be achieved. The relevant indicator to be minimised is the unit fuel cost, expressed on a primary energy basis:

\[ UPC_{\text{biomass fuel}} \] [€/J].

Here, the fuel cost, as delivered to the power plant is meant. Thus transportation cost is also a relevant parameter. Note also that the form in which the fuel is delivered makes a difference due to variations in conversion efficiencies (for example, prior to conversion in a pulverised fuel combustor, charcoal needs less preparation energy than wood). Therefore, the unit biomass fuel cost is a parameter which needs to be evaluated with care taking into account conversion technologies and energy efficiencies. However, for technologies which have equal fuel quality requirements, it is a straightforward indicator.

On a generic level, so beyond the scope of the example used here, the principle concerns the minimisation of the unit raw material costs, to a feasible but fair value.

A key role in technology selection is played by the countries committed under the Kyoto Protocol (the Annex I countries). In their absence, the demand for the types of projects considered here would not even exist (and the interest in developing the appropriate renewable energy technologies would be less). From the viewpoint of Annex I countries, the leading principle in technology evaluation is the minimisation of the aggregate cost of both electricity production and GHG emission reduction, i.e. the minimisation of:

\[ Total \ cost \ = \ UPC_{\text{electricity}} \times j \ \text{Electricity units} \% UPC_{\text{GHG ERUs}} \times j \ \text{GHG ERUs}. \]

For a single technology for electricity production, the total GHG emission reduction can be expressed as a linear function of electricity production:

\[ j \ \text{GHG ERUs} \ = \ \rho \times j \ \text{Electricity units}, \]

where \( \rho \) is a unit-specific emission coefficient with the dimension t GHG/MWh. Therefore the required minimisation is the minimisation of:

\[ Total \ cost \ = \ (UPC_{\text{electricity}} \% \rho \times UPC_{\text{GHG ERUs}}) \times j \ \text{Electricity units}. \]
Since the total quantity of electricity units produced is the same for whichever electricity production technology, it can be concluded that Annex I countries are basically interested in the minimisation of:

$$UPC_{electricity} \% \times UPC_{GHS\ ERUs}.$$  

More generally, ignoring the particular example of climate change and sustainable electricity production discussed here, the indicator reflects the principle of minimised unit production cost of the basic societal service (principal product) and its associated environmental component.

For the analysis of competing technologies, the net present value (NPV) and the discounted costs (PVC) would also be appropriate indicators. This can be demonstrated as follows:

• Unit production costs (UPC) are defined as the ratio of the present value of costs (PVC) and the discounted product flows:

$$UPC = \frac{PVC}{PV \ of \ product}.$$  

• And secondly, the production profile over time (the denominator in the above equation) is assumed equal for the technologies compared. Therefore minimisation of UPC implies minimisation of PVC. For the sake of completeness, the definition of PVC, given implicitly above, is repeated:

$$PVC = \sum_{j}^{project\ duration} \frac{cash\ outflow_{j}}{(1 \% discount \ rate)^{yr\ j}}.$$  

The net present value (NPV) is an indicator which encompasses the PVC. It is broader since it not only includes costs, but also revenues. For the projects considered here, the revenues are equal: they concern different technologies to produce the same product with the same quality and quantity. As a consequence of sign conventions NPV should be maximised rather than minimised. Overall, because of the initial condition that mutually exclusive technologies are to be compared, the three indicators NPV, PVC, and UPC, are equivalents. Expressed symbolically:

$$NPV_{Technology \ A} < NPV_{Technology \ B}$$  

$$PVC_{Technology \ A} > PVC_{Technology \ B}$$  

$$UPC_{Technology \ A} > UPC_{Technology \ B}.$$
3.2.2 Indicators for the producer’s system

In the electricity market as it exists or is being created in most industrialised countries, electricity producers are investors guided by the productivity of their capital. In their position the internal rate of return (IRR) is the most appropriate indicator. With this indicator the following criteria apply (Table 11):

<table>
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<tr>
<th>Condition (if)</th>
<th>Indication (then)</th>
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<tbody>
<tr>
<td>1) IRR (i) (\geq) discount rate (DR)</td>
<td>Technology (i) is economically feasible</td>
</tr>
<tr>
<td>2) IRR(_A) (&gt;) IRR(_B)</td>
<td>Technology (A) is preferred over Technology (B)</td>
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Again, this principle applies beyond the particular example considered in this section.

IRR (and also UPC, see p. 99) can be calculated using the fully-fledged discounted cashflow method. Alternatively, annuity calculus might be suitable. Both methods are investigated in some detail here. In the discounted cashflow method, each future cashflow is discounted to its present value at the chosen discount rate over the applicable period:

\[
P_V^{\text{cashflow } i} = \frac{\text{cash flow } i}{(1 \% \text{discount rate})^j}
\]

where \(i\) is the year number. IRR is defined through the following implicit equation:

\[
\text{IRR} = \frac{\text{project duration}}{\sum_{j=1}^{\text{project duration}} \frac{\text{cash flow } i}{(1 \% \text{IRR})^j}},
\]

or, in words, it is the rate\(^{162}\) which yields equal present outflows and inflows of cash. Therefore, if the project concerns a production process, the IRR is the rate at which UPC equals the unit product sales price.

This method of determining IRR requires the generation of a complete cashflow profile. The method is distinctive when comparing projects which show large differences in cashflow profiles over time. However, for projects which are intended to provide equal services, revenue profiles over time are similar, and therefore a less cumbersome method for determining IRR would be preferable. Such an alternative method can be developed on the basis of the principles of annuity calculus, as is shown below. The fundamental

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\(^{162}\): Often IRR is defined as the *discount rate* at which this condition is satisfied (e.g. by Behrens and Hawranek (1991), p. 280). Although the succinctness of such phrasing is appealing, it is essentially incorrect. A discount rate, after all, is an economic property of the *investor* (i.e. the required productivity of his investment, see Section 2.2.1), whereas an internal rate of return is an economic property of an *investment*: its expected productivity. The inaccuracy in the definition of IRR is probably encouraged by the fact that the net present value of an investment is defined by a similar equation:
difference between the discounting and the annuity method is that whereas through
discounting the present value of future cashflows is determined, the annuity calculation
method averages an investment over future years. The method takes account of the time
value of investments by applying the following equation:

$$\frac{Annuity_{good \ x}}{Investment_{good \ x} \times \text{discount rate}}$$

$$\frac{1 \times (1 \ % \text{discount rate})^{t_x}}{t_x}$$

where $t_x$ is the technical lifetime of good $x$. Note that the technical lifetime ($t_x$) of
component $x$, rather than the project lifetime, is employed to calculate the annuity. If the
technical lifetimes of some of the investments are shorter than the project duration, a
reinvestment is needed but this does not change the total annuity of the project investment,
which is defined as:

$$\frac{Annuity_{total \ investment}}{Investment_{total \ investment} \times \text{discount rate}}$$

$$\frac{1 \times (1 \ % \text{discount rate})^{t_x}}{t_x}$$

In this calculation, the annuity of a reinvestment - if it occurs - should not be included,
since this would be a form of double counting. Any reinvestment has already been
accounted for by employing the shorter technical lifetime, rather than the project lifetime.
The ‘internal rate of return by annuity’ $\text{IRR}_a$ can now be defined as the rate at which:

$$\frac{total \ investment \ x}{Investment_{good \ x} \times \text{IRR}_a}$$

$$\frac{Annual \ revenue \ & \ Annual \ operating \ cost.}{1 \times (1 \ % \text{IRR}_a)^{t_x}}$$

By means of the addition of the phrase ‘by annuity’ this rate is distinguished from the IRR
defined on the basis of discounted cashflows. Although calculated in different manners,
and although, occasionally, their values may differ, the two indicators have a conceptual
characteristic in common: they are the rate at which the annual production costs (which
is the total of capital costs and operating costs) equals the annual revenue, or in other
words, the rate at which the unit production cost (UPC) exactly matches the unit product
sales price ($\approx$ Annual revenue / annual production). Earlier it was already shown that this
applies to the conventional IRR. That it holds for the IRR by annuity as well is evident if
we define the ‘unit production cost by annuity’ (UPCa) using the following equation:

$$UPC_a = \frac{Annuity_{total \ investment} \times Annual \ operational \ cost}{Annual \ production}$$

163/ I have not come across it elsewhere, and hence this daring new name. The internal rate of
return by annuity is not the same as the simple, or annual, rate of return, as explained by Behrens and
Hawranek (1991) (p. 287). The latter applies to enterprise analysis and depends on local accounting
conventions. Neither is the internal rate of return by annuity equal to the return on investment (ROI), as
defined by Holland, Watson and Wilkinson (1987), p. 25-41. The ROI is the reciprocal of the simple
payback period.
From mathematical analysis it is apparent that for projects which do show constant operational cashflows, IRR and IRR₀ are equal. An objection to the use of the internal rate of return by annuity could be that it would not support the inclusion of costs and benefits which occur at project termination (termination cost, residual equipment values). However, it does. Such issues can simply be included as additional costs and benefits annualized over the entire project duration. Thus it can be shown that annuity calculus enables an accurate handling of all occasional costs (capital investments as well as termination costs), as precisely as the discounted cashflow method. With regard to operational cashflows (costs and revenues) during the course of a project, annuity calculus presupposes that they are uniform over time. Therefore, for projects where this is not the case, this method is less accurate than the discounted cashflow method. If such conditions are known in advance, the discounted cashflow method could be considered. Otherwise the annuity method is to be preferred on account of its simplicity: it requires less data inputs and less complicated algorithms.

3.2.3 Integration of the three indicators

The three indicators identified in the preceding sections - unit raw material cost, unit product cost, and IRR, are interdependent. IRR cannot be determined if revenues or costs are not defined, an affordable raw material cost level cannot be determined if discount rate (minimum required internal rate of return) or revenue are unknown, etc. Together they form a balanced system, but they are also dependent on external factors: the fairness of a price paid to suppliers of raw materials, the willingness to pay for the delivered service, and the acceptability of an internal rate of return. In an investigation into future technologies, the two UPC parameters are especially unknown. The reason being that UPCs are strongly influenced by changing market perceptions of sustainability and by potential price adaptations of non-sustainable raw materials (such as the substituted for fossil fuels in the example employed in this chapter). To a lesser extent such uncertainty also applies to the future opportunity cost of capital. For this reason it is appropriate to treat UPC parameters as variables, for example along an abscissa and an ordinate on a two-dimensional graph.

This approach can be followed when considering two competing technological concepts, intended to provide the same services, based on conversion of the same raw materials. The differences are in the investments required to produce equal quantities and in the conversion efficiencies (Table 12). Let us suppose that the low-cost/low-efficiency technology (L) is mature, and that the high-cost/high-efficiency technology is a proposed innovation.

<table>
<thead>
<tr>
<th>Table 12, General characterisation of two competing technological concepts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology L</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>Investment</td>
</tr>
<tr>
<td>Conversion efficiency</td>
</tr>
</tbody>
</table>
For each combination of unit product costs and unit material costs, each of the two technological concepts will have an IRR. But there exists a set of UPCs for which the IRRs of the two technological concepts are equal. This set of UPCs is the equi-IRR line in Figure 16. The equi-IRR line divides the UPC field into two distinct areas. In one, with higher raw material costs and lower unit product costs, the IRR of the high-investment/high-efficiency technology is always higher than that of the low-investment/low-efficiency technology (and *vice versa*).

![Figure 16](image)

**Figure 16.** The equi-IRR line in the UPC field, comparing two competing technologies (Data do not generally apply and are illustrative only).

This is not sufficient to determine the feasibility of the respective technologies as, in addition to the comparative requirement, there is an absolute requisite as well: the IRR must be larger than the discount rate DR (compare with Table 11). This additional criterion is analysed as follows. For each of the two technological concepts, there exist individual sets of UPCs for which the IRR is constant: *iso-IRR lines*. An iso-IRR line divides the UPC field into two areas. If determined for IRR = DR, the iso-IRR line defines an area of high unit product cost and low unit raw material cost where a technology, judged on its own, is economically feasible (see Figure 17). Iso-IRR lines for the two competing technologies H and L are depicted in Figure 18. The difference in the conversion efficiencies of the two technological concepts, H and L, results in distinct inclinations of the respective iso-IRR lines. Steeper iso-IRR lines reflect a lower conversion efficiency. Figure 18 also shows iso-IRR lines for various IRR levels (10%, 20% and 30%) and thus illustrates that IRR increases with lower raw material costs and higher unit product costs. Necessarily, the previously determined equi-IRR line connects the intersection points of the iso-IRR lines drawn at varying levels of IRR.
Figure 17. The iso-IRR line (for IRR = DR) for a single technology in the UPC field (Data do not generally apply and are illustrative only).

Figure 18. Iso-IRR lines (broken lines) in the UPC field, for both competing technologies. Intersection points are connected by the equi-IRR line (solid line). (Data do not generally apply and are illustrative only).

The two criteria (IRR \(_A > DR\), IRR \(_A > IRR \(_B\)), when combined, yield the graph displayed in Figure 19. Note that the iso-IRR lines are for an IRR of 10\%, which was merely selected to serve as an example. This is a meaningful choice where the discount rate (which is the IRR cut-off value for the future investor) equals 10\%.
For UPCs below both iso-IRR lines (areas I and VI in Figure 19) neither technological concept is economically feasible, as the condition that IRR should be larger than the discount rate is not satisfied. With respect to that same feasibility condition, it is apparent that in area II only the low-cost/low-efficiency technology (L) is economically feasible. Similarly, if the conditions are those of area V, the high-cost/high-efficiency technology (H) is the only one which is economically feasible. If UPCs are in areas III or IV, the threshold value for the IRR is surpassed so that both technologies would yield acceptable financial results for an investor. However both are not equally attractive, since the IRRs of both concepts, generally, are not equal. The UPC conditions where they are equal are indicated by the equi-IRR line. Left of this line (lower raw material costs) the IRR of the low-cost/low-efficiency technology is higher. The corresponding technology is therefore preferred in area III. Finally, in area IV, the high-cost/high-efficiency technology has the higher IRR and is superior. The result is that two niches are identified expressing, on economic grounds, a distinct preference for one of the two technologies. The niches are shown in Figure 20. On the one hand the niches are bounded by the feasibility condition that the IRR should be greater than the discount rate, and on the other, the niches are separated by the condition of equal IRRs.

The niche where the innovative high-cost/high-efficiency technology is economically feasible is further divided into two areas. One where the new technology expands the economic feasibility of manufacturing a product with higher raw material costs or lower product costs (which of the two occurs will depend on market conditions) (area V), and one where the new technology pushes the old low-cost/low-efficiency technology aside (area IV).
The position and inclination of the equi-IRR line and the iso-IRR lines determine the potential role of a new, more efficient, technology. The inclination of the iso-IRR line for the high-efficiency technology determines the size of the newly created market niche in the direction of higher unit raw material costs or lower product cost (area V). It has already been shown that this inclination is determined by the projected conversion efficiency of the new technology. The position of the equi-IRR line, on the other hand, is especially decisive in the competition between the new high-efficiency concept and its mature alternative (in area IV). Naturally, if the capital cost component of the high-efficiency technology becomes lower as a result of technology development and learning, this technology becomes more attractive in terms of IRR for lower raw material costs (ceteris paribus unit product costs). Hence, with reduced unit capital costs, the equi-IRR line will shift towards such lower raw material costs. This effect is greater at higher values of IRR, and therefore the inclination of the equi-IRR line increases if the capital costs of the high-efficiency/high-cost technology are reduced due to technology development and learning. This is illustrated for a number of capital cost levels in Figure 21. The graph suggests that there is a pivot point near the origin. Whether, or under which conditions such a point exists, and where it is located in the field of IRR and UPCs, can be shown mathematically, but this is not really relevant to the insights gathered here. (The mathematics of changing iso-IRR and equi-IRR lines, and more specifically, the sensitivity to conversion efficiencies and capital requirements of market niches where competing technologies are economically feasible, are fully investigated in Appendix A).

In Figure 21, both positive and negative raw material costs are considered. Negative costs are relevant in waste markets. Occasionally biomass fuels carry a negative price (e.g. excess bagasse from sugar manufacture).
Figure 21. Influence of capital cost reduction for the high-efficiency technology from 100% of the original estimate to 85% and 70% on the equi-IRR line of two competing technologies. (Data do not generally apply and are illustrative only).

The analysis framework provided here, can serve as a tool to establish targets in terms of unit specific capital needs and conversion efficiencies for the development of new technologies. However, such an assessment cannot be a mere mathematical affair, and should be rooted in market realities, as well as in the objectives of the public organisations and firms which support the particular technology developments investigated. Innovative technologies have the potential to either result in lower product costs, an increase in the affordable raw material costs, or increased profitability. Whichever occurs is a matter of market dynamics, and whichever is pursued by investors in new technologies will depend on their market position and societal objectives. This assessment - the mathematics together with the projection of technology in a more sustainable market reality - is at the heart of the investigations discussed in the following chapters.

3.2.4 Parameters and uncertainty

For the determination of the required economic feasibility indicators, a summary of costs and revenues is required. These can be broken down in many ways. Some basic distinctions are:

• Capital costs versus operational costs,
• Fixed costs versus variable costs.

Such distinctions serve specific purposes (project finance acquisition, risk assessment, etc.). For the approach defined above the division into capital costs and operational costs is appropriate, but it is not that critical, as long as all costs and revenues are accounted for. The cost items by which capital costs and operational costs are broken down (such as
labour costs, and fuel costs) depend on a large number of parameters. In the case of targeting technology development it makes sense to distinguish two basic parameter types:

- Technology parameters, and
- Site parameters.

Technology parameters are characteristics of each individual considered technology, whereas site parameters apply universally to the various technologies. Site parameters may differ from place to place, and thus technology preference may similarly vary from place to place. The proposed distinction into technology and site parameters enables an assessment of their particular influence on technology preference. In Table 13 the distinction is further exemplified for biomass energy systems in particular.

Table 13. Parameter distinction into technology and site parameters (some parameters specifically for biomass-fuelled power plant).

<table>
<thead>
<tr>
<th>Technology parameters</th>
<th>Site parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>Project lifetime (economic lifetime)</td>
</tr>
<tr>
<td>Technical lifetime of system components</td>
<td>Capacity factor</td>
</tr>
<tr>
<td>Energy conversion efficiency</td>
<td>Unit operator costs</td>
</tr>
<tr>
<td>Fuel calorific values</td>
<td>Unit consumables costs</td>
</tr>
<tr>
<td>Number of operators</td>
<td>Unit electricity sale price</td>
</tr>
<tr>
<td>Consumables utilisation</td>
<td>Unit GHG emission reduction sales price</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>Unit biomass fuel costs</td>
</tr>
<tr>
<td>Working capital</td>
<td>Discount rate</td>
</tr>
</tbody>
</table>

Some parameters that are generally applicable to investment projects can be left out of the analyses. These are: inflation, profit tax, loan gearing, and project development costs. These apply to all the various technologies and therefore in a technology-specific approach would serve no purpose. However, in a universal manner, inflation and profit tax can be incorporated in the discount rate.

Four parameters from Table 13 (Unit electricity sale price, Unit GHG emission reduction sales price, Unit biomass fuel costs, and Discount rate) are already explicit in the methodology. These can be determined from an analysis of the sites where the technologies involved may become operational. However, they remain variables, since sites are different. This is the reason why they are placed along the axes of the ‘niche graph’. Some of the parameters can be estimated with reasonable accuracy, these are:

- Fuel calorific values;
- Consumables utilisation;
- Maintenance costs;
- Working capital;
- Project lifetime (economic lifetime);
- Capacity factor;
- Unit operator costs;
- Unit consumables costs.

Less easily assessed are the four remaining ones:

- Investment;
- Technical lifetime of system components;
• Energy conversion efficiency;
• Number of operators (controllable in technical design).

These four are then the parameters for which development targets can be set, in such a manner: *If a particular technological concept is intended for a particular market niche, then the specific investment should not exceed a level of x cost/capacity; costs associated with maintenance and labour should remain lower than y cost/product unit; and the efficiency should at least be z%.* However, a preliminary estimate has to be made for these parameters, since otherwise a start cannot be made with the analysis. The analysis is then an iterative procedure.

### 3.3 CALCULATION PROCEDURES

The analyses made in the following chapters are carried out using a modern computer spreadsheet programme. The procedures offered by this type of programme facilitate specific numerical algorithms, but alternative approaches may also be feasible. For example, the analytical solutions, derived in Appendix A, for the iso-IRR and the equi-IRR lines can also be used. The calculation procedure followed here for the technologyspecific iso-IRR line starts with selecting an IRR, for which an iso-IRR line is to be determined. In a first iterative calculation the discount rate is assumed to be equal to this value of IRR. Given a set of technology and site parameters, the balance (B) of unit specific manufacturing costs and revenues is calculated using the procedure given in Table 14. Generally this ‘balance’ will not equal zero. This implies that the original assumption, that the IRR of the investment would equal the discount rate DR, was incorrect. We are then interested in determining that set of UPC values (UPC product, UPC raw material) for which B = 0. This set is identical with the iso-IRR line of IRR = DR.

<table>
<thead>
<tr>
<th>Table 14. General calculation procedure for the technology-specific iso-IRR line for selected levels of IRR.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology A</strong></td>
</tr>
<tr>
<td><strong>Technology parameters</strong></td>
</tr>
<tr>
<td>Unit specific manufacturing cost (€/UP), 3 of:</td>
</tr>
<tr>
<td>Capital cost (annuity at DR = IRR)</td>
</tr>
<tr>
<td>Production system</td>
</tr>
<tr>
<td>Working capital</td>
</tr>
<tr>
<td>Operational cost</td>
</tr>
<tr>
<td>Labour</td>
</tr>
<tr>
<td>Raw materials</td>
</tr>
<tr>
<td>Consumables</td>
</tr>
<tr>
<td>Maintenance</td>
</tr>
<tr>
<td>Unit specific revenues (€/UP)</td>
</tr>
<tr>
<td>Balance (€/UP)</td>
</tr>
</tbody>
</table>

Given the assumed values of UPC raw material and UPC product, then the UPC raw material for which the balance B equals zero, results from the following equation:
Varying the primary assumed input values for UPC\textsubscript{product} will yield the entire iso-IRR line for IRR\textsubscript{a} = DR. An alternative algorithm, for the same purpose, calculates the UPC\textsubscript{product} for which the balance B equals zero, i.e.:

\[ \text{UPC}_{\text{raw material}} \times \text{break-even} \times \left( \text{UPC}_{\text{raw material}} \times (1 \% \text{B/RMC}) \right) \text{assumed} \]

where, once again, the parameter values on the right hand side are the original assumptions. Subsequent variation of the originally assumed UPC\textsubscript{raw material} results in the same iso-IRR line. Spreadsheet programmes offer simple procedures for such parameter value variation.

To determine the equi-IRR line for two technologies, the points of intersection of the respective iso-IRR lines is calculated for a range of arbitrary discount rates using a spreadsheet procedure. The resulting set of points constitutes the equi-IRR line.
PART B: APPLICATIONS TO BIOMASS BASED RENEWABLE ENERGY CONCEPTS
INTRODUCTION TO PART B

In the chapters that follow, the analysis method developed in the previous part of this thesis is employed in an assessment of technologies for the production of electricity from biomass fuels. The topic is important because, in the analyses prepared by international institutions such as the IEA, the OECD, and the IPCC, biomass-based electricity production is recognised as an option for GHG mitigation and, in general, for making the energy sector more sustainable. This view is supported by a number of national governments and the European Commission.

In this introduction to Part B of this thesis, two major questions are addressed, i.e.:

• What is biomass, and which biomass types should be considered?
• Whereas some types of biomass belong to the category of wastes, and are usually incinerated (combusted, gasified, or pyrolysed) with electricity recovery - does an assessment of R&D targets for innovative technologies proceed in the same manner, independently of whether a biomass fuel is a waste or not?

What is biomass and which types of biomass should be considered?\(^{164}\)

Whereas in biological sciences, biomass is the amount of living matter, expressed in grammes per unit area or per volume of habitat, the energy sector defines biomass in a more limited way as the fuel source which originates from plant materials and animal waste. Plant-based biomass mainly consists of three chemical structures: cellulose, hemicellulose and lignine, all of which are compounds of carbon, hydrogen and oxygen. These types of biomass contain only few other elements such as nitrogen, sulphur and certain metals. Animal-derived biomass consists mainly of fats and proteins. They are also made up of carbon, hydrogen and oxygen - although their ratios differ from those observed in vegetable biomass - their content of nitrogen, sulphur and metals is usually higher than that found in biomass from vegetable origin. Biomass can be made available in a variety of shapes: logs, chips, bales, charcoal, sludges, fluids, powders, etc. These facts are relevant for the design of suitable energy conversion technologies. They also determine the economy of biomass energy technologies.

The resources of current and future biomass fuels can be categorized as indicated below in the matrix:

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164/ The text of this section has been published separately in Energy Policy, Siemons (2002).
The categories in this overview are exhaustive, yet there are some conceptual difficulties. Energy crops are a clear concept, these are products which are deliberately grown to produce energy. We find them only occasionally in industrialized countries. Oil seeds, such as rapeseed grown in France and Austria, for the manufacture of diesel fuel substitutes (bio-diesel) are an example. In developing countries, one may come across fuelwood plantations, managed to provide fuel to specific industries (tobacco curing, tea manufacture). In practice, the conceptual difficulties arise with regard to the meaning of expressions such as ‘residues’ and ‘wastes’.

On the one hand, residues are the remains of a raw material generated during its processing for some other product. They are not a main product, but rather a by-product. In practice, the further handling and processing of residues is regulated on the basis of the physical characteristics of these residues, and perhaps of the processes involved, but not on the fact that they are residues. For wastes the situation is different. The mere fact that a material is labelled a waste poses certain regulations for its employment, particularly with respect to allowable emissions and permit allocation procedures, or at least this applies in the member states of the European Union. As a result of European policy, the production of electricity from commercial fuels is regulated in a manner different from the production of electricity from waste. The consequences are far-reaching. For example, in the Netherlands, sulphur emissions from high-sulphur coal-fuelled electricity plant are limited to 133 mg/Nm³, whereas a corresponding limit is set at 40 mg/Nm³ for waste-fuelled electricity plant, even if low-sulphur waste is concerned (BEES-A (2000), BLA (2000)). In view of the costs of conversion technologies (costs of exhaust gas cleaning are substantial) and of permit acquisition, this situation makes it quite relevant for an assessment of demand curves of biomass fuels whether a biomass type falls within the category of wastes or not.

What is waste? In the context discussed here, waste is a label applied by governments for the purpose of environmental management. The governmental definition should therefore be adopted. According to EU legislation, waste is defined as follows: (a) ‘waste’ means any substance or object which the holder disposes of or is required to dispose of pursuant to the provisions of national law in force. Indirectly the article quoted defines ‘to dispose of’ as well:

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**Table:**

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residues</td>
<td>Agricultural residues, Straw, Forest residues, Sawdust, bagasse</td>
</tr>
<tr>
<td></td>
<td>Forestry residues, Tops, thinnings</td>
</tr>
<tr>
<td></td>
<td>Industrial residues</td>
</tr>
<tr>
<td>Wastes consisting of,</td>
<td>Regulated wastes, Municipal waste</td>
</tr>
<tr>
<td>or containing, biomass</td>
<td>Non-regulated wastes, Landfill gas, sludge gas</td>
</tr>
<tr>
<td>Energy crops</td>
<td>Miscanthus, willow, eucalyptus</td>
</tr>
</tbody>
</table>

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165/ Compare e.g. EU (2000c) the coverage of which includes the regulation of electricity production from waste, and EU (1988) and EU (1994) which regulate among other issues the production of electricity from ordinary, non-waste, fuels.

166/ EU (1975), Article 1.
(b) ‘disposal’ means: - the collection, sorting, transport and treatment of waste as well as its storage and tipping above or under ground, - the transformation operations necessary for its re-use, recovery or recycling.

A step forward, away from the legalistic standpoint that any waste biomass fuel should be legally treated as a waste according to the environmental laws on waste incineration, was made by the European Commission in Common Position (EC) No 52/2000. This position paper proposes to regulate the use of particular types of waste biomass in the same way as other non-waste fuels in combustion plants. These biomass types are:

“(a) vegetable waste from agriculture and forestry;
(b) vegetable waste from the food processing industry;
(c) vegetable waste from virgin pulp production and from production of paper from pulp;
(d) cork waste;
(e) wood waste with the exception of wood waste which may contain halogenated organic compounds or heavy metals as a result of treatment with wood preservatives or coating, and which includes in particular such wood waste originating from construction and demolition waste;”

Simultaneously with announcing this political approach, the European Parliament and the Council created the necessary room within the legislation for waste management by excluding from the coverage of the new waste incineration directive, electricity production plants which do not convert other wastes than those listed above (Directive 2000/76/EC). The reason for exempting the energy conversion of these types of wastes from the legislation concerning waste incineration, is that these waste types, in comparison with other wastes, are typically not, or substantially less, contaminated with those substances which are a cause of increased environmental concern, such as chlorine, sulphur, fluor and heavy metals. They are clean. Nevertheless, there remains one area of conflict between the waste incineration directive and the position paper on waste utilisation as an ordinary fuel. Directive 2000/76/EC on waste incineration says that, in order to be exempted from its coverage, pulp and paper waste should be converted into energy at the place of its production. By placing this additional condition on the fuel application of these waste types, the directive on waste incineration keeps the potential trade in this type of biomass fuel in check. In parallel with the European Parliament and Council, the Dutch Government is preparing its own list of clean and contaminated waste biomass fuels, thereby exempting the clean waste biomass from waste legislation. The draft list deviates from the European one cited above. As recognised in the draft text of the Dutch circular, a legal basis fails and, at the time of preparing this thesis, it should be

167/ EU (2000b).
168/ EU (2000b), Article 2.11.
169/ EU (2000c), Article 2.2, states: “Scope: 1. This Directive covers incineration and co-incineration plants. 2. The following plants shall however be excluded from the scope of this Directive: (a) Plants treating only the following wastes: (follows a listing of the same biomass types as quoted above from EU (2000b)).”
170/ EU (2000c), Article 2.2: “The following plants shall however be excluded from the scope of this Directive: (a) Plants treating only the following wastes: ... (iii) fibrous vegetable waste from virgin pulp production and from production of paper from pulp, if it is co-incinerated at the place of production ...”
172/ Pronk (2000).
doubted whether the Dutch policy can ever become effective in view of European Union legislation. Whatever the intended and coincidental consequences of these developments for particular types of biomass will be, the conclusion can be drawn that in view of waste legislation three distinct types of biomass fuels will result:

- non-waste biomass fuels legally treated the same as other non-waste fuels (NWB: non-waste biomass)
- waste biomass fuels legally treated as non-waste fuels (EWB: exempted waste biomass)
- waste biomass fuels legally treated as wastes (WB: waste biomass)

The distinction is illustrated in Figure 22. For sake of simplicity, the first two types can be referred to as ‘clean’ biomass, the third one as ‘contaminated’ biomass.

**Figure 22.** Categorization of biomass in view of European environmental legislation.

In the European Union, all these biomass types may be used as fuels. However, the stricter emission limit values for waste incineration will have to be applied for those waste biomass fuels which are not exempted from the waste incineration legislation. As a consequence, stricter emission limit values will be set for electricity plants which employ contaminated biomass (WB) than for electricity plants which are fired with fossil fuels, or clean biomass (NWB or EWB). In this way, the use of non-exempted waste biomass for electricity production is either prevented or made more expensive. If prevented, the non-exempted waste biomass is likely to be incinerated in a dedicated waste incineration plant at a low electricity recovery efficiency, and the balance of the electricity consumption is likely to be made up by firing additional coal in an electricity plant, with all associated additional emissions. In this situation the environment loses. If its use as a fuel in electricity plant is not prevented, but does take place, then its conversion costs are higher than under a non-waste regime. By replacing fossil fuels, the emission of GHGs will be reduced. But not only those - also SO₂, and dust emissions from the aggregate of
power plants and waste incineration plants, will be lower, since stricter emission limits apply for these substances in this situation than if released from fossil fuels or clean biomass. The additional costs therefore of substituting for fossil fuels with waste, should not be regarded as costs made solely to reduce GHG emissions, but rather as expenses to also achieve other environmental objectives.

Since recovery and recycling are clearly implied in the use of non-exempted waste biomass types (WB) for electricity production, it is important to know, in view of biomass fuel trade and the selection of energy conversion technologies, at which, if any, processing stage a waste biomass gets rid of its defaming label. In any case, every waste which is recycled in some way or another does loose that label, somewhere during the transformation operations referred to in the governmental definition of waste disposal quoted earlier. Would it be possible to manufacture a biomass fuel by some means of preparation such that it is legally recognized as a fuel just like coal, natural gas and furnace oil? Conceivable manufacturing processes are for example:

- Upgrading of mixed waste types by material separation recovering combustible materials of various qualities.
- Upgrading of demolition wood by making a heterogeneous product more homogeneous (e.g. chipping).
- Upgrading of wood shavings by pelletisation.
- Gas manufacture from digestible wastes such as animal manure.
- Oil manufacture from contaminated wood (e.g. by liquefaction).

Both European Union law and Dutch law have been analysed and it was concluded that the question as to whether the products resulting from these, or similar, processes are wastes or not, is not legally resolved. Relevant jurisdiction is currently being developed with regard to the coal-fired Gelderland power plant situated in Nijmegen which has installed a co-firing facility for wood. The power plant owner intends to use chips made from demolition wood bought from the waste management company BFI. Environmental NGOs object to the permit granted by the authority, stating that the chips should be considered a waste. The case is currently being considered.

Perhaps an economic consideration could shed some light on the evaluation. At the root of a waste management chain, the value of a waste is always negative since even its handling by the owner has a cost. However, what is a waste for one may become a valuable material for another to the extent that this value is paid to the primary owner. An example: in some instances sawdust and wood shavings which serve no purpose at a timber factory when space heating or wood drying are not required, are disposed of at the factory by means of incineration, in other instances they are sold to fuel briquette manufacturers. It is an established economic principle that a positive value develops for any material which becomes scarce. This can also happen with a waste material. Such a development may take place over time, if new technologies or products are developed, or if market circumstances change. Alternatively, a waste may become valuable in the course of a processing chain. The opposite may also occur: a valuable product may become a waste if market conditions change. Recently, this happened with pig manure in the Netherlands. Being a valuable provider of nutrients in agriculture, it became an available surplus and, for some producers, even a waste when the balance between its production
and use was disturbed. Wouldn’t it be an option to make the value of a material one of the indicators of whether it is a waste or not, in the sense that only negatively valued materials can be wastes?

Although considerable attention has been given, above, to the definition of waste biomass and the economic consequences of this determination, it is necessary to discuss the topic of waste, and its role in energy provision, from another angle as well: that of sustainability. In the policies of those countries committed to increased sustainability of the energy sector, biomass and waste as energy sources are virtually always taken together.¹⁷³ Waste is a much broader category than biomass, however. Municipal waste, for example, contains plastics that usually do not originate from biomass resources. Where statistical data, and quantified policy targets regarding renewable energy, categorize biomass and waste under the same heading, it is not possible to determine how much biomass is involved. Yet, this is clearly desirable for a study into issues of energy from biomass. With its new directive on the promotion of electricity from renewable energy sources (in preparation, 1 September 2001), the European Commission proposes to only include the biodegradable fraction of wastes in the category of renewable sources.¹⁷⁴ This is a new position and has, since all wastes are no longer considered renewable, immediate consequences for the means usable to achieve the targets on the implementation of renewable energy, for example those in the EU’s White Paper ‘Energy for the future’.¹⁷⁵

A further consequence of this is that it will be possible to generate renewable energy from contaminated biomass fuels (the category WB, identified earlier). Thus, applications of biogas from landfills and sewage water treatment plants can be included in the balance of renewable energy, even though the original wastes out of which this gas is produced does not appear in the list of clean biomass types. Further, the producers of electricity from contaminated biomass types, such as demolition wood, may participate in the market for Green Certificates (Green Certificates will be issued to the producers of renewable energy, and may be sold). This opens up new perspectives for the waste management sector, and also for operators in the electricity sector who accept contaminated biomass fuels. At the same time, it is also becoming clear that not all forms of waste conversion into energy will come under the label of renewable energy. Electricity generation from the non-biodegradable component of municipal waste, is evidently excluded.

To summarise, the result of the developments described above result in the following regulatory perspectives for biomass:

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¹⁷³/ Just two examples are the policies of the European Union and the Netherlands. See, for example, the European Union’s ‘Energy for the future’, EU (1995), and, for the Netherlands, ‘Renewable energy - advancing power’, Wijers (1997).

¹⁷⁴/ EU (2001b), Article 2b: “biomass shall mean the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste;”

¹⁷⁵/ EU (1997c).
It is not the intention in the analysis contained in the following chapters to focus on, or even to include, technologies for the energy conversion of wastes. Therefore, in this assessment of the future demand for biomass fuels, only the clean types of biomass are considered in line with the renewed European law:

As discussed in Section 3.2.4, the technology analysis carried out in Chapter 6 needs cost information about the biomass fuel inputs. To yield appropriate data, a market assessment of these biomass types is included as a separate chapter (Chapter 4).

*Does an assessment of R&D targets for innovative technologies for waste processing and electricity production proceed in the same manner?*

Above, it was shown that the results of the political debate about the distinction between biomass fuels and waste biomass, has implications for technology specifications and societal regulation, as well as for national renewable energy balances. Even the development of a market for biomass fuels will be influenced by the outcome of this debate. The reason why this debate has evolved at all, lies in the similarities between biomass fuels and many waste types. Among those similarities, the high carbon and hydrogen content, in a form suitable for reaction into CO$_2$ and H$_2$O, stand out. There are also numerous differences between the two. Many wastes, contain high concentrations of chemical elements (such as chlorine) and compounds which may result in the formation of hazardous gases or vapours, the emission of which should be limited. It is precisely the similarities between biomass fuels and waste biomass that are the reasons why both these fuels and these wastes are suitable sources for electricity production. However, the physical properties of the input materials, and the applicable regulatory framework, both of which differ for biomass fuels and waste biomass, lead to particular adaptations to the technical concepts when designed for electricity production or for waste processing.
While the technologies for electricity generation from biomass fuels, further explored in Chapter 5, are designed around combustion, gasification and pyrolysis processes; the same processes can be adapted for the processing of a wide range of wastes by taking into account the respective and particular boundary conditions posed by the source materials and the societal framework. In other words, the technical core of both applications is principally the same. Thus, waste processing applications employing these technologies do more than process waste; they also produce electricity. It is therefore not surprising that the question is raised as to under what conditions a specific technology, say gasification, is suitable for the processing of waste (with simultaneous electricity production) or for the production of electricity from biomass. Such questions are generally formulated under a technology perspective, and are naturally posed by promoters of particular technologies. An example of a study which was carried out in view of the technology perspective for gasifiers integrated in combined cycles, and which addresses both electricity production and waste processing, was reported by Faaij, Meuleman and Van Ree (1998) for Novem.

Although the considered waste processing facilities are also net electricity producers, there is a large difference between the evaluation frameworks for electricity production applications, and for waste processing applications with an electricity by-product, even if the core technologies are the same. The starting point of a waste processing project is a flow of waste (t/yr) which needs to be processed, that of a power plant is an annual quantity of electricity and hence a power capacity (MW). In the first instance, the power capacity of the electricity by-product is a result of the waste processing capacity and the energy conversion efficiency. Here, for a given waste processing capacity, the resulting electric power capacities vary with technology type. In the second case of electricity production, the power capacity is primary, and the required flow of biomass fuel follows from the applicable conversion efficiency. Here, for a given power capacity, with a range of conversion technologies and respective conversion efficiencies, fuel input flows differ. This is why the results of the R&D assessments contained in the following chapters, about electricity production and based around power capacities, have no implications for R&D into waste processing technologies, even if similar technologies are involved. In fact, the assessments are not really about technologies, but rather about specific applications of technologies.

With regard to the analysis methodology, the matter is reflected in the selection of the functional unit (discussed in Sections 2.1.1 and 2.2.1). In the preceding chapters it has been shown that the functional unit for electricity production technologies is a quantity of electricity. For an evaluation of technologies for waste processing, the appropriate functional unit is naturally the quantity of waste processed. A CBA of waste processing technologies, if carried out from the perspective of the public interest, would select the unit processing cost (€/t waste, with a given discount rate) as the feasibility indicator. Any revenue from electricity sales would be regarded as a fixed parameter. The result...
of the analysis would be that preference is given to technologies which show the lowest waste processing cost. This analytical approach of combined waste processing and energy concepts has been followed by McGowin and Wiltsee (1996), Morris and Waldheim (1998) (stakeholders in the TPS gasification technology), De Holanda and Balestieri (1999), and by Campbell, McCahey, Williams et al. (2000).
4 BIOMASS FUEL MARKETS

In the Introduction to Part B of this thesis, the reason for including a specific chapter on biomass fuel markets was explained. By providing price information for a particular production input, biomass, this chapter forms part of the preparations for the R&D assessment carried out in Chapter 6.

4.1 THE EXISTING SITUATION

Already, biomass is a fuel resource of considerable importance. In the first place this applies to most developing countries; the relevant sectors being household energy (cooking, space heating), informal industries (e.g. brick making), and several agro-industries (e.g. palm oil and sugar manufacture). In industrialised countries, biomass fuels are rarely used in the household sector, but industries do make use of these fuels if they become available as one of their by-products. Examples are timber industries using their sawdust, shavings and off-cuts as fuel for drying kilns and the heat provision to panel presses (for plywood, MDF, etc.), and paper mills using their residues for the generation of process electricity and process heat. Neither in developing countries, nor in industrialised countries, are biomass fuels used at significant levels for electricity production by the electricity sector. For the IEA member countries this is reflected in Table 15. Coal, oil and natural gas together make up about 60% of the fuels used. The share of biomass has steadily increased but, by the year 2000, the biomass contribution was still only 1.9%.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Output (TWh)</td>
<td>Share (%)</td>
<td>Output (TWh)</td>
<td>Share (%)</td>
<td>Output (TWh)</td>
<td>Share (%)</td>
</tr>
<tr>
<td>Coal</td>
<td>1570.8</td>
<td>36.9</td>
<td>1977.7</td>
<td>37.7</td>
<td>3144.5</td>
<td>38.3</td>
</tr>
<tr>
<td>Oil</td>
<td>1088.4</td>
<td>25.5</td>
<td>1016</td>
<td>19.3</td>
<td>510.1</td>
<td>6.2</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>512.2</td>
<td>12</td>
<td>597.6</td>
<td>11.4</td>
<td>1125.3</td>
<td>13.7</td>
</tr>
<tr>
<td>Combustible Renewables &amp; Wastes</td>
<td>6.9</td>
<td>0.2</td>
<td>11.8</td>
<td>0.2</td>
<td>133.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Nuclear</td>
<td>188.3</td>
<td>4.4</td>
<td>570.3</td>
<td>10.9</td>
<td>1967.2</td>
<td>24</td>
</tr>
<tr>
<td>Hydro</td>
<td>888.8</td>
<td>20.9</td>
<td>1069.1</td>
<td>20.4</td>
<td>1290.2</td>
<td>15.7</td>
</tr>
<tr>
<td>Geothermal</td>
<td>6.4</td>
<td>0.2</td>
<td>8.6</td>
<td>0.2</td>
<td>24.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Solar/Wind</td>
<td>0.6</td>
<td>0</td>
<td>0.5</td>
<td>0</td>
<td>13.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>4262.4</td>
<td>100</td>
<td>5251.6</td>
<td>100</td>
<td>8208.9</td>
<td>100</td>
</tr>
</tbody>
</table>

To place the analysis that follows on the use of biomass fuels in some perspective, Table 16 provides general statistics on energy consumption, by region and population (1998 data).
Statistics showing biomass-based energy consumption for the individual countries are not immediately, without using very approximate estimation methods, available from the IEA, OECD or other international organisations. The IEA and OECD represent some 30 countries, the statistics provided by the WEC cover only 91 countries, whereas the total number of countries is about 200. A reason which aggravates the difficulty of proper accounting is the fact that, in developing countries, biomass fuels are often traded in the informal sector. It is true that, for most developing countries, the World Bank, mainly within the ESMAP programme, has prepared energy balances which cover commercial and non-commercial fuels, both categories including biomass fuels. However, ESMAP’s statistics are not updated regularly and are therefore not included in continually maintained data bases. A further reason for the lack of data is the fact that industrially used residues are hardly traded at all.

From data provided by the IEA, it can be inferred (see Table 17) that in the non-OECD countries, the annual per capita primary energy consumption of biomass is about 0.19 toe/capita. The corresponding value is lower (0.15 toe/capita) for the OECD countries. In the IEA statistics consulted it is not clear to what extent non-commercial fuels are included. Given the data quality, the true figure of per capita consumption of biomass in non-OECD countries is probably larger rather than smaller. For low-income countries this is confirmed when comparing the IEA data with data provided by the World Bank. The latter, in the bank’s World Development Indicators 2001, are more stratified in terms of country categories (low-income, middle-income, etc.) (see Table 17). The overall data are not dissimilar from those given by the IEA. In so far as this concerns the IEA countries, this is not surprising since the World Bank partly relies on the IEA statistics. Another source for the World Bank is the Energy Statistics Yearbook published


<table>
<thead>
<tr>
<th>Region</th>
<th>Population (million)</th>
<th>TPES (Mtoe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>World /b</td>
<td>5839</td>
<td>9559</td>
</tr>
<tr>
<td>OECD</td>
<td>1101</td>
<td>5097</td>
</tr>
<tr>
<td>Middle East</td>
<td>160</td>
<td>356</td>
</tr>
<tr>
<td>Former USSR</td>
<td>292</td>
<td>893</td>
</tr>
<tr>
<td>Non-OECD Europe /c</td>
<td>61</td>
<td>116</td>
</tr>
<tr>
<td>China</td>
<td>1245</td>
<td>1048</td>
</tr>
<tr>
<td>Asia /d</td>
<td>1821</td>
<td>999</td>
</tr>
<tr>
<td>Latin America</td>
<td>403</td>
<td>444</td>
</tr>
<tr>
<td>Africa</td>
<td>757</td>
<td>482</td>
</tr>
</tbody>
</table>

a/ TPES: total primary energy supply (TPES) is made up of indigenous production + imports - exports - international marine bunkers ± stock changes. For the World Total, TPES excludes international marine bunkers.

b/ World excludes Albania and DPR of Korea.

c/ Non-OECD Europe excludes Albania.

d/ Asia excludes China and DPR of Korea.


178/ http://www.worldenergy.org/wec-geis/

179/ ESMAP (the 'Energy sector management assistance program') is a joint programme of the World Bank and UNDP.

by the United Nations Statistic Division. In turn, the latter relies strongly on the FAO for data on the use of traditional fuels. The World Bank reports a biomass fuel consumption of 0.17 toe/cap as a global average. For low-income countries a figure of 0.24 toe/cap is given, for the aggregate of low and middle-income countries a figure of 0.17 toe/cap. The estimated share of biomass fuels in the total worldwide primary energy supply, as reported by the IEA and the World Bank, is about 10%.

A comparison with the analysis made by the often cited authorities Hall, Rosillo-Calle, Williams *et al.* (1993), prepared in response to the United Nations Conference on Environment and Development (Rio de Janeiro, 1992), is appropriate here. Their analysis concerns the year 1985, and it should be noted that before 1999 energy from biomass was not included in the referred to World Bank statistics. In view of the growing world economy since 1985, the global 1985 data given by Hall, Rosillo-Calle *et al.* are naturally lower than those provided by the IEA and the World Bank for 1998. It is remarkable though that Hall, Rosillo-Calle *et al.* estimate the global per capita biomass fuels consumption at the relatively high value of 0.27 toe, and the global share of biomass fuels as high as 15%. According to these authors, the per capita biomass energy consumption in developing countries amounts to 0.31 toe (Table 17).

To gain an impression of where all this biomass is used, some estimates have been produced by making use of FAO statistics (FAOSTAT), and experience gained with the preparation of investment appraisals (Table 18). The relevant data taken from FAOSTAT concern fuelwood and charcoal production as well as the production of cane sugar, industrial wood products and palm oil. It appears that most biomass fuel consists of

### Table 17. Energy indicators for several types of countries.

<table>
<thead>
<tr>
<th>Population (million)</th>
<th>Primary Energy Supply (TPES) (Mtoe)</th>
<th>Biomass (Mtoe) /a</th>
<th>TPES/Pop (toe/cap)</th>
<th>Biomass (toe/capita) /a</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1998 IEA data (derived from data reviewed in Appendix B):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>World</td>
<td>5800</td>
<td>9620</td>
<td>1060</td>
<td>1.65</td>
</tr>
<tr>
<td>OECD</td>
<td>1100</td>
<td>5100</td>
<td>170</td>
<td>4.63</td>
</tr>
<tr>
<td>Non-OECD</td>
<td>4700</td>
<td>4520</td>
<td>890</td>
<td>0.95</td>
</tr>
<tr>
<td><strong>Hall, Rosillo-Calle, <em>et al.</em> (1992), (1985 data):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>World</td>
<td>4900</td>
<td>8920</td>
<td>1310</td>
<td>1.83</td>
</tr>
<tr>
<td>Industrialised countries</td>
<td>1200</td>
<td>5910</td>
<td>170</td>
<td>4.84</td>
</tr>
<tr>
<td>Developing countries</td>
<td>3700</td>
<td>3010</td>
<td>1150</td>
<td>0.83</td>
</tr>
<tr>
<td><strong>Derived from World Development Indicators 2001 (World Bank) (1998 data):</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>World</td>
<td>5600</td>
<td>10300</td>
<td>936</td>
<td>1.83</td>
</tr>
<tr>
<td>Low income</td>
<td>3100</td>
<td>1680</td>
<td>500</td>
<td>0.78</td>
</tr>
<tr>
<td>Lower middle income</td>
<td>2200</td>
<td>2420</td>
<td>138</td>
<td>1.18</td>
</tr>
<tr>
<td>Upper middle income</td>
<td>620</td>
<td>1260</td>
<td>134</td>
<td>2.27</td>
</tr>
<tr>
<td>High income</td>
<td>920</td>
<td>4920</td>
<td>167</td>
<td>5.55</td>
</tr>
<tr>
<td>Of these: Europe EMU</td>
<td>300</td>
<td>1140</td>
<td>29</td>
<td>3.93</td>
</tr>
</tbody>
</table>

*a* In the quoted IEA source, this entry is given as ‘Combustible Renewables & Waste’. In the World Development Indicators of the World Bank this entry is given as ‘Traditional fuel use’. This is a category similar to combustible renewable and waste, since it is defined as the use of fuelwood, charcoal, animal residues, vegetable residues and of the industrial fuel bagasse. The World Development Indicators 2001 do not give absolute figures for the year 1998, but rather percentages of the total energy use of 1997. However, this source does provide total energy use for 1998, and the same percentage of traditional fuel use was assumed in order to derive an estimate of biomass use in 1998 from the World Bank data.
fuelwood (480 Mtoe/yr) utilised by households and small industries for the manufacture of bricks, tiles, and tea. The next largest biomass consumers are cane sugar manufacturers (90 Mtoe/yr) and wood panel industries (40 Mtoe/yr). These consumers account for more than 65% of the total estimated biomass fuel consumption (compare with Table 17). Again with this estimate, data quality is doubtful. It is not even clear to what extent non-traded fuelwood, grown in plantations for the direct provision of agro-industries such as tea and tobacco manufacture, is included in the FAO database.\textsuperscript{181}

\textbf{Table 18. Biomass consumption in major sectors (Mtoe) (estimate for the year 1998).}

<table>
<thead>
<tr>
<th></th>
<th>Fuelwood/f</th>
<th>Cane sugar (bagasse)</th>
<th>Wood industries /b</th>
<th>Palm oil (residues)</th>
<th>Total of these sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>481</td>
<td>92</td>
<td>40</td>
<td>8</td>
<td>620</td>
</tr>
<tr>
<td>Developed Countries</td>
<td>41</td>
<td>7</td>
<td>30</td>
<td>0</td>
<td>78</td>
</tr>
<tr>
<td>Developing Countries</td>
<td>439</td>
<td>85</td>
<td>10</td>
<td>8</td>
<td>542</td>
</tr>
</tbody>
</table>

a/ Fuelwood includes: Households, charcoal manufacture, industries other than wood processing
b/ Wood industries include: Fibreboard, Hardboard, MDF, Particle Board, Plywood

Underlying production data (t/yr) are taken from FAOSTAT (http://apps.fao.org/).

Assumptions:
- Fuelwood moisture content 20% wet basis (kg/kg)
- NCV\textsubscript{f} fuelwood 14 GJ/t\textsubscript{f}
- Wood conversion yield for charcoal 12% t\textsubscript{c}/t\textsubscript{w}
- Cane fibre content 17% t\textsubscript{c}/t\textsubscript{f}
- NCV\textsubscript{f} bagasse 18 GJ/t\textsubscript{f}
- Industrial biomass fuel use 100% of output (kg used/kg produced)
- Primary energy use in palm oil manufacture 3.3 GJ/t Fresh Fruit Bunch

The quoted statistics generally do not explain their data acquisition and interpretation methods. It is therefore difficult to judge their quality. Given the detail provided, the preferred data source for energy statistics, in as far as ballpark figures are concerned, seems to be the referenced World Bank report. But a few intriguing questions should be noted:

- To what extent, and based on which measurements, are non-commercial household fuels taken into account?
- Has an average charcoal yield (kg charcoal/kg wood) been assumed for charcoal manufacture? If so, how large?
- Are all the industrial uses of biomass fuels taken into account? (The most relevant industries are wood products, cane sugar, and palm oil). Are the figures based on the gross or the net calorific value? (Given the typical moisture contents this may make a difference of a factor of two or more.)
- Much industrial biomass combustion is also a means of waste incineration (energy conversion efficiencies are deliberately low): is such biomass fully included as energy supplies?
- Finally: how relevant are the specific approaches to these issues for the resulting data?

\textsuperscript{181} On the other hand, the particular example of tea manufacture has a limited influence on the final estimate. In 1998, worldwide production of 'made tea' (MT) amounted to 3 Million t (FAOSTAT). The specific energy consumption for the withering and drying process is about 20 GJ/t MT. Hence, annual biomass consumption in this sector is limited to about 1.5 Mtoe.
4.2 A GROWING DEMAND FOR BIOMASS FUELS

Given that increased utilisation of biomass fuels is one of the options for mitigating climate change, are there any quantitative objectives set by the clients for avoided GHG emissions (i.e. national governments) for the contribution of biomass to this goal? The IPCC, due to its character as a forum that focuses on the problem of global warming and on the options for its mitigation, does not set policy targets but rather identifies the increased use of biomass fuels as merely one of the many options. However, based on the IPCC’s analyses, and those of others, a number of national governments committed to the Kyoto Protocol, as well as the European Commission at the level of the EU, have prepared such targets. Since essentially intended for market economies, these targets should be regarded as scenarios, based on which facilitating policies in the area of fiscal measures and R&D subvention are to be determined. On a government level, the USA has not prepared plans or formulated expectations concerning the future use of biomass-based energy.\footnote{182} The focus in the remainder of this section is on the European Union. Firstly, the expectations for the totals of the relevant sectors are discussed (energy production sector, industries, transport sector). Secondly, anticipated trends for specific applications are investigated.

*Aggregate demand outlook*

The first steps in establishing targets for biomass-based energy within the EU were made in the EU’s 1995 White Paper on energy policy.\footnote{183} Deciding to promote renewables, the White Paper announced a strategy to that effect (p. 34). It was published in ‘Energy for the future’, which declared that, for the year 2010, the target for renewable energy was set at 12%, as an indicative share by renewable sources to the gross energy consumption.\footnote{184} A preceding scenario study, TERES II,\footnote{185} provided some of the technical and economic justifications.\footnote{186} A further, and more recent, source of biomass market expectations at the governmental EU level is the Shared Analysis Project. In 1998, this project was initiated by the Directorate General for Energy of the European Commission with the aim of integrating the potentials for energy policy analysis within the member states of the EU. One of the first publications of the Shared Analysis Project is the ‘European Union energy outlook to 2020’.\footnote{187} Both these studies are investigated more closely here.

The TERES II study forecasts an annual contribution of 106 Mtoe from energy crops and residual biomass in its Best Practice Scenario for the year 2020.\footnote{188} Including wastes, the Best Practice Scenario of TERES II estimates an amount of 160 Mtoe/yr in 2020, from ‘crops, residues and wastes’ (Table 19). Notice that, in TERES II, the biomass

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\footnote{182} Cheney, Powell, O'Neill et al. (2001).
\footnote{183} EU (1995).
\footnote{184} EU (1997c), p. 9.
\footnote{185} ESD (1996).
\footnote{186} EU (1997c), p. 7.
\footnote{187} Capros, Mantzos, Petrellis et al. (1999).
\footnote{188} ESD (1996), p. xv.
Concluded from IEA (1998).

The contribution to the energy balance concerns more than just electricity and heat, it also includes transportation fuels.

Table 19. Contribution of three biomass fuel types in the Best Practice Scenario for 2020 of TERES II (it is assumed that primary energy is concerned).

<table>
<thead>
<tr>
<th>Type</th>
<th>Mtoe/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crops</td>
<td>71</td>
</tr>
<tr>
<td>Waste</td>
<td>56</td>
</tr>
<tr>
<td>Residues</td>
<td>35</td>
</tr>
</tbody>
</table>

Extracting the market expectations contained in ‘Energy for the future’ is complicated. This is due to the fact that end-use data on electricity and heat production are reported without reference to the technical assumptions regarding current and future conversion efficiencies. This is not only relevant in view of potential efficiency increases over a 15 year period of technology development, but also in view of changing modes of application (increased use of combined heat and power generation for district heating would result in an increased average conversion efficiency, without any technology development). Reference to the TERES II background study, does not help to resolve these matters since that study does not report on its premises either. An attempt at an interpretation is made here. The data taken from ‘Energy for the future’ are:

- Electricity production from biomass is expected to increase from 23 (1995) to 230 TWh by 2010 (p. 51).
- Heat production from biomass fuels will increase from 38 (1995) to 75 Mtoe/yr by the year 2010 (p. 52).
- One third of the additional biomass fuel utilisation is assumed to be generated in the form of combined heat and power (CHP) (p. 18).
- For the year 2010, a contribution of 18 Mtoe is assumed for liquid transportation fuels (p. 38) (understood as primary biomass input).

A possible solution is given in Table 20. Some assumptions had to be made:

- For 1995, this interpretation assumes that the use of biomass-fuelled CHP amounts to a primary fuel input of 4 Mtoe at the EU15 level.189
- In 1995, the use of biomass for the manufacture of transportation fuels was virtually nil.
- Efficiencies are kept constant throughout the evaluation period, although they may be expected to increase for specific technologies, but not for all. Precisely because the technology mixes of 1995 and of 2010 are not specified, a general distinction between the two target years cannot be made. The assumed figures should, however, suffice for generating ballpark figures.
- The assumed Heat/Power ratio of 2.4 is high, and contradicts the projected value of 1.0 made by the Shared Analysis Project for district heating in the year 2010. However, such a low Heat/Power ratio will only be achieved with gaseous or liquid

189/ Concluded from IEA (1998).
fuel fired technologies. This is confirmed by one of the resource papers of the Shared Analysis Project.  

It follows that, according to the projections expressed in ‘Energy for the future’, a total of about 150 Mtoe of biomass fuels will be utilised in the year 2010. Wastes are included in these estimates. How well the 2010 expectations in ‘Energy for the future’ correspond to those of the 2020 outlook given by TERES II is not clear, but they do not contradict.

The other study consulted to analyse the future biomass demand in the EU is the ‘European Union energy outlook to 2020’, produced by the Shared Analysis Project. The assumed Baseline Scenario is reported in sufficient detail to derive projected biomass fuel consumptions. For the combined flows of biomass and waste, the referred to study reports an increase in thermal input from 44.2 Mtoe in 1995 to 52.5 Mtoe in 2010. Specifically, for the power and steam generation sector, a figure of 31 Mtoe is given. As no further details are given for biomass fuel consumption under the more climate friendly scenarios also investigated, one has to fall back on an interpretation based on other reported indicators. This is done below, in Table 21, using the assumption that the contribution of biomass varies proportionally to the contribution of renewables in general. The Shared Analysis Project foresees no significant introduction of biomass-based liquid transportation fuels.

<table>
<thead>
<tr>
<th>Year</th>
<th>1995</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-uses</td>
<td>Biomass fuels supply (Mtoe)</td>
<td>Electricity produced (TWh)</td>
</tr>
<tr>
<td>Non-CHP electricity</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Non-CHP heat</td>
<td>42</td>
<td>0</td>
</tr>
<tr>
<td>CHP electricity and heat</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Liquid transportation fuels</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td>23</td>
</tr>
<tr>
<td>Additional biomass (2010 - 1995) (Mtoe/yr)</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>CHP Biomass share (2010) of additional biomass (based on primary energy)</td>
<td>33%</td>
<td></td>
</tr>
<tr>
<td>Heat/Power ratio</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Assumed efficiencies:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-CHP electricity</td>
<td>38%</td>
<td></td>
</tr>
<tr>
<td>Non-CHP heat supplied</td>
<td>85%</td>
<td></td>
</tr>
<tr>
<td>CHP heat and electricity</td>
<td>85%</td>
<td></td>
</tr>
</tbody>
</table>

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192/ Capros, Mantzos, Petrellis et al. (1999), p. 186.
194/ Due to “expectations of costs and the absence of new policy initiatives”, Capros, Mantzos, Petrellis et al. (1999), p. 133.
It is striking, using the data derived from the quoted study, that neither in the Baseline Scenario, nor in any of the other three scenarios, is the political objective expressed in the EU’s White Paper on ‘Energy for the future’ (’12% renewable by 2010’) achieved. In the most optimistic scenario (S6) one only reaches 7.3% by 2010, and 8.4% by the year 2020 (Table 22). In view of the EU’s Kyoto obligations this is not critical, because, on the one hand, the European energy sector is not the only one which can contribute to emission reductions, and on the other hand, at least the S3 and S6 scenarios do show a net GHG emission reduction for the energy sector with reference to the target year of 1990. However, the limited potential contribution of the electricity sector should be a cause of political concern, and perhaps lead to a reevaluation of the EU’s policy with regard to the introduction of renewable energy. In the context of this chapter, this does not need further investigation.

One critical remark should be made here though: the ‘European Union energy outlook to 2020’ states that the reason for the limited growth in biomass energy is its constrained resource base, in other words, the supply side. Unfortunately, the authors do not present an analysis to justify this position, nor do they make reference to any biomass sourcing study. In contrast, TERES II, one of the background papers for the EU’s policy on renewables, estimates the technical potential for biomass and waste in the EU 15 at 210 Mtoe/yr - a figure three times as large as the projected usage by the ‘European Union energy outlook to 2020’. At first glance this contradicts the view that the limited availability of biomass prevents its use above a level of about 70 Mtoe/yr. Naturally, the supply elasticity of biomass is decisive in the position adopted in the ‘European Union

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Table 21. The future consumption of biomass and waste fuels in the EU 15 according to four scenarios.

<table>
<thead>
<tr>
<th>Year</th>
<th>Baseline</th>
<th>S0</th>
<th>S3</th>
<th>S6</th>
<th>Baseline</th>
<th>S0</th>
<th>S3</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biomass and waste (Mtoe/yr)</td>
<td>53 /a</td>
<td>57</td>
<td>61</td>
<td>64</td>
<td>57 /a</td>
<td>66</td>
<td>69</td>
<td>72</td>
</tr>
<tr>
<td>Increase in renewable energy sources /b</td>
<td>8.6%</td>
<td>15.0%</td>
<td>21.1%</td>
<td>17%</td>
<td>22%</td>
<td>27%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: European Union energy outlook to 2020, p. 74

Table 22. Future renewable energy in the EU 15 according to four scenarios.

<table>
<thead>
<tr>
<th>Year</th>
<th>Baseline</th>
<th>S0</th>
<th>S3</th>
<th>S6</th>
<th>Baseline</th>
<th>S0</th>
<th>S3</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross inland consumption (Mtoe/yr)</td>
<td>1552</td>
<td>1501</td>
<td>1482</td>
<td>1464</td>
<td>1609</td>
<td>1553</td>
<td>1532</td>
<td>1511</td>
</tr>
<tr>
<td>Increase in consumption</td>
<td>-3.3%</td>
<td>-4.5%</td>
<td>-5.7%</td>
<td>-3.5%</td>
<td>-4.8%</td>
<td>-6.1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renewables (Mtoe/yr)</td>
<td>88</td>
<td>96</td>
<td>101</td>
<td>107</td>
<td>100</td>
<td>117</td>
<td>122</td>
<td>127</td>
</tr>
<tr>
<td>Increase in renewable energy sources</td>
<td>8.6%</td>
<td>15.0%</td>
<td>21.1%</td>
<td>17%</td>
<td>22%</td>
<td>27%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage renewables</td>
<td>5.7%</td>
<td>6.4%</td>
<td>6.8%</td>
<td>7.3%</td>
<td>6.2%</td>
<td>7.6%</td>
<td>7.9%</td>
<td>8.4%</td>
</tr>
</tbody>
</table>

Source: European Union energy outlook to 2020, p. 74.

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195/ For details, see Capros, Mantzos, Petrellis et al. (1999), p. 93.
196/ Capros, Mantzos, Petrellis et al. (1999), p. 96.
energy outlook to 2020’, further information about which is not given in TERES II. In this context it is also relevant to note that not one of the scenarios evaluated in the ‘European Union energy outlook to 2020’, or in TERES II, foresees imports into the EU 15 of biomass fuels or of biomass-derived fuels. Technically, this is an option and it is further investigated in Section 4.3.

Although most member states of the European Union made individual assessments of the future use of biomass fuels,198 a further investigation, beyond the analyses made on the European level, does not seem to yield further insights into the future European demand for biomass fuels.

Anticipated trends for specific applications

Scenario studies, such as those referred to above, are strongly dependent on the views of the researchers on the relevant energy conversion technologies in terms of conversion efficiencies and cost. Such views on these technology characteristics are not obvious, and, as shown in Chapter 5, the scientific literature on biomass conversion technologies is far from agreement. The reported scenario studies carried out by TERES II and the Shared Analysis Project, do not fully explain their assumptions, and so a critical review of these studies is not possible here. Nevertheless, it is interesting to indicate the particular technologies, and the energy subsectors for their application, where policy makers, based on these scenario studies, place their bets. According to ‘Energy for the future’, the major applications of biomass fuels are:199

1 Co-firing of biomass with coal in power plants and coal-fired district heating plants;
2 Biomass-fuelled district heating, combined with small-scale electricity production (CHP);
3 Gasification in a combined cycle for electricity production (at capacities of 25-50 MW);
4 Electricity production from waste biomass (waste incineration, landfill gas recovery, anaerobic digestion);
5 Transportation fuels from oil seeds and ethanol.

The technological determination is apparent, and unavoidable, in the formulation of concrete policies. Yet, with regard to the third application (gasification), the objection can be raised that the existing technology characterisations are insufficiently robust to enable a vigorous technology selection (this position is substantiated in the following chapters) and the author is of the opinion that it would have been better to phrase the application in a less technologically biassed manner, i.e. as ‘centralised electricity production in dedicated biomass-fuelled power plants’. This would include the exciting, but as yet undemonstrated, conversion technology of gasification in a combined cycle. However, it is broader and also includes conventional combustion and steam technology as well as liquefaction technology. Additionally, the implied size of power plants, in the proposed formulation, is not restricted. For the application of centralised electricity production,

198/ An overview is presented in EU (1997c), p. 45.
technologies and capacities are identified and further assessed in Chapters 5 and 6. Apart from this qualification, the assessment of energy subsectors, as identified by the European Commission, appears to be reasonable, although it cannot be precluded that investigations into innovative technologies for liquid transportation fuels would produce similar objections to the technological bias given in the fifth application identified by the Commission. Certainly, there are other technologies, suitable for the manufacture of transportation fuels from biomass, which are potentially more attractive (due to more efficient use of production factors such as land for energy crops, or due to the ability to utilise low-value wet residues).200

The main question addressed in the following paragraphs is, how large a market volume will the various subsectors, or applications, occupy by 2010.

**Co-firing:** In the context of ‘Energy for the future’, co-firing concerns the partial substitution of biomass for coal in:

- Existing coal fired subcritical combustion/steam plants; and
- Existing district heating plants.

The reasons for promoting this method of biomass utilisation are probably the rapid implementation opportunities, for which only limited R&D efforts are required, and the achievable economies of scale. Co-firing of biomass with coal in subcritical combustion/steam plants involves relatively small capacities (effectively about 30-60 MW),201 the basic idea behind this concept being that a small proportions of the capacity, in the order of 5%-10%,202 would be given over to biomass fuels. In this manner, the biomass component would share, to a large extent, the economies of scale of the entire plant. This concerns the conversion efficiency, the exhaust gas cleaning equipment and plant management. Some of the investment and operational costs could not take advantage of the overall plant’s economy of scale; these being the biomass storage, handling and fuel preparation facilities, as well as their operation. The extent of these costs varies with the proportion of biomass used. In comparison with dedicated biomass power plants of the same effective capacity, the conversion efficiency of co-firing is very high, at least in view of state-of-the-art energy technologies. As discussed in Chapter 5, researchers are aiming to further develop technologies for biomass conversion such that, at even relatively small scales, the conversion efficiency surpasses that of conventional coal fired power plants. If this is achieved, co-firing in combustion/steam power plants will have lost some of its attraction. Given today’s standards however, this application remains a strong competitor to dedicated biomass-fuelled power plants, so that this application is a major determinant for prices of biomass fuels.

Whether co-firing is equally attractive with innovative coal-conversion concepts, such as the gasification/combined-cycle technology, and the supercritical steam cycle, is uncertain. Specific integration technologies, enabling the coupling of a biomass component to the coal fired unit, will be required. Options include: a separate biomass

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200/ Two examples are pyrolysis of cellulosic biomass followed by a Fischer-Tropsch reaction to produce diesel fuel, and supercritical gasification of biomass rich sludges followed by synthesis reaction to produce petrol.

201/ The effective capacity is defined as the total plant capacity multiplied by the energy ratio of biomass substitution.

gasifier providing fuel gas to the combined cycle, a biomass liquefaction plant providing fuel gas and fuel oil to the combined cycle, and a separate biomass reactor providing heat to the steam cycle (this option is called ‘steam-side integration’). These, however, result in reduced advantages of scale. In coal-fuelled gasification/combined cycle plants it might also be possible to gasify some biomass in the gasifier already used for coal. For the co-firing of biomass in supercritical steam boilers, a technical solution to the corrosion difficulties posed by the alkaline content of biomass fuels is to specifically adapt the materials used in the boiler.\textsuperscript{203} Again, the loss of economy of scale benefits is obvious. The economic feasibility of such advanced concepts, in comparison with other options for electricity production from biomass, has not yet been studied in a systematic manner. However, the specific application foreseen in ‘Energy for the future’ is typically a short-term option, i.e. technically feasible and economically attractive until the subcritical combustion/steam technology for coal is phased out. An investigation covering all EU-based electricity producers would be required to find out when this is likely to happen, since publications by the IEA do not provide this type of information. Taking the situation in the Netherlands as an example, decommissioning of existing subcritical coal-fired power plants is expected to take place between about 2011 and 2024.\textsuperscript{204} The sector is potentially able to contribute significantly to the short-term EU targets. Based on 1997 coal consumption data provided by the IEA,\textsuperscript{205} and assuming a 10% substitution on an energy basis, the potential in the EU15 is about 70 TWh\textsubscript{e}/yr. This figure is significant in view of the target for non-CHP electricity (136 TWh\textsubscript{e}/yr), indicated in Table 20. At the relatively high efficiency achievable with this application (about 38%), the required quantity of biomass fuel equates to 16 Mt\textsubscript{e}/yr. ‘Energy for the future’ sets the 2010 target for co-firing at a substantially lower level, i.e. at 6 Mt\textsubscript{e}/yr.\textsuperscript{206}

Co-firing of biomass with coal, or even the complete replacement of coal, in existing district heating plants, is an option which offers limited and short-term opportunities - short-term in an ambiguous sense: rapidly achievable but also only relevant over a short period. The option becomes obsolete if the EU’s policy to promote CHP is successful, since many locations, where this type of substitution is technically feasible now, may then be expected to have switched from heat-only to CHP. Further, the option has very limited potential, even today, as coal is hardly being used for district heating. The only EU countries for which the IEA reports such utilisation are Denmark, Finland and Sweden (total consumption: 0.125 Mt\textsubscript{e}/yr fuel input in 1995).\textsuperscript{207}

\textit{Biomass-fuelled district heating with combined electricity production (CHP):} In this application, the produced heat is sold to the residential sector, mainly for the purpose of space heating, and the electricity is fed into the grid. As derived above (Table 20), ‘Energy for the future’ implies an increased usage of biomass from about 4 Mt\textsubscript{e} (primary energy) in 1995 to 34 Mt\textsubscript{e} annually by the year 2010. One may suspect that the market for this

\textsuperscript{203} Biomass fuels are generally rich in alkalines. For technology considerations see Sondreal, Benson, Hurley et al. (2001) and Tillman (2000a).
\textsuperscript{204} Van Ree, Korbee and De Lange (2000).
\textsuperscript{205} OECD (1999a).
\textsuperscript{206} EU (1997c), p. 39.
\textsuperscript{207} IEA (1998).
application will be in the northernmost countries of the EU, where the demand for space heating is considerable. New technologies are not needed to make this development possible. From the EU policy documents, one gets the impression that to achieve the increased implementation of district heating by means of CHP is first and foremost a matter of removing institutional barriers. The rationale behind the promotion of CHP for district heating is often viewed in two distinct manners, each of which sheds its own light on the attraction of the technology:

- **Heat supply as a marginal operation relative to electricity production**: In comparison with separate electricity production, the efficient use of the fuel employed by a power plant is increased by investing in equipment which enables the use of otherwise wasted low-quality heat. The validity of this view is limited because, in modern power plants, the temperature of the residual heat is so low that its application for district heating is impossible. CHP can then only be realized at the expense of electricity generation efficiency.

- **Electricity production as a marginal activity relative to heating**: The marginal investment in addition to a required heating plant, for a so-called topping cycle for the production of electricity, would enable electricity production at an attractive price relative to separate electricity production. The validity of this argument is limited by the facts that additional fuel is required for the electricity component of a CHP plant, and that, given the small scale, the conversion efficiencies of the electricity component are low.

In reality, increased use of CHP for district heating has the following long-term economic effects (ceterus paribus the demands for electricity and heat):

- Investment in large-scale electricity generation capacity is reduced, but investment in small capacities of topping cycles is increased. Due to the loss of scale advantages, the net investment in electricity generation capacity increases.
- Investment in heating capacity remains unchanged.
- Fuel usage at large-scale power plants is reduced.
- Fuel usage at heating sites, now operating in CHP mode, is increased.

Additionally, the seasonal variation in heat demand when residential heating is involved has to be taken into account. This variation results in reduced efficiencies away from fixed design points. The balance in terms of money, energy, and emissions, is region specific, certainly not obvious, and needs careful evaluation. Whether this has been done for biomass-fuelled CHP is unclear. Certainly it was not reported by TERES II. The EU’s strategy to promote CHP refers to a number of general CHP supporting studies but these did not cover biomass-fuelled CHP for district heating. It can be assumed that the ‘European Union energy outlook to 2020’, prepared by the Shared Analysis Project, is actually framed by these types of considerations, including biomass-fuelled CHP. Overall, the ‘European Union energy outlook to 2020’ does not foresee a substantial increase in

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208/ As confirmed by Grohnheit (1999), p. 28.
210/ EU (1997a).
Transportation fuels: As indicated above (Table 20), ‘Energy for the future’ anticipates a market share of 18 Mtoe primary biomass inputs into the manufacture of transportation fuels. The policy to pursue this application is further developed in the Green Paper on energy security by the European Commission. The biomass types, from which these fuels should be produced, according to the views expressed in the referenced studies and reports, are oil seeds (e.g. rape seed, sunflower seed) and sugar or starch rich crops (e.g. wheat, beetroot, sorghum). From oil seeds, methyl ester could be made (a diesel fuel substitute), whereas ethanol could be made from sugar or starch, as a substitute for petrol. The primary resource, thus, is agricultural land. The amount of agricultural land required, depends on the following basic parameters:

- Crop yield (t crop/yr);
- Conversion ratio (J fuel/t crop).

Both differ for the two conversion routes (methyl ester and ethanol). They also vary with land productivity. Indicative data for rape seed methyl ester were evaluated by Williamson and Badr (1998). They reported an overall productivity level of 43 GJ/(ha yr) with the possibility of doubling this amount. In this figure the energy inputs into the production system are not included. Assuming that all biomass-based transportation fuels would be made from rapeseed, a total agricultural area of 17.5 Million ha would be required (23% of the arable land of the EU15). The ethanol route is less demanding. The land area needed for sugar beet cultivation, to provide the entire amount of biomass-based transportation fuels, would only amount to 6.1 Million ha (based on productivity data cited by Diamantidis and Koukios (2000)). This is equivalent to 8% of the arable land in the EU15. In ‘Energy for the future’, the European Commission doubts that more than 10 Million ha would become available for energy crops. It must be concluded, therefore, that if a production mix of methyl ester and ethanol did emerge, and the targets satisfied, there would hardly be any space left for other types of energy crop production. Although the vast land area involved is placed here in the perspective of the arable land available in the EU15, local production is not the only option for the manufacture of renewable transportation fuels. Although that is assumed in ‘Energy for the future’, it is conceivable that the raw materials for renewable transportation fuels could be grown elsewhere, and that intermediate, or finished, products are then imported into the European Union.
Waste: In accordance with the European directive on the promotion of electricity from renewable energy sources, energy produced from the biodegradable component of waste, in waste incineration plants and co-firing plants, will be considered as renewable energy. ‘Energy for the future’ does not explicitly consider possible changes in waste production, nor any shift of combustible waste biomass from waste incineration plants to co-firing plants. Hence, a specific role for waste incineration plants in electricity and heat generation is not quantified. A possible explanation is that the relevant amounts are negligible.

‘Energy for the future’ does, however, expect an increased utilisation of biogas, originating from landfills, municipal and industrial sewage and sludges, as well as from livestock manure digestion. According to the list quoted on page 131 it is supposed that electricity production is the obvious application. However, biogas could also be used for non-CHP heat, and also for CHP. A clear preference in this regard has not been justified. The reason to include landfill gas and sewage gas as potential additional supplies is not that it would be technically feasible or desirable to increase the production of these gases. In fact, biogas arises, unavoidably, from the biological processes that occur in landfills, and in most waste-water treatment plants. What is actually implied here, is that its utilisation as an energy source might increase. ‘Energy for the future’ reports a 2010 potential of 15 Mtoe/yr (including biogas from manure).

Conclusion

It appears that the, derived, aggregate demand outlook (Table 20), and the data provided for each application in ‘Energy for the future’ cannot be reconciled on a one to one basis. The comparison is shown in Table 23. There is particularly an appreciable difference for non-CHP electricity (28 vs. 21 Mtoe/yr). Also with regard to the total incremental use of biomass fuels, the interpretation of the aggregate sectoral data shows a substantially larger increase in biomass utilisation (98 vs. 90 Mtoe/yr). As a possible solution, it could be suggested that the missing 7-8 Mtoe/yr is taken up by dedicated biomass-fuelled power plants, omitted from the quantified targets for the respective applications. However, such an explanation conflicts with the reported supply side increment, which ‘Energy for the future’ quantifies as 90 Mtoe/yr. The TERES II study forecasts a much higher contribution by biomass fuels (160 Mtoe/yr, Best Practice Scenario). However this is for a time horizon of 10 years further ahead (2020). The least optimistic with regard to the use of biomass fuels, is the Shared Analysis Project, which predicts an increase from 44 Mtoe/yr in 1995 to a maximum of only 64 Mtoe/yr in 2010.

Thus, at the political level, the market for biomass fuels in the European Union is anticipated to grow by a factor of three over the next 10 years. The lower expected growth rate by the scientists’ Shared Analysis Project is a result of the manner in which its scenarios are defined (more precisely: the economic framework of those scenarios) or of its technical input data (such as biomass availability).

Once the opportunity of co-firing, offered by existing coal-fired power plants, has become obsolete - an event which is expected to occur between 2010 and 2024 - an alternative for the electricity sector needs to have been developed. This could be innovative technologies for dedicated biomass-fuelled power plants or, alternatively, by new technologies offering co-firing opportunities at future state-of-the-art electricity plants fuelled by coal, oil, or gas. Only if such technology is developed timely and successfully, can the contribution of biomass to electricity production be maintained or increased. In Chapters 5 and 6, this thesis focuses on the development of technology for the first option: innovative technologies for dedicated biomass-fuelled power plants.

As a result of the evolving legislation with regard to the utilisation of wastes for the renewable production of heat and electricity (see the Introduction to Part B of this thesis), the market for contaminated biomass fuels will be separated from the market for clean biomass fuels, whether labelled waste or not. Whether standard waste incineration plants will be able to compete for contaminated biomass fuels with the other four applications identified in ‘Energy for the future’ - i.e., co-firing, CHP district heating, stand-alone biomass electricity, and transportation fuels - depends on:

• The ongoing aggravation, in parallel with technology development, of emission regulations for waste incineration, and on

• Ongoing technology development for the processing of contaminated biomass into energy products.

This matter is not further investigated here, since waste management technology is not the focus. The topic is electricity production from biomass; and its major resource, for reasons of availability relative to the demand for biomass-based electricity, will be clean, rather

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**Table 23. Sectoral usage of biomass fuels (Mtoe/yr) according to ‘Energy for the future’**

<table>
<thead>
<tr>
<th></th>
<th>Interpretation of the aggregate data in ‘Energy for the future’</th>
<th>Increment by 2010 according to application data in ‘Energy for the future’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-CHP electricity</td>
<td>2</td>
<td>31</td>
</tr>
<tr>
<td>Co-firing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dedicated biomass-fuelled plant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biogas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-CHP heat</td>
<td>42</td>
<td>65</td>
</tr>
<tr>
<td>CHP electricity and heat</td>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td>Liquid transportation fuels</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td>147</td>
</tr>
</tbody>
</table>

/a No specific target for dedicated biomass-fuelled plants is set in the subsectoral analysis of ‘Energy for the future’. 

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137
than contaminated, biomass. In that context, it is very unlikely that the conventional waste incineration plants will continue to attract clean waste biomass, since conversion efficiencies in such plants are much lower than in plants specifically constructed for energy conversion. A likely development is therefore that, in the future, only the other four applications identified in ‘Energy for the future’ - i.e., co-firing, CHP district heating, stand-alone biomass electricity, and transportation fuels - will compete for clean biomass fuels. In the first place, electricity plants dedicated to biomass fuels are capable of using the same type of biomass fuels as utilised in co-fired power plants and district heating plants. A third competitor for biomass fuels is the transportation sector. Although the types of biomass concerned may be different - transportation fuels can be made from biomass types which, for technical reasons, are not relevant for electricity production (e.g. oil seeds) - the applications have one production factor in common: agricultural land. Land can be utilized to grow crops for the manufacture of transportation fuels or, alternatively, for crops for the production of electricity.

4.3 SUPPLYING A GROWING DEMAND FOR BIOMASS FUELS

In this section, on biomass fuel supply, the arena of potential biomass resources capable of providing substantial quantities in view of the expected demand is investigated. In future biomass fuel markets, biomass fuels will either be by-products of other economic activities, ranging from agriculture and forestry, industries (food, construction, paper, etc.) to households (municipal waste), or they will be direct products of agriculture. Subject to forces in the energy market, by-products could be withdrawn from current uses and destined for fuel applications. For example, straw, in the Netherlands currently often used for animal bedding, may become a recognised fuel in the Dutch energy sector. The same has already happened in Denmark. The matter is further complicated by potential changes, again as a result of energy market developments, in biomass recycling flows. The dynamics of markets for by-products is further illustrated with a reference to recent changes in India and Pakistan. Here, sugar factories accustomed to low-efficiency energy generation for self-sufficiency from their bagasse (a cane processing residue), installed more efficient equipment aimed at producing a surplus of electricity for sale to the electricity grid.

With regard to biomass by-products, therefore, one cannot simply assume that these are first and foremost available for energy applications, and that their availability should be supplemented by energy crops to make up the total demand for biomass fuels. The pricing mechanism is insufficiently known to justify such a presumption. Instead, it must be concluded that the future market for biomass fuels will be the dynamic result of competition between:

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218/ In this manner, short-rotation forestry is considered a type of agriculture. Whether or not it would be preferred to schedule it under forestry, is semantics.

219/ According to the Danish Biomass Agreement, the electricity sector plans to use 1.2 Mt of straw per year before the year 2000 (Christiansen, Fock, Werling et al. (2000), p. 5).

220/ This includes direct recycling (e.g. used paper to new paper in the paper industry) and indirect recycling (one discarded product into another product type: e.g. wooden furniture to particle board), sometimes referred to by the expression ‘cascade utilisation’. Due to increased residence time, any type of recycling reduces the availability of residues for fuel applications.
Alternative applications of biomass by-products,
• Alternative types of land use.

It is for this reason that the concept of ‘biomass fuel availability’ appears to be inappropriate when describing the investigated market. Biomass fuels do not simply lie around somewhere, waiting to be found. Instead of the static concept of resource availability, the dynamic concept of resource mobilisation seems to be more appropriate here.

A first legitimate question is, whether it is at all possible to sustainably produce enough biomass fuels to meet the ambitions, without conflicting with other essential land uses in general, or of biomass utilisation in particular. With regard to self-sufficiency on the EU level, the TERES II study and ‘Energy for the future’ are positive, whereas the Shared Analysis Project is negative (as quoted in the previous section, see p. 130). Considering the Netherlands, and in view of the specific renewable energy targets set by the Dutch government, Siemons and Kolk (1999) showed that self-sufficiency is only possible with the development of revolutionary, and unlikely, social and economic scenarios in the Dutch agricultural sector. At least intra-EU trade and perhaps even global trade in biomass fuels would be a necessity. This makes one wonder whether sustainable biomass fuel supplies, at the required level, are possible on a worldwide scale. Since about 1990, numerous scenario studies on this subject have been published. 17 of them were reviewed by Hoogwijk, Berndes, Broek et al. (2000). They show that the lowest biomass energy potential for the year 2050 was reported by Battjes (1994), i.e. 1120 Mtoe/yr. This is only slightly more than today’s biomass fuel utilisation (see Table 17). Battjes restricted his analysis to the production of energy crops, considered only fallow lands, and excluded Asia and Africa. His study is therefore probably the least relevant in a review of biomass resource mobilisation. Other studies reviewed by Hoogwijk, Berndes, Broek et al. arrive at resource potentials ranging between 3000 and 10700 Mtoe/yr. Based on this review, the integrated assessment reported by UCE, UU-NW&S, RIVM et al. (2000) arrives at a biomass fuel supply potential of 26300 Mtoe/yr. This value is much higher than the estimates in the individual studies reviewed by Hoogwijk, Berndes, Broek et al., because it aggregates the various potential resource types which are not fully covered in the particular assessments. The quantities reported are in the order of 30%-110% (Hoogwijk, et al.) and 270% (UCE, et al.) of current worldwide primary energy supplies, both renewable and non-renewable (compare again with Table 17). Time horizons for these assessments, however, range between 2025 and 2100; and by then, total primary energy supplies can be expected to have risen. In their review, Hoogwijk, Berndes, Broek et al. rightly point out various weaknesses in the model interactions and the assumed parameter values. However, their plea for improved studies, for example by incorporating economics of biomass energy systems, seems to lack justification as long as one is only interested in the question as to whether long-term sustainable supplies of biomass fuels are possible without prohibitive conflicts with other interests.

It must be concluded that, in principal, a sustainable supply possibility exists. The sustainability of biomass supply, however, is not something which emerges on its own, and is a particular responsibility for those countries which choose, or feel forced, to import
these resources from countries with weaker democratic government traditions or stronger internal economic contrasts. To this effect, the authors of the review study discussed above make some specially relevant suggestions which boil down to the development of measurable social, economic and environmental criteria, combined with certification.

An essential question for the current study is, at what cost can sustainably produced biomass fuels be acquired. The further development of this issue requires a principal market consideration. Renewable electricity is a combined product of electricity and sustainability. Its value is therefore higher than that of simple electricity. This fact is not always observed immediately by consumers, but in such cases the effects of taxes and subsidies obscure their view on the market. One possible expression for the value of sustainability is €/t avoided GHG emissions, but by employing the specific emission rate of the fossil fuel-derived electricity replaced, it can also be expressed per unit of electricity (€/kWh) (this is done by means of the factor \( \rho \), introduced in Section 3.2.1). The value of sustainability, thus expressed as a marginal component of the value of sustainable electricity, is, in the case of biomass-based production, used to finance two items:

- Incremental costs of biomass fuels in comparison with fossil fuels, including an element to ensure sustainability, and
- Incremental costs of biomass conversion technology in comparison with fossil fuel conversion technology.

How the marginal added value of sustainability is divided between the two will differ from case to case. This division does not depend on case-specific fuel provision costs as experienced by the fuel supplier, or the technology costs experienced by the electricity producer. After all, there are many types of biomass fuels and many biomass suppliers, and there are many different producers of sustainable electricity employing different technologies and operating on different scales. But the truly constant parameter, that is to say constant for each player in the arena of fuel provision and technology use, is the marginal value of sustainability. As a result, once a market has been established, the prices of biomass fuels delivered at the plant gate will solely depend on the inherent fuel qualities, and thus some biomass fuel providers will obtain higher profit margins than others, the differences depending on their production costs rather than on the sales prices of their product. It would be a mistake to assume in a market for clean biomass fuels that there will be differences in fuel gate prices solely on the basis of the origin of a fuel. In this context, ‘origin’ refers not only to the remoteness of a production site relative to the place of use, but also to the issue as to whether the biomass is a waste for its owner or a primary product. In the absence of monopolies, any differences in gate prices may be expected to depend only on variations in additional processing costs observed by the buyer (such as grinding and drying operations). The argument runs entirely parallel with Ricardo’s explanation for the amount of land rent being a result of wheat prices.²²²

In the analysis argued above, fuel quality, rather than origin or production costs, should be a leading principle for classifying biomass fuels. As a second step, potential supply quantities and delivery costs are to be analysed, because these determine the potential role

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²²²/ Ricardo (1951).
of a biomass fuel type in an established market. The focus is on clean\textsuperscript{223} biomass. Biogas, a secondary biomass-based fuel, from landfills (landfill gas) and sludge gas, which results from sewage water and industrial water cleaning, are not investigated here. The reason is that biogas and sludge gas are available anyway, without any competition for resources. In reality, the position of biogas and sludge gas utilisation in the renewable energy market is so strong that its share will be largely limited by the technical potential (of course within the constraints of the economic feasibility of its utilisation).

A qualitative classification of clean biomass should be based on the observation of the users of these fuels. These users avail of a conversion technology which is adapted to the biomass quality. Conversion technology, therefore, determines quality categories. The major quality classes thus derived are as follows:

- Dry ligno-cellulosic biomass. Origin: residues, waste and energy crops (such as miscanthus and short-rotation coppice);
- Wet cellulosic biomass. Origin: residues and waste (this category includes manure, but also waste flows from agro-industries) as well as specific energy crops (e.g. algae);
- Other energy crops (oil seeds for methyl ester, sugar/starch crops for ethanol);

These are further elaborated upon in Table 24. Quality classes are not delimited by impermeable boundaries. To some extent, flowing transitions from one class to another may be observed. The quantified qualities given in Table 24 are therefore intended to be only indicative, and the review should be read as follows:

- For users employing combustion, gasification or liquefaction technologies, the highest quality class is dry biomass (ligno-cellulosic or cellulosic).\textsuperscript{224} They can also utilise wet ligno-cellulosic or wet cellulosic biomass, but then they need an additional drying operation, which makes this fuel quality less desirable.
- Users employing digestion, will prefer wet cellulosic biomass types (lignine cannot easily be digested).
- Manufacturers of methyl ester will favour oil seeds, and manufacturers of ethanol will prefer materials which are rich in sugar or starch.

The presented overview of technologies and fuel qualities is based on the experience of the author, and it is understood that the review is debatable. For example, some ethanol producers could claim to highly appreciate certain cellulosic biomass types as a raw material for their process.\textsuperscript{225} It may also be claimed that the technology of supercritical gasification is promising for the conversion of wet ligno-cellulosic or cellulosic biomass types, but I would counter that the technology is still in infancy. However, serious research and development into this technique has started.\textsuperscript{226} Other points of view on this issue - and

\textsuperscript{223} Including clean waste biomass, according to the European Common Position on emissions from large combustion plants (EU (2000b)) and the European Directive 2000/76/EC on the incineration of waste (EU (2000c)). See the discussion in the Introduction to Part B of this thesis, p. 113.

\textsuperscript{224} Ligno-cellulosic biomass is rich in lignine and cellulose, cellulosic biomass is also rich in cellulose but poor in lignine. Examples of the first are wood, and energy crops such as miscanthus. Potato, wheat and sugar beet are examples of cellulosic biomass.

\textsuperscript{225} For a specific evaluation of technologies and feedstock qualities for gaseous and liquid biomass-based fuels, see Siemons and Meuleman (1999).

\textsuperscript{226} See for example Kritzer and Dinjus (2001). Matsumura, Nonaka, Yokura et al. (1999) and Schmieder, Abeln, Boukis et al. (2000).
these may change along with progress made with the development of innovative technologies - are very welcome since they can improve the current analysis.

Table 24. Quality classes for clean biomass fuels based on conversion technologies.

<table>
<thead>
<tr>
<th>Fuel categories based on quality</th>
<th>Fuel quality (indicative)</th>
<th>Primary conversion technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry (ligno-)cellulosic residues and waste as well as (ligno-)cellulosic energy crops</td>
<td>Moisture content (w) &lt; 50%; Morphology = granules, lumps or pieces; Variable ash content</td>
<td>Combustion, gasification or liquefaction</td>
</tr>
<tr>
<td>Wet cellulosic residues, waste and energy crops (e.g. algae)</td>
<td>Moisture content (w) &gt; 70%; Morphology = sludge, pumpable slurries; Variable ash content</td>
<td>Digestion</td>
</tr>
<tr>
<td>Other energy crops: Oil seeds for methyl ester</td>
<td>Moisture content (w) &lt; 20%; High vegetable oil content; Low ash content</td>
<td>Extraction</td>
</tr>
<tr>
<td>Sugar/starch crops for ethanol</td>
<td>Moisture content (w) &gt; 50%; High sugar or starch content</td>
<td>Fermentation</td>
</tr>
</tbody>
</table>

Specifically for biomass fuels which belong to these basic quality classes, their cost factors and supply potentials must be investigated in order to establish an understanding of biomass fuel prices. The cost factors which, in the supplier’s perception, determine these prices, are:

- Production costs of biomass fuels and
- Their transportation costs from production site to energy conversion plant.

Thus, a division between supply and demand is somewhat arbitrarily drawn at the gate of a conversion plant. Alternatively, and particularly if international trade is concerned, a boundary could have been conceived at the port of shipment (f.o.b. costs) or port of arrival (c.i.f. costs). The issue is not really critical here, and the cost factors are discussed in the following subsections. Here, the focus is on the first quality category (dry (ligno-)cellulosic biomass), since the technology assessment in Chapter 6 is about combustion, gasification and liquefaction.

4.3.1 Production costs of biomass fuels

Residues and wastes

Production costs of residues and wastes are confined to upgrading (such as separating, drying, chipping, pelletizing, etc.). Only occasionally will collection costs have to be included as well. These apply for example to residues which in the absence of an energy application, would have remained in agricultural fields (such as straw, on occasions) or in forests (branches). They do not apply if a material is a waste and requires proper handling in any case (e.g. discarded railway sleepers).

The category of dry (ligno-)cellulosic residues and wastes includes the following materials:

- Straw,
- Sawdust and shavings (timber milling residues),
- Forestry thinnings.
The list can be extended almost endlessly, but relevance diminishes as available quantities decrease. Straw is often excluded without thorough reflection, and the Danish practice suggests that it might be worth having a closer look. Quantities of straw cannot be found in the accessible statistics of the FAO and the EU, however, production data for cereals are available and using an approximate straw/cereal ratio, straw production can be estimated. Assuming a ratio of 0.54 t/t, a total straw production of 87 Million t/yr for the EU15 is found. This amount relates to barley, oats, rice, rye, and wheat production data for the year 1999. This estimated quantity is equivalent to 31 Mtoe/yr (compare this to the EU’s ambitions with regard to the use of biomass for energy). Prices for straw used for animal bedding fluctuate between 10-100 €/t, delivered.227

Today, the lowest quality residues from wood processing industries (sawdust, shavings) are often incinerated (with partial energy recovery), and only limited quantities are processed into products such as fuel briquettes. The occasionally traded amounts are delivered at values around 20 €/t.228 The lion share of this amount covers transportation costs. There are no statistics available about the production of such residues. Forestry residues are sometimes suggested as being a biomass type suitable for the energy market. However, with the state-of-the-art tree harvesting techniques of today, the lowest quality wood is chipped into an assortment suitable for various types of panels (fibreboard, hardboard, insulating board, mdf, and particle board). There are virtually no residues of a suitable fuel quality from forests which are under commercial management. A majority of the thinnings are used for paper manufacture. Where this is not so, they also end up in the panel industry. The trade in wood chips and particles gives a fair indication of prices and quantities of the lowest quality by-products generated by both wood processing industries and forestry. During 1998-2000, production of this material in the EU15 increased from 21 to 35 Million solid m³.229 The equivalent primary energy value is about 6.5 Mtoe/yr (30 Million m³). Delivered costs including transportation, vary between 25-40 €/t.230 Transportation costs (road transport) amount to about 50% of the total.

An illustrative case of residues that have found a market is provided by the trade in raw materials for animal fodder. Intercontinentally-traded products include soya scraps, soya hulls, sunflower scraps - all shipped from Argentina and Brazil to Europe - and coco and palm kernel scraps, mainly shipped from Indonesia and the Philippines. At an f.o.b. price of about 50-60 $/t, soya hulls are about the cheapest of these materials. F.o.b. prices of sunflower scraps fluctuate between 50-100 $/t.231 During 1997-1999, the imports into the EU15 of coconut cake, palm kernel cake, soya bean cake, and sunflower seed cake, all materials for the animal fodder industry, rose from 18 to 25 Million t/yr.232 The energy equivalent (if one assumes an NCVw of 20 GJ/t) is 9-12 Mtoe/yr.

228/ Brandt (2001).
229/ FAO Stat.
231/ Visser (2001)
Energy crops

Energy crops that can provide dry ligno-cellulosic fuels are miscanthus and switch grass (both grass types), willow and poplar (both as short rotation coppice (SRC)). Various studies into the production costs of these crops exist, and the costs reported vary widely. The reasons for these differences are mainly due to differences in analysis methods, and can only partly be explained by the parameter values used. The most straightforward method of cost calculation would follow the schedule presented in Table 25. In view of the investment character of both costs and yields, annual production and cash flows would be determined for the year of their occurrence and then they would be discounted at the applicable rate. Unit specific production costs would result from dividing the discounted costs by the discounted production (compare Section 3.2.1). If sufficient parameter values could be established, the method could be employed both for existing farms switching to the cultivation of energy crops, and for newly established companies dedicated to such production. In practice, this is barely possible for existing farms, due to difficulties in assessing parameter values for the costs of self-provided labour and land use in agriculture. With regard to self-provided labour, there are no accounts on which its value can be determined. As for land use, land is either owned or rented, and only in the latter case are the costs explicit. It appears that land rents are way below the interest rates prevailing on the capital market (1.75% vs. 6.5% is not uncommon).

Table 25. Review of cost items in the determination of production costs for energy crops.

<table>
<thead>
<tr>
<th>Capital costs</th>
<th>Operational costs</th>
<th>Subsidies (subtract)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land</td>
<td>Labour (farmer, assistants)</td>
<td>Materials (seeds, seedlings, fertiliser, fuels, etc.)</td>
<td></td>
</tr>
<tr>
<td>Buildings</td>
<td>Supplementary services</td>
<td>Maintenance</td>
<td></td>
</tr>
<tr>
<td>Machinery</td>
<td>Rented machinery</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A method proposed by the Dutch Agricultural Economics Research Institute (LEI-DLO) and employed in Dinkelbach, Doorn, Jager et al. (1998) calculates a standardized net hourly labour income for a typical arable farmer (equivalent to 7.95 €/h) as well as the physical labour input required for the production of energy crops. Labour costs for energy crop production are subsequently found by multiplying the two. Since, in comparison with traditional agriculture, considerably less labour is needed for growing energy crops (at least this applies to the multi-annual crops, miscanthus, SRC-willow, and SRC-poplar), farmer incomes would decrease sharply if energy crops were sold for a price reflecting the

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233/ A particular characteristic of multi-annual energy crops is that substantial onetime costs for start-up and termination are involved and that these crops achieve their maximum yields only after a prolonged starting period of several years.

234/ Meeusen-Van Onna (1997).
costs thus determined, unless additional types of income could be generated. As a result of this approach, energy crops cannot be considered a serious option for the agricultural sector. CPV, IMAG-DLO and ECN (1996) employed a similar evaluation methodology, albeit by assuming a twice as high cost for unpaid labour by the farmer. Additionally they applied a margin of 5% over the turnover. Costs calculated in this manner are more favourable for the farmer. However, the cost calculations in both studies bear no relationship with the real cash flows required in farming, and the resulting values cannot be considered to reflect production cost indicators.

Evaluations by Venturi, Huisman and Molenaar (1997) and Bullard (2001) start from the standard gross margin (SGM), as defined in the EU’s agricultural accountancy data network. On an enterprise level, the gross margin is defined as the value of production minus certain costs. Standardization is achieved by taking an average, based on region and farm type. Making use of regionally averaged farm sizes, the SGM is expressed on an area basis (€/(ha.yr)), SGM<sub>a</sub>. The cost items subtracted are defined in Commission Decision 85/377/EEC concerning a common typology for agricultural holdings in the EU. They concern costs which can be directly allocated to the crop produced, and include supplementary contracted services. Agricultural subsidies are included in the SGM as positive proceeds. Unit specific production costs (€/t crop) result by dividing the sum of SGM<sub>a</sub> and directly allocated costs, by area specific yield:

\[
\text{UPC} = \frac{\text{SGM}_a \% \text{area specific direct cost}}{\text{area specific yield}}
\]

In the calculation of the SGM, capital costs, the fuels to operate machinery, and self-provided labour are not deducted. As a result, the gross margin is available to finance precisely these non-deducted costs, including the farmer’s income. Therefore, in contrast with the analysis method of LEI-DLO, the production costs calculated in this manner do reflect accepted incomes in agriculture since the accepted farmer income is a result of the aggregate area-specific gross margin of established holdings. The prevailing variations in holding size and farmer’s income are taken as a given fact. If, however, in the longer term, the average holding size substantially increases ceteris paribus farmer’s income, then such an estimate of production costs of energy crops, based on currently prevailing SGMs, would be too high. A further drawback is that an SGM-based cost analysis leaves implicit any distinction between farmer’s income and capital costs (land, buildings and machinery). Hence, the method does not enable production cost calculations for enterprises specifically established for the growing of energy crops.

A third cost calculation method, presented by Meeusen-Van Onna (1997), claims to yield a ‘long-term partial cost of production’. Whereas the pure SGM-based method, employed by Venturi, Huisman and Bullard, takes production costs as the sum of directly allocated costs and SGM, this new method also adds the incremental unpaid self-provided labour required for the energy crop (i.e. incremental in comparison with the substituted

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235/ EU (1985).
236/ EU (1985).
crop). Physical differences in unpaid self-provided labour can be determined relatively easily (and they can be positive or negative), but their valuation is more complicated. Meeusen-Van Onna proposes the following:

- If the unpaid labour increment is negative, its value would equal the income gained from alternative activities carried out by the farmer during the hours freed. This additional income would thus result in decreased production costs for an energy crop.
- If the unpaid labour increment is positive, its value would be somewhere between zero and market values for labour. Production costs of energy crops would increase by this amount.

A third option contemplated by Meeusen-Van Onna does not exist: that the labour increment is positive, and the farmer cannot provide it. By definition, he can, since only self-provided labour inputs are considered here. Labour which a farmer cannot provide himself is covered by hired additional services, accounted for under the heading of direct costs and therefore already accounted for in the calculation of production costs. Against the proposed valuation method for freed hours resulting from growing energy crops (the negative increment), the objection can be raised that it stands in the way of properly valuing the additional activities. After all, the resulting income is allocated to the production of the energy crop and effectively deducted from its costs. Against the proposed valuation method for positive additional self-provided labour, the objection can be raised that a farmer operating under such circumstances has evidently plenty of unvalued time. Otherwise he would not have been physically able to grow energy crops without hiring additional labour. In view of the fact that the pure SGM method already assumes generally accepted farmer’s incomes, a zero value for the positive unpaid labour increment would therefore be reasonable. Although it cannot be denied that there are changes in self-provided labour when switching over from traditional agriculture to growing energy crops, the calculation method proposed by Meeusen-Van Onna does not appear to be improved in comparison with the pure SGM method.

The agricultural subsidies applicable to certain crops in the EU15 complicate the matter. There is one agricultural subsidy that may also be paid out to the producer of energy crops, i.e. the existing subsidy for fallow (Commission Regulation (EC) No 2461/1999). This implies that part of the production costs is paid by the government and that, as long as the subsidy is granted, the relevant value should be deducted from the production costs (as perceived by the farmer) of energy crops. The system of agricultural subsidies is under political debate almost continually, and it may change. If it changes, it will do so as a result of its own social, political and economic dynamics which do not depend on the relatively small events in the field of biomass energy. It is therefore reasonable to accept the current subsidies for energy crops as a true factor leading to reduced production costs. Since the subsidy applicable to energy crops differs in size from the subsidies paid for food crops, a correction should be made in the method applied by Venturi and Huisman, and by Bullard. While taking the necessary discounting operations into account, an improved cost estimate for existing farmers would proceed as follows:
In this calculation, the average standard subsidy consists of all agricultural subsidies including the one for fallow, since the average of all subsidies is included in the SGM. The thus estimated unit cost is an indicator for a fair price payable by the client at the farm gate. The cost estimates for miscanthus cultivation produced by Bullard are quoted below (Table 26). Note that these estimates do not take account of the suggested correction for agricultural subsidies. The highest costs are expected in the Netherlands, the lowest in Spain. Table 26 shows estimated production costs for a range of yields. The reason for doing so is the uncertainty still persisting among agricultural researchers. In view of the yields achieved with beetroot and silage maize in the Netherlands, 15 t/ha appears to be a quite reasonable long-term expectation for miscanthus cultivation in Dutch circumstances. In terms of yields and costs, miscanthus is a representative example of an energy crop for dry ligno-cellulosic fuels. The major differences between miscanthus, switch grass, SRC-poplar and SRC-willow are of an agricultural character (suitability for different soil types, the possibility for integration into a crop rotation schedule, etc.). The unavoidable conclusion is that biomass fuel costs, as assumed in a number of feasibility studies and technology evaluations regarding energy production from specially cultivated biomass fuels, were far too low.

Table 26. Unit production costs for miscanthus on cereal farms in different member states of the EU, according to yield and SGM.

<table>
<thead>
<tr>
<th>Predicted annual yield (ECU/t_0)</th>
<th>12 t/ha</th>
<th>15 t/ha</th>
<th>18 t/ha</th>
<th>21 t/ha</th>
<th>24 t/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>125</td>
<td>102</td>
<td>86</td>
<td>74</td>
<td>65</td>
</tr>
<tr>
<td>Denmark</td>
<td>90</td>
<td>73</td>
<td>62</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>Germany</td>
<td>134</td>
<td>109</td>
<td>92</td>
<td>80</td>
<td>70</td>
</tr>
<tr>
<td>Greece</td>
<td>90</td>
<td>73</td>
<td>61</td>
<td>53</td>
<td>47</td>
</tr>
<tr>
<td>Spain</td>
<td>39</td>
<td>32</td>
<td>27</td>
<td>23</td>
<td>20</td>
</tr>
<tr>
<td>France</td>
<td>87</td>
<td>71</td>
<td>59</td>
<td>51</td>
<td>45</td>
</tr>
<tr>
<td>Ireland</td>
<td>73</td>
<td>59</td>
<td>50</td>
<td>43</td>
<td>38</td>
</tr>
<tr>
<td>Italy</td>
<td>91</td>
<td>74</td>
<td>62</td>
<td>54</td>
<td>47</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>188</td>
<td>153</td>
<td>129</td>
<td>111</td>
<td>98</td>
</tr>
<tr>
<td>Portugal</td>
<td>54</td>
<td>44</td>
<td>37</td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>80</td>
<td>65</td>
<td>55</td>
<td>47</td>
<td>42</td>
</tr>
<tr>
<td>Mean</td>
<td>105</td>
<td>85</td>
<td>72</td>
<td>62</td>
<td>55</td>
</tr>
</tbody>
</table>


Siemons and Kolk (1999) showed that production costs of energy crops are very sensitive to average holding size and cost of land use (ceteris paribus farmer income) (see Figures 23 and 24). Either or both of these parameters may be the reason for the large national differences found by Bullard. The, as yet unspecified, parameter of farmer income, may also vary strongly across the various EU15 member states. Further study into the economy of energy crops, and effective policies for their promotion, should pay attention to this issue.

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240/ For example: Faaij, Meuleman and Van Ree (1998) and Dinkelbach, Doorn, Jager et al. (1998).
According to ‘Energy for the future’, the maximum available land area in the EU15 for energy crops is 10 Million ha. This is 7% of the utilised agricultural area and 13% of the arable land. If, on average, an annual yield of 15 t\(\text{ha}^{-1}\) was achievable, the equivalent energy production would amount to 65 Mtoe/yr. The figure is substantially higher than the...
target in ‘Energy for the future’ (45 Mtoe/yr from energy crops), and this is due to the fact that the policy document, aside from ligno-cellulosic crop types, also assumes crops which are much less productive (oil seeds). Whereas ligno-cellulosic crops yield an energy equivalent of about 270 GJ/(ha.yr) (at 15 t/(ha.yr) and 18 GJ/t), a crop such as rapeseed yields only about 43 GJ/(ha.yr).

Note, that there is no a priori reason to restrict the cultivation of energy crops for use in the EU15, to the EU15’s agricultural lands. In a study on the import of sustainably grown plantation wood, Wasser and Brown (1995) report 21 $/t, and 24 $/t, for Eucalyptus logs and chips respectively, loaded f.o.b. in Montevideo (Uruguay). A condition for cultivation elsewhere is that transportation costs are sufficiently low. Imports of both the dried products as well as certain preparations, e.g. carbonised or liquefied materials, can be considered. Carbonisation and liquefaction result in increased energy densities (per mass or per volume), and thus may make long-distance transportation cost efficient. In the next section, transportation costs are further investigated.

In the section now being closed a number of prices have been reviewed. Only the prices for energy crops are true unit production costs, the others are mere indicators of such costs. The most important costs are listed in Table 27. It is not self-evident that a crop such as miscanthus (and likewise SRC-willow or SRC-poplar), if grown, should be cultivated for the energy market. It is conceivable that energy applications will replace the existing uses of chips and particles for board and panels, the producers of which could then convert to more expensive alternatives provided by this type of non-food crops.

<table>
<thead>
<tr>
<th>Product</th>
<th>Source</th>
<th>Price Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw EU (delivered)</td>
<td>Bullard (2000)</td>
<td>10-100 €/t</td>
</tr>
<tr>
<td>Chips delivered particle board industries</td>
<td>Kuiper (2001)</td>
<td>23-38 €/t</td>
</tr>
<tr>
<td>Cake of soya f.o.b. Argentina, Brazil</td>
<td>Visser (2001)</td>
<td>129-272 $/t</td>
</tr>
<tr>
<td>Soya hulls f.o.b. Argentina, Brazil</td>
<td>Visser (2001)</td>
<td>56-57 $/t</td>
</tr>
<tr>
<td>Cake of sunflower f.o.b. Argentina</td>
<td>Visser (2001)</td>
<td>48-98 $/t</td>
</tr>
<tr>
<td>Miscanthus f.o.b. farm gate /a</td>
<td>Bullard (2000)</td>
<td>32-153 €/t /a</td>
</tr>
</tbody>
</table>

a/ At a yield of 15 t/ha.

### 4.3.2 Biomass transportation costs

Although there are many situations, notably in agro-industries such as sugar and palm oil manufacture, where biomass fuels are used without any cost for fuel transportation, this is not the case for the systems considered in the chapters that follow. Any biomass-fuelled electricity, heat, or CHP plant, operated separately from biomass processing industries, will need biomass fuel to be delivered from outside.

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243/ See the discussion on page 135.
In several studies, it is assumed that biomass-fuelled energy conversion plants are placed in the centre of a region from within which the biomass fuel is supplied. The rationale behind this approach is that, in such a configuration, average transportation distance, and hence transportation costs, would be minimised. If fuels originate from the immediate surroundings of an energy plant, the average transportation distance of the provided fuel increases with the square root of plant capacity. Hence, as plants get larger, average fuel transportation costs increase, rapidly at first, and slower as plant sizes continue to grow. However sensitive to plant size, this relationship points towards small plant capacities. In view of the economies of scale of plant investment and conversion efficiency, which encourages large plants, there arises an interesting optimisation problem, the solutions of which are certainly not obvious. Jenkins (1997) shows capacity optimums which range from 230-1240 MWₑ. However, even though it is true that fuels which originate from around a power plant will have the lowest delivery costs, this does not at all imply that gate prices of delivered fuels, if acquired from the plant vicinity, will necessarily be the lowest. Increased transportation costs resulting from increased transportation distances may be offset by lower fuel supplier prices. If fuel is acquired from elsewhere, then transportation distances are independent of plant capacity and related solely to the remoteness of the fuel producer relative to the site of the conversion plant. This necessitates a closer investigation of transportation costs. In general, such costs depend on the transportation distance, the means of transport, and the number of transshipments. It is not the intention to develop an exhaustive transportation model in this section, rather a number of key data are given.

Faaij, Meuleman and Van Ree (1998) present a cost estimate, based on tariffs prevailing in the Dutch waste management sector, for the costs of biomass transport by truck and containers. The cost for wood chip transportation is approximately 0.9-1.1 €/(t.km). An average 50 km journey would thus result in a total cost of 45-55 €/t.

Already by 1995, the possibility of international imports of biomass from overseas was recognized in a study co-funded by the FAO and the Dutch Novem. Further studies elaborated on the potential, and international biomass imports were subsequently identified as a possible contribution to the Dutch policy on renewable energy. Together with the Swedish Nutek and Novem, the EU ALTENER programme supported a broader study which, in addition to costs also addressed GHG balances and macroeconomic effects. All these studies concerned the imports of wood logs and wood chips. The 1996 study by BTG and Kema also considered wood charcoal and liquefied wood (through pyrolysis). Agterberg included methanol made from wood. In a study awaiting publication, Wagenaar and Vis (2001) evaluate the costs of importing pyrolytic oil from Indonesia to Rotterdam.

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245/ A simple model is described by Jenkins (1997).
250/ The pyrolysis technology is explained in Chapter 5.
Doyle (1986) found that the marine transport market operates as a virtually perfect competitive market. The supply of cargo capacity is characterized by two types of agents: those who offer second-hand written-off vessels, and those who offer newer vessels which still need to recover their capital costs. As a result, the costs of bulk freight fluctuates strongly with the state of the economy. An indicator used in descriptions of the market for dry bulk ocean freights - relevant when studying the transport of wood chips and logs - is the Baltic Dry Index (BDI). During the last ten years the BDI has fluctuated by ± 40% (Figure 25). This indicates that, in the evaluation of freight costs, one should be careful with price quotations since these cannot be anything else but spot values in a volatile market. Long-term average costs can be estimated from economic costing models, which take proper account of all the cost items involved. Of the studies mentioned above, on the imports of woody biomass, the studies by BTG and Kema (1996) and by Agterberg and Faaij (1998) are based on one off inquiries without reflection on market developments. The estimates given by Wasser and Brown (1995), on the other hand, are based on a long-term costing model provided by Doyle (1986). Lako and Van Rooijen (1998) do the same, and add some cargo carrier types to the analysis.

![Figure 25](image_url)

In addition to the costs of purchase, the cost items involved if biomass or biomass-derived fuels are imported, are the following:

- Local transport (from fuel supplier to port, unloading),
- Storage,
- Departure port (harbour fees or groundage, loading costs),
- Sea transport (vessel depreciation, maintenance, insurance, fuel, crew, other),
- Arrival port (harbour fees or groundage, unloading costs),
- Storage,
- Transport from port to end-user.

Depending on logistics, storage can sometimes be avoided. Here, an attempt is made to review the costs of shipment of biomass, or biomass derived fuels, which are delivered f.o.b. Hence only the last four cost items listed above are relevant.

For shipments of wood logs and chips, the relevant data can be extracted from the studies by Wasser and Brown, and by Lako and van Rooijen. The first shows costs between 14-17 $/t for wood imported from Estonia. Wood brought from Latin America (Uruguay) would be shipped at prices between 34-47 $/t. Lako and van Rooijen find a somewhat broader
range, as a result of additional vessel types being evaluated: 12-19 $/t for shipments from Estonia, and 22-68 $/t for imports from Uruguay. Chips can be loaded and unloaded quicker than logs, resulting in lower harbour dues. On the other hand, cargo loads of chips are much lighter than those of logs. On a per tonne basis, bunker fuel consumption for the latter is higher, but crew and capital costs are lower. As a result wood logs can be shipped more cheaply than chips, especially over long distances.

The referenced studies all assume the use of existing infrastructures and particularly of standard Handysize, Handymax, Panamax and Capesize dry bulk carriers. These vessels are designed for cargoes of a substantially higher bulk density than can be achieved with wood logs or chips. Whereas wood logs can be loaded at only about 0.3-0.4 t/m³, and chips at 0.20-0.24 t/m³, a typical mass/volume ratio for cargo is 0.7 t/m³, similar to the usual bulk density of wheat (0.70-0.79 t/m³). (Along with ore and steam coal, wheat is one of the major bulk commodities). The implication is that such typical carriers cannot be loaded to their full weight capacity with wood logs or chips, but only to 30%-60% of maximum tonnage. A ballpark figure for the actual transportation costs of wood can therefore be obtained by dividing prevailing rates for wheat by these percentages.

To get an impression of the costs of shipment per unit of energy, a cost range of 15-50 $/t wood is equivalent to 1.1-3.7 $/GJ (1.2-4.2 €/GJ).

Wagenaar and Vis (2001) calculated a cost of 77-92 €/t, for pyrolytic oil brought from Sumatera (Indonesia) and delivered to a power plant in the Netherlands. With an NCV w of 16 GJ/t, this is equal to 4.8-5.7 €/GJ. These costs concern transportation only, after the product being loaded f.o.b., and they were determined for a triannual shipment of 3300 t each. Ocean transport was planned around a parcel tanker with 1600 t stainless steel tanks. The investigated operation is, in fact, very small and does not reflect large scale manufacture of such fuels for utilisation in Europe. Lako and Van Rooijen (1998) estimated long-term costs for transporting so-called ‘biocrude’ (a type of liquefied biomass, with a relatively high NCV of about 29 GJ/t) at only 0.25 $/GJ (Uruguay-Rotterdam). Unfortunately this estimate cannot be evaluated due to a lack of references.

Neither the pyrolysis technology, nor the biocrude manufacturing process, are yet developed to a commercial scale. But liquefaction does seem to be attractive, since liquefied biomass has densities which are close to those of the commodities for which tanker vessels are designed. Hence full utilisation of cargo capacities can be achieved. There is a difference, though, with regard to the calorific values. Whereas crude oil has an NCV of about 40 GJ/t, pyrolytic oil has an NCV of 16-18 GJ/t, and ‘biocrude’, which in the past has received a lot of attention by Shell, has an NCV of about 29 GJ/t. Hence, if use is made of similar infrastructures to those for crude oil, the transport of pyrolytic oils and biocrude, on an energy basis, will be at least 2.5 and 1.4 time respectively more expensive. Making use of similar facilities, for that matter, will not be that easy.

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253/ Handysize: 10,000 dwt - 30,000 dwt; Handymax: 30,001 dwt - 50,000 dwt; Panamax: 50,001 dwt - 80,000 dwt; Capesize: 80,001 dwt and larger.
254/ Notice that these densities depend on moisture content. For wheat and wood, 15% and 25% are assumed respectively (wet basis). The wood types assumed are aspen and eucalyptus.
255/ Calculated from data reviewed by Venderbosch, Sander and Tjeerdsm (2000).
It is interesting to compare these prices with those for the transport of coal and crude oil. In spring 2000, the Commodities Team of the World Bank reported that shipment of Australian coal to Europe cost $15/t (a five year high). This is equivalent to 0.60 €/GJ. Six months earlier the rate was about half. In 2000, international transport of crude oil cost 0.06-0.47 €/GJ. Fluctuations in the oil market are the cause of the variations in shipping rates by a factor of about five. The remaining differences are due to the type of carrier employed (VLCC, Suezmax, or Aframax, with typical cargo loads of 250,000, 130,000 and 80,000 dwt respectively). Compared with the data determined for the import of wood logs and chips, these freight rates are extremely low. This is not so much the result of the high energy density (in terms of GJ/t or GJ/m³) - as often speculated - but rather due to the successful optimisation of carrier designs and logistics. Similar optimisations are theoretically also possible for biomass. It seems clear that in the case of coal and crude oil, the achieved rates are only possible as a result of the size of the traded volumes. Such volumes for biomass and biomass-derived fuels are not even contemplated in the most ambitious plans for renewable energy. Hence, although tremendous optimisation appears to be possible in theory, the international sea transport of biomass is destined to make use of existing infrastructures.

Since the calorific value of charcoal is about twice that of wood, and its bulk density is only slightly lower than that of stacked wood logs, sea transport of charcoal might also be an interesting option. Its transportation, expressed on an energy basis, is likely to be cheaper. Although approximately half of the energy originally available in the biomass raw material is lost during the manufacturing process, a production and utilisation chain of charcoal can be closed so as to be CO₂-neutral. In view of the GHG balance, it is important that all the gaseous carbon compounds released during charcoal manufacture are fully converted into CO₂, or in other words, that formation of methane is avoided. Furthermore, the release of N₂O should be prevented. This can be ensured if use is made of industrial carbonisation techniques. This option is not further elaborated upon here.

4.4 MATCHING SUPPLY AND DEMAND

In the previous section, biomass supply options were investigated. The identified European resources for dry (ligno-)cellulosic biomass with a substantial potential are:

- Ligno-cellulosic energy crops cultivated in Europe (maximum 65 Mtoe/yr),
- Straw grown in Europe, currently used or removed (current maximum 31 Mtoe/yr),
- Wood chips and particles produced in Europe (current maximum 6.5 Mtoe/yr).

In view of these quantities and the expected demand, imports do not appear to be an absolute necessity, but costwise they might be attractive. These materials could alternatively be produced outside the EU15, notably in C&E Europe as well as overseas, for export to the EU15. Imports make certain other options worth considering as well. These include:

- Tree plantations set up overseas for the import of fuel logs or chips,

256/ WB (2000).
258/ Rates calculated from data provided by Informare (2001).
• Liquefaction technology used with non-utilized or under-utilized types of biomass in developing countries, such as rice husks and sugar cane bagasse.

At the same time an insight was gained into the costs of supply. These costs are not the same as market prices, since these will depend on supply and demand. Therefore, one could be tempted to elaborate the analysis further, by preparing supply and demand curves for delivered biomass fuels. However, in view of the infinite array of possible technical development paths, such attempt seems inappropriate, although the existence of scenario studies suggests otherwise. In these studies different future situations are postulated, and, ideally, also the development paths towards such futures are made explicit. It seems possible to project an operational innovative technology, as well as a degree of its dissemination, as a component of at least one of such possible futures. In the context of such data, future demand and supply curves could perhaps be quantified and made part of such a projection. Whether it would make sense is doubtful though. This is because the developments in various technologies are not isolated events. They influence each other, and this makes technology scenario development, as soon as consistent technical detail is required, an arduous endeavour. The difficulty is illustrated here with respect to the technologies which form the subject of this thesis.

The demand analysis made in Section 4.2 showed that the European Union, on a policy level, aims at options for biomass-fuelled electricity production (co-combustion with coal) which will be obsolete by 2010-2024. Already by that period alternatives must be entering the commercial phase, if the policy of sustainable development is to be sustained. The most obvious future alternatives in the biomass energy sector are innovative technologies for biomass-fuelled CHP with a much lower heat/power ratio than currently technically feasible, biomass-fuelled stand-alone electricity plants as well as co-fired combined cycles (combining gas turbines with steam cycles). With all these innovative concepts, gasification or liquefaction processes are necessary links in the production chain. However, as soon as one considers the development of these technologies, new horizons open up in the field of transportation fuels. This is because gasification and liquefaction are not only suitable intermediate processes for the manufacture of electricity, they are also suitable for the production of liquid transportation fuels. The gaining of this understanding by policy makers, industries, and by technology researchers, has been one of the merits of the Dutch STD programme, previously discussed (Chapter 1), and its offspring, the Dutch GAVE programme. The implication is that commercial successes in biomass-fuelled electricity production, anticipated by 2010, may have an immediate impact on the EU’s policies with regard to block heating and district heating (with an associated reduced demand for pure electricity production as a result of the implementation of CHP technologies) and with regard to GHG-neutral liquid transportation fuels. Currently, the latter policy is focussed on methyl ester made from oil seeds. Later, dry (ligno-)cellulosic fuels may become a more attractive alternative raw material, the reason being the unfavourable energy balance and the high cost of oil seed cultivation. Given these uncertainties one must conclude that the gamut of potential technological futures, even within the context of any one scenario found in the studies referred to previously (Section

259/ See footnote 88.
This is not a plea against scenario studies, but rather against scenario elaborations into unjustified detail. It is not a plea against making assumptions either. Certainly, at least one scenario-like assumption is made in the further analyses: namely that the technologies considered will be used on a wide scale. If not, the further analysis is superfluous. Setting objectives for the development of biomass conversion technology, which is the subject of the next chapter, should preferably be done on the basis of a range of biomass costs. From the analysis carried out in the previous section, it appears reasonable to assume a cost range of 5-15 €/GJ. These figures are further explained in Table 28. Prices which will emerge on the market as a result of the supply and demand mechanism will naturally be different to those indicated.

Table 28. Cost approximations of several biomass types (€/GJ).

<table>
<thead>
<tr>
<th>Supplier's cost</th>
<th>Transportation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straw EU /a</td>
<td>0.0</td>
<td>3.3-6.7</td>
</tr>
<tr>
<td>Chips and particles EU /a</td>
<td>1.0</td>
<td>3.3-6.7</td>
</tr>
<tr>
<td>Miscanthus NL /a</td>
<td>8.5</td>
<td>2.8-5.6</td>
</tr>
<tr>
<td>Eucalyptus Uruguay /b</td>
<td>1.9</td>
<td>2.8-7.8</td>
</tr>
</tbody>
</table>

a/ Truck transport, 50-100 km at 1 €/(t.km).
b/ Possible fluctuations by a factor of 2 are assumed for the most expensive sea transports found from the long-term economic model reported by Wasser (1995).
5 A CONCISE EXPLORATION INTO TECHNOLOGIES FOR CENTRALISED BIOMASS-FUELLED ELECTRICITY GENERATION

The evaluation of technologies, and more specifically their development, for central biomass-fuelled electricity generation starts with a Design Assessment. Here, the candidate biomass conversion technologies are identified and physically characterised. First, biomass-based electricity generation is placed into the perspective of the prevailing technical context of central electricity production.

5.1 IDENTIFICATION OF THE ELECTRICITY GENERATION TECHNIQUES

The term ‘central’ is used here as the opposite of ‘captive’. Whereas the latter denotes electricity which is produced for self-sufficiency; centrally produced electricity is intended for distribution. The European electricity sector is currently being reorganised. Although the idealised objectives are to separate the sector into producers, transmitters, distributers, and end-users - each of which fundamentally enabled to enter into market-based relationships with the others - the political debate about the extent to which this goal should be realised, and about the appropriate regulations is not yet finalised. Neither do the developments in the various European countries keep pace with each other. Whereas, during the past 50 to 100 years or so, the electricity sector was largely governmental in most countries, today, the sector reforms in the United Kingdom, of all the European countries, are among the most market-oriented. Generally, therefore, the roles of those companies that are active in the electricity sector are not entirely clear. For example, it is possible for a so-called distribution company to own and operate a wood-fuelled electricity production plant (until 2000 PNEM/MEGA owned a 25 MW<sub>e</sub> plant located in Cuijk, the Netherlands). In everyday language such electricity production is often called ‘decentralised’. However, since the product is intended for distribution, the term ‘centralised’ would also be appropriate. Despite colloquial language varying from place to place, this type of electricity production, since it is intended for distribution, is deliberately included in the analysis here.

The capacity range considered is 3-300 MW<sub>e</sub>, based on the following considerations:

- Electricity producers active in the markets of IEA member countries show an interest in these capacities.
- Researchers have produced a number of evaluations of biomass power systems within this capacity range.

Base-load operation is a prerequisite, since it is the intention to make a substantial impact with biomass fuels for electricity production, substituting for fossil fuels.

*Conversion technologies for fossil fuels*

Technical concepts for energy conversion of fossil fuels (coal, oil and natural gas) are in principle also suitable - or can be made to be,- for biomass fuels. For example, as with coal, biomass can be burned in combustors integrated with a steam cycle. Concepts for the energy conversion of fossil fuels are briefly reviewed below since in the technical
development of biomass-fuelled technologies one should be able to learn from developments in fossil fuel conversion technology. To a large extent components are interchangeable between the two. At the same time it is recognized that some issues are specific to each fuel.\textsuperscript{260} However, note that the analysis of biomass-fuelled concepts is not focussed on the competition of these with their fossil-fuelled counterparts. It is rather about the competition between the alternative biomass concepts themselves within the context of two markets, namely:

- An electricity market which is currently mainly fed by large coal fuelled and nuclear power plants (in 1997 by 62%),\textsuperscript{261} and
- A market for reduced GHG emissions which is broader than the energy market alone.

Fossil-fuelled central electricity generation uses a range of mature and proven technological concepts. Yet technical developments have continued since the introduction of central power plants around the end of the 19th century.\textsuperscript{262} Today, the two major conversion technologies for fossil fuels are:

- Combustion integrated with a steam cycle (abbreviated here to CS). With this technology, in principle, the energy conversion is performed in two stages. First, the chemical energy contained in the fuel is turned into energy carried by steam in a furnace/boiler. Subsequently, the steam carried energy is converted into electricity by means of a steam turbine and generator.

- Combined cycle (abbreviated to CC) for gaseous or liquid fuels (natural gas, oil). In the combined cycle, the combustion furnace of the CS concept is replaced by a gas turbine. The steam cycle remains and is fed by the gas turbine’s exhaust gas. Using the gas turbine a so-called topping cycle is added to the CS technology. A topping cycle converts thermal energy to electricity at a higher temperature. Conversion efficiencies are therefore higher (this issue is discussed in more detail in Section 5.2).

Other technologies employed for central electricity production are the diesel engine for liquid fuels such as furnace oil, and the gas turbine for gaseous and liquid fuels. In industrialised countries these technologies are mainly used for peak load service. In such economies, because of the lower associated conversion efficiencies in combination with fuel costs, they are not appropriate for providing base load. Therefore they are less relevant for this investigation. In an attempt to take advantage of the higher efficiencies achievable with gaseous and liquid fuels using the CC concept, two different approaches for making this concept suitable for solid fuels are being followed. In one approach, the gas turbine is preceded by a gasifier. The resulting fuel gas is subsequently combusted and expanded in a gas turbine. Here, this concept is abbreviated to GCC.\textsuperscript{263} Typical fuels for the GCC technology are coal, petcoke and heavy oil (asphalt). Following another approach, the gas turbine is preceded by a pressurised solid fuel combustor. The

\textsuperscript{260/} Such as ash sintering behaviour, ash recycling opportunities, and fuel reactivity. A discussion of such issues is beyond the scope of the current investigation.

\textsuperscript{261/} OECD (1999a), p. 240.

\textsuperscript{262/} Zomers (2001).

\textsuperscript{263/} G denotes ‘gasification’. Alternatively, the expression IGCC is used in some literature, where I stands for ‘integrated’.
Pressurised combustion products are expanded in a gas turbine and drive a steam generator coupled to the turbine exhaust. Suppliers offering this type of plants, usually employ fluidised-bed combustors, and denote the concept with the acronym PFBC (for Pressurised Fluidised-Bed Combustion). In this systematic review of fundamental concepts, the acronym PCCC (Pressurised Combustion Combined Cycle) is preferred.

Coal-fuelled CS technology is the most widespread technology used in central electricity production. This is understandable in view of fuel availability and cost, as well as the cost and performance of electricity generation technologies. In the USA, 305 GW (41% of total installed capacity) consists of coal fuelled CS technology, whereas the gas fuelled CC technology provides only 15 GW (representing 2%) of the capacity. A similar situation can be estimated for the total of all IEA countries. Capacities of modern coal fired power plants are in the range of 500-1000 MW. Combined cycle power plants fuelled with natural gas or liquid fuels are also numerous and exist worldwide, mainly in the capacity range of 100-600 MW.

With the new GCC technology for solid fossil fuels, already several demonstration plants have been realised:

- Buggenum, Netherlands (253 MW), start-up 1993;
- Polk Country, USA (250 MW), start-up 1996;
- Wabash River, USA (262 MW), start-up 1996;
- Puertollano, Spain (300 MW), “under start-up” 1998;
- Piñon Pine, USA (100 MW), commissioned 1999.

The chemical industry is also showing an interest in the GCC concept. A few examples extracted from Stambler (1996) include: the 35 MW El Dorado plant (Texaco) which was commissioned in 1996, and, at the end of 1996, the construction of two 500 MW projects and of two 250 MW projects was about to be started in Italy (respectively the ISAB and SARAS plants, and the API and Agip Petrol plants). Their fuels are asphalt and visbreaker residue. One of the reasons why this industrial sector is establishing this type of technology is that the gas resulting from the gasifier can also be utilised as a synthesis gas in the manufacture of various chemical products. Thus, the technology offers flexibility as to the product mix of electricity, heat, and materials (and is therefore sometimes referred to as trigeneration).

There exist also several examples of coal-fuelled PCCC plants:

- The 70 MW Tidd Plant in Brilliant, Ohio (since 1990, American Electric Power).
- The 135 MW (combining two units) operated by Vartan (Sweden).
- The 80 MW unit of Escatron (Spain).
- The 71 MW unit of Wakamatsu (Japan).
- The 71 MW unit in Cottbus (Germany).
- The 360 MW unit of Karita (Japan).

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265/ Based on OECD (1999a), p. 240. Assuming an average capacity factor of 80% for all power plants, aggregate electric power capacity is estimated at 1200 GW.
266/ Campbell, McMullan and Williams (2000) and Scott and Nilsson (1999).
Reasons for the electricity sector to develop the GCC and PCCC concepts, as an alternative to CS, are both economic and environmental. The potentially higher energy conversion efficiency has already been mentioned above (however, the potential of further developing the CS concept towards higher energy efficiencies should not be overlooked; for a more thorough discussion see Section 5.2). Naturally, if driven by economic motives, the higher efficiency is evaluated in combination with other operational characteristics and the required investment. However, a higher energy efficiency also implies reduced GHG emissions per unit product. Further environmental advantages are the potential to achieve low SOx and NOx emissions at a lower cost than with the CS concept. Development of these innovative technologies is supported by the Clean Coal Centre of the IEA, and by development programmes in the EU (e.g. the ECSC Coal RTD Programme, Framework 4, and JOULE/THERMIE) and the USA (Clean Coal Technology Demonstration Program).

Conversion technologies for biomass fuels

Of the technical concepts for converting biomass into electricity, the CS concept represents the state-of-the-art. It is available in the range of 3-100 MW_e, and also with smaller capacities (but these are not relevant for this study). The electricity sectors in Denmark, Finland, Sweden, the Netherlands, and the USA have implemented biomass-fuelled CS technology in various power plants, often in CHP plants which produce both electricity and heat. With a capacity of 85 MW_e, the power plant of the International Paper Company (Pine Bluff, USA) is the largest operational 100% wood fuelled CS power plant in the world, producing electricity for the electricity sector. Indeed, the biomass-fuelled CS technology is most commonly installed by industries which provide their own fuels (residues), who entirely or partly utilise the electricity produced, and who have a use for the heat which is unavoidably produced in addition to the electricity. These circumstances apply, for example, to all the cane sugar and palm oil mills, worldwide, and the majority of these mills operate a CS energy plant. The Renewable Electric Plant Information System (maintained by NREL) reports that in the USA the aggregate capacity of this type of technology is about 7,200 MW_e. According to Bain, Overend et al. (1998) this concerns approximately 1000 plants, typically in the range of 10-25 MW_e. Captive electricity production is included in this figure.

The combined cycle (CC) concept is also a possibility for the conversion of biomass fuels. At least two principal options can be distinguished:

- Gasification followed by a gas turbine and a steam cycle (abbreviated here to GCC).
- Liquefaction followed by a gas turbine and a steam cycle (abbreviated here to LCC). (Liquefaction is a technology that produces a liquid fuel from biomass. In this study the product is referred to as ‘bio-oil’).

268/ Of this figure, 71 MW_e should be subtracted as it is in the form of co-firing capacity in coal-fired power plants, Porter, Trickett and Bird (2000).

269/ In some literature this concept is referred to by the acronym BIG/GT (see footnote 155), or by IGCC (see footnote 263).
A third option is pressurised combustion, followed by a gas turbine and a steam cycle. Although successfully utilised for the conversion of coal into electricity, this concept has received little attention in the biomass research community. Technology evaluations have gone as far as reviewing the biomass-fuelled GCC concept up to capacities of 100-200 MW. \(^{270}\) This is substantially smaller than the capacities demonstrated for coal-fuelled CC systems. The reason for this difference in size is not clear. To date, for biomass-fuelled GCC, a pilot phase has been reached, but demonstration projects have not been established. Current biomass-fuelled GCC pilot projects are reviewed in Table 29. The largest project planned has a capacity of 75 MW. R&D on the biomass-fuelled GCC concept is being carried out both in the EU and the USA (for reviews see Costello (1999) and Maniatis (1999)). External financial support is given by the EU, the World Bank, UNDP, and also by national governmental institutions such as the USA DOE, and the Dutch Novem.

The integration of biomass liquefaction with the combined cycle into the LCC technology is still at a conceptual stage. The technology was discussed by Solantausta (from VTT), Bridgwater (Aston University) and Beckman (Zeton Inc.) in Solantausta, Bridgwater and Beckman (1995) and, more elaborately, in Solantausta, Bridgwater and Beckman (1996). Further evaluations of the concept have yet to be published. The liquefaction component of the concept has passed the laboratory phase, reached the pilot phase, and is heading towards larger scale demonstration (see Table 30). A literature survey using the ETDE database\(^{271}\) of the IEA, and the science citation index, reveals that the very first R&D plans for the application of bio-oil in gas turbines were reviewed in 1994 by Andrews, Patnaik, Liu \textit{et al.} (1994). Only a few test results have been published, i.e. by Boucher, Chaala and Roy (2000), Boucher, Chaala, Pakdel \textit{et al.} (2000), and by López-Juste and Salvá-Monfort (2000). On April 2, 2001, the installation and commercial operation of the first bench-scale gas turbine (2.5 MW) operated on bio-oil was announced in a press release by Dynamotive, a company active in the development of pyrolysis technology. Although, for the companies involved, the project is about testing and demonstrating a commercial scale technology, it is only a bench-scale project in terms of the appropriate capacities for central electricity production discussed in this study. These developments are mainly financed by the EU, national governmental institutions, and the private sector companies involved.


\(^{271}\) ETDE = Energy Technology Data Exchange (www.etde.org/etdeweb/).
So far, the relevant technologies have been identified. The principles of their mutual relationships are indicated, as well as their current state of development. In the next section, their energy conversion efficiencies are investigated.

### 5.2 TECHNICAL FEASIBILITY AND CONVERSION EFFICIENCY

Although the reduction of environmentally harmful emissions such as SO\(_x\) and NO\(_x\) is also important in the further development of electricity generation technologies, a major driving force is the improvement of conversion efficiency. Although this pertains to fossil-fuelled generation technologies, it applies even more so to their biomass-fuelled counterparts. The reason is that SO\(_x\) and NO\(_x\) emissions - two environmental issues which deserve significant R&D attention in the case of fossil fuel conversion - are less problematic in the biomass conversion processes.

The CS and CC concepts, that convert chemical energy into electricity, belong to the category of thermal processes. To understand the efficiency developments of these concepts, a basic understanding of the conversion efficiency of thermal cycles is required and is therefore discussed here. Since the analyses of Carnot (1824) (although old, they

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**Table 29.** Review of GCC projects larger than 5 MW\(_e\) (Source: Beenackers and Maniatis (1998) and other contributions to the same issue of Biomass & Bioenergy).

<table>
<thead>
<tr>
<th>Name (Operator)</th>
<th>Country</th>
<th>Electrical capacity (MW)</th>
<th>Status 1998</th>
</tr>
</thead>
<tbody>
<tr>
<td>Värnamo (Sydkraft)</td>
<td>Sweden</td>
<td>6</td>
<td>Operational</td>
</tr>
<tr>
<td>Energy Farm (Biolettrica)</td>
<td>Italy</td>
<td>12</td>
<td>Construction</td>
</tr>
<tr>
<td>ARBRE (ARBRE Energy)</td>
<td>U.K.</td>
<td>8</td>
<td>Construction</td>
</tr>
<tr>
<td>North Holland (ENW)</td>
<td>Netherlands</td>
<td>30</td>
<td>Design</td>
</tr>
<tr>
<td>Maui (IGT)</td>
<td>Hawaii (USA)</td>
<td>5</td>
<td>Construction</td>
</tr>
<tr>
<td>Burlington</td>
<td>Vermont (USA)</td>
<td>15</td>
<td>Construction</td>
</tr>
<tr>
<td>Agripower (MAP)</td>
<td>Minnesota (USA)</td>
<td>75</td>
<td>Planned</td>
</tr>
<tr>
<td>WBPI/SIGAME</td>
<td>Brazil</td>
<td>32</td>
<td>Preparation</td>
</tr>
<tr>
<td>Biocycle (Elsam/Elkraft)</td>
<td>Denmark</td>
<td>7</td>
<td>Halted</td>
</tr>
<tr>
<td>Biocycle (Kotka Energy)</td>
<td>Finland</td>
<td>7</td>
<td>Halted</td>
</tr>
</tbody>
</table>

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**Table 30.** Review of biomass liquefaction projects

<table>
<thead>
<tr>
<th>Name (Operator)</th>
<th>Country</th>
<th>Thermal capacity (MW(_t))</th>
<th>Status 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTG</td>
<td>Netherlands</td>
<td>1</td>
<td>Operational</td>
</tr>
<tr>
<td>BTG</td>
<td>Netherlands</td>
<td>5</td>
<td>Design</td>
</tr>
<tr>
<td>BTG</td>
<td>Netherlands</td>
<td>10</td>
<td>Design</td>
</tr>
<tr>
<td>Dynamotive</td>
<td>Canada</td>
<td>2.5</td>
<td>Commissioning</td>
</tr>
<tr>
<td>Dynamotive (Border Biofuel) /a</td>
<td>U.K.</td>
<td>5</td>
<td>Planned</td>
</tr>
<tr>
<td>Dynamotive</td>
<td>Canada</td>
<td>7.5</td>
<td>Design</td>
</tr>
<tr>
<td>ENEL/Ensyn</td>
<td>Italy</td>
<td>3.1</td>
<td>Halted</td>
</tr>
<tr>
<td>Pyrovac</td>
<td>Canada</td>
<td>17.5</td>
<td>Operational</td>
</tr>
<tr>
<td>Red Arrow/Ensyn</td>
<td>USA</td>
<td>6.3</td>
<td>Operational</td>
</tr>
<tr>
<td>Red Arrow/Ensyn</td>
<td>USA</td>
<td>5</td>
<td>Operational</td>
</tr>
<tr>
<td>Vapo Oy (Fortum)</td>
<td>Finland</td>
<td>1.8</td>
<td>Planned</td>
</tr>
<tr>
<td>Wellman</td>
<td>U.K.</td>
<td>1.25</td>
<td>Commissioning</td>
</tr>
</tbody>
</table>

are not old-fashioned), it is known that the conversion efficiency of thermal processes is limited by the upper and lower temperature levels by which they are characterised, as follows:

\[ \eta_{\text{maximum}} = 1 - \frac{(T_{\text{sink}} - 273.15)}{(T_{\text{source}} - 273.15)} \]

where temperature levels are expressed in °C. The maximum possible efficiency, so expressed, can only be achieved by means of processes which, as a tribute to their inventor, are called Carnot cycles. A Carnot cycle consists of the following steps:

• Entropy is added to a medium at a constant high source temperature (by adding heat),
• The temperature of the medium is decreased at constant entropy, by extracting work from the medium.
• By extracting heat from the medium, at a constant sink temperature, the entropy of the medium is decreased.
• Finally, by performing work upon the medium, the temperature of the medium is increased at constant entropy towards the source temperature. In this manner the cycle is closed and can be repeated.

The net work (work output minus work input) resulting from a Carnot cycle is positive. The cycles for the CS and the CC concepts are different from the Carnot cycle, and therefore these concepts have a lower efficiency. However, precisely because the concept of the Carnot cycle is an ideal, a comparison of the CS and CC concepts with the Carnot cycle can provide an understanding of the ongoing developments with these concepts.

The first step carried out in thermal electricity-generation processes is to create a high temperature source by combusting fuel. When combusted with air, the maximum achievable source temperatures of fossil and biomass fuels are relatively close to each other at around 2000 °C.\(^{272}\) Assuming a minimum practical sink temperature of 60 °C, this would indicate a maximum possible efficiency of 85% (using the above equation). This figure is indicative for all conceivable thermal electricity-production processes. Practice is less favourable. In the CS concept, the following major concessions to this idealised position are made:

• The upper temperature of the recycled medium (water) is limited by the mechanics of heat exchanger materials (currently at about 540 °C). This has a major impact on efficiency since the temperature is reduced prior to any electricity being produced. At the indicated temperature level the maximum possible efficiency is 59%. That is to say, if the cycle were a Carnot cycle. But it is not; it is a so-called Rankine cycle, the major difference of which when compared with the Carnot cycle is that:

\(^{272}\) Under stoichiometric conditions the combustion of dry wood yields an adiabatic flame temperature of about 2100 °C, and furnace oil a temperature of approximately 2000 °C. This occurs despite the fact that, on a mass basis, the calorific value of wood is less than half that of furnace oil. The explanation is the difference in air requirements due to the presence of chemically bound oxygen in the fuel, able to react further. With the combustion of furnace oil, 2½ times more nitrogen gas - inert ballast taken from and returned to the air - is heated (on a fuel mass basis). For a detailed elaboration see Appendix E.
• The temperature at which heat is provided into the recycled medium is not constant but increases sharply with entropy.
• The entropy of the recycled medium increases during work extraction by the turbine, due to process imperfections (another deviation to the Carnot cycle).
• A substantial part of the chemical energy contained in the fuel does not contribute to operating the steam cycle, but is rather released at a relatively high temperature through the exhaust stack (increasing proportionally with the amount of excess air).

From this review the following technical development issues can be deduced:
• Improvement of heat exchanger materials allowing higher temperatures.
• Increasing the average upper temperature by applying regenerative feed-water preheating and steam reheat. This turns the Rankine cycle into a cycle which more closely approximates the Carnot cycle.
• Improvement to the aerodynamic properties of turbine blades and nozzles, to reduce entropy production during work extraction.
• Improvement of combustion technology to reduce stack losses.

Today, efficiency improvements for CS technology for the conversion of coal emphasises the first issue. Over time, research into the latter three has become less urgent.

The enormous efficiency loss as a result of temperature limitations in the steam boiler is considerably reduced in the CC concept since the gas turbine placed prior to the steam boiler accepts substantially higher temperatures (1100 to 1230 °C for industrial gas turbines and aeroderivatives respectively). On an overall level, the system’s Carnot efficiency, in comparison with the CS concept, is thus increased from 59% to 76%-79% (for this estimate, the steam turbine exhaust temperature is assumed to be 60 °C). The exhaust temperature of a gas turbine, if not placed in a combined cycle with steam, may be as low as 350 °C. However, integrated into a CC system this is changed, and the gas turbine exhaust temperature is set as a result of two considerations:
• What temperature is technically feasible for the steam generator? (An upper boundary is set by material properties).
• At what exhaust temperature is an optimum reached in terms of investment and efficiency?

For CC systems, Sheard and Raine (1998) report a gas turbine exhaust temperature of about 500 °C. General Electric offers CC power plants in which the gas turbine exhaust temperature is higher at 600 °C. If the gas turbine could operate as a Carnot machine, the temperature path of 1100 to 500 °C would allow an electricity efficiency of nearly 44%. In practice, the deviations of the gas-turbine cycle (Brayton cycle) from the Carnot cycle, and the imperfections in gas expansion and compression, limit the efficiency of the gas turbine to about 35%-38%. These efficiencies are already impressive and have been reached by modifications to the original Brayton cycle, by making use of recuperation and regeneration. As with the improvements to the Rankine cycle for steam, these are modifications to the Brayton cycle making it closer to the Carnot cycle. A combined gas

274/ Brooks (2000).
and steam turbine cycle, fuelled with natural gas or oil, is in rapid development. In 1996, reported overall efficiencies reached values of 49%-56%\textsuperscript{277} General Electric plans to offer these systems with efficiencies of up to 60% by the year 2003.\textsuperscript{278} A similar expectation is expressed by Taud, Karg and O’Leary (2000). Development of the CC technology is primarily focussed on improving turbine blade material and blade cooling so as to enable increased inlet temperatures. Particularly with coal-fuelled GCC, there is a parallel stress on improved integration of the gasifier and the steam cycle so that heat removed from the hot fuel gas\textsuperscript{279} can be utilised at the highest possible temperature, only limited by the steam generator materials. Through such considerations it is shown how efficiency improvement is a driving force in the technology development from CS towards CC for solid fuel application. At the same time it has to be recognised that this trajectory necessitates quite a number of development issues aimed at technical feasibility \textit{per se}, such as gas cleaning, and avoidance of turbine blade erosion and corrosion.

In the following sections, energy efficiency is elaborated upon in more detail for the three major biomass conversion concepts.

### 5.2.1 Efficiencies of biomass-fuelled Combustion-Steam cycles

Efficiencies of biomass-fuelled CS systems are shown in Figure 26. The data are taken from various surveys given in the literature,\textsuperscript{280} and a survey of manufactures offering plants with capacities up to 30 MW\textsubscript{e}. Energy efficiency increases with capacity. However, this increase is only partly technology dependent, and mainly a result of a cost/quality consideration taking place within the market in view of locally prevailing economic conditions. Those cost/quality considerations are also the reason for the wide scatter occurring for each capacity. In other words; at low capacities (e.g. 5 MW\textsubscript{e}), high energy efficiencies (e.g. 40%) are technically feasible, albeit at very high costs.

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\textsuperscript{277} Ramachandran and Conway (1996).
\textsuperscript{278} Chase and Kehoe (2000).
\textsuperscript{279} Cooling of the fuel gas, prior to combustion, is necessary to clean the gas of condensible ashes which would harm the gas turbine.
\textsuperscript{280} Williams and Larson (1993), Bridgwater (1995), Van den Broek, Faaij and Van Wijk (1995), and DeMeo and Galdo (1997). Where necessary, GCV efficiencies were recalculated to NCV efficiencies (for the procedure see Appendix D).
The various terms of the equation are further explained in Appendix D.


This thesis


This thesis

Bridgewater (1995)

Williams & Larson (1993)

Figure 26. Net energy efficiency of biomass-fuelled CS power plants.

The major parameters responsible for the low efficiencies in the lower capacity range are the applicable steam conditions and the commercial availability and cost of high-efficiency steam turbines. The influence of these parameters is derived from the following equation which describes the energy efficiency of a CS system:\textsuperscript{281}

\[
\eta_{\text{N, system}} = \eta_{\text{N, boiler}} \times \eta_{\text{M, turbine}} \times \eta_{\text{generator}} \times \frac{\eta_{\text{S, cycle}} \times \eta_{\text{S, turbine}}}{(\eta_{\text{S, cycle}} \% \eta_{\text{S, turbine}})} \times \eta_{\text{parasitic}}.
\]

This particular manner of making the steam cycle efficiency, \(\eta_{\text{S, cycle}}\times\eta_{\text{S, turbine}}\), explicit is unusual and derived in Appendix D. It makes it clear that the efficiency is built-up of a number of component efficiencies, placed in series with each other. The item that is the most sensitive to cost differences is the steam cycle efficiency, consisting of the isentropic cycle efficiency (\(\eta_{\text{S, cycle}}\)) and the isentropic turbine efficiency (\(\eta_{\text{S, turbine}}\)). In view of the remarks made above, about the Carnot efficiency, it is clear that the high-pressure steam temperature determines the first. The maximum reported high-pressure steam temperature in biomass CS systems is 538 °C. Most CS power plants have high-pressure steam temperatures as low as 420 °C.\textsuperscript{282} The costs are mainly influenced by material properties of the heat exchanger (alkalines in biomass pose specific fouling and corrosion difficulties). In Figure 27, the dependence of isentropic turbine efficiency on scale is shown. The lines show idealised relationships given by literature sources, the points are taken from manufacturers’ information. It is clearly shown that at lower capacities a

\textsuperscript{281} The various terms of the equation are further explained in Appendix D.

\textsuperscript{282} Bain, Overend and Craig (1998).
number of less efficient steam turbines are offered. However, on a capacity basis ($€/W_e$), they are significantly cheaper than the more efficient ones.

![Chart](chart.png)

**Figure 27.** Isentropic steam turbine efficiency. (Sources: 1) Orlando (1996), 2) Dietzel (1980), 3) Perry (1984), 4) this thesis).

Improvements to heat exchanger materials, mainly in view of the fouling and corrosion behaviour of biomass combustion products, aimed at obtaining elevated steam conditions at the high-pressure side is an important development issue with larger capacities (where this might be economically justified). But, given the characteristics of commercially available equipment and the impact of turbine efficiency on overall plant efficiency, it may be stated with confidence that steam turbine technology is fully mature. I disagree with the conclusion of Van den Broek and Faaij, that there is a significant potential for further development of steam turbine technology. Their conclusion is probably the result of not explicitly recognising the relevance of the steam cycle efficiency, as defined above.

### 5.2.2 Efficiencies of biomass-fuelled Gasification-Combined cycles

As reported in Section 5.1, there is little experience with biomass-fuelled GCC systems. However, there is a wealth of literature on the conceptual analyses of this type of system. Efficiency data for both theoretical and existing designs are summarised in Figure 28. For comparison, the efficiencies of coal-fired demonstration GCC plants, as well as those of

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283/ “If the turbine efficiencies of the selected plants are compared with theoretical maxima, it can be concluded that efficiency improvements in turbines is still possible from a technical point of view” (Van den Broek, Faaij and Van Wijk (1996), p. 280).
natural gas and oil-fuelled CC power plants, are indicated. Where necessary, GCV efficiencies were recalculated to NCV efficiencies (for the procedure see Appendix D).

Two biomass-fuelled GCC concepts can be distinguished:

- A gas turbine and a steam turbine integrated into a single turbo-machine (often abbreviated STIG, standing for steam injected gas turbine). Steam is released into the air and thus a constant flow of make-up water is required.
- A separate gas turbine and steam turbine (abbreviated to GAST). Here, the gas turbine’s exhaust gas is used to generate steam for expansion in a steam turbine placed in a separate condensing cycle.

Especially the STIG concept has received a lot of attention in forums of the United Nations, as it was proposed by Williams and Larson (1993) to the 1992 United Nations Conference on Environment and Development in Rio de Janeiro. Yet, the STIG concept remains an outsider since it does not fit in the general development course towards higher efficiencies. This is because the steam cycle used in the STIG concept is less efficient than in the GAST concept, primarily because:

- In GAST, steam pressures are higher than in STIG,
- In GAST, steam is expanded into a vacuum rather than to the atmosphere (as in STIG).

It cannot, however, be assumed that the STIG concept would not be a winning concept. All depends on, as is elaborated below, an optimisation of cost and quality. However, the

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STIG concept has not received sufficient attention from the R&D community to enable a balanced comparison of the various concepts. It is therefore excluded from further analysis here. For sake of completeness, however, Williams’ efficiency estimates are also depicted - without further evaluation - in the efficiency overview given in Figure 28.

As discussed in the introduction to this section, the efficiency of CC plants in current practice is limited to 49%-56%, with an expectation of a maximum of 60%. Since GAST is an extension of CC, there is no reason why GAST should perform any better than CC at any stage of technology development. In fact there is one issue which gives rise to an inherently lower efficiency with GAST. This is the fact that the fuel gas resulting from gasification needs to be cooled before being ignited in the gas turbine. Fuel gas cooling serves to precipitate out the alkalines present in virtually all biomass types to an extent which would harm the gas turbine if they were not removed. As yet, no alternative technical solution to this difficulty has been proposed. Although part of the heat thus removed can be used in the steam cycle (with proper integration of the steam cycle with the gasifier), the efficiency at which this is done is substantially lower than if the entire combined cycle could be used for the energy conversion. The same phenomenon is reported for coal fuelled GAST systems. Note that fuel gas cooling is not an unavoidable necessity in order to limit firing temperatures to technically feasible levels. If a turbine is fuelled by natural gas or oil, the same difficulty has to be faced to the same degree (flame temperatures of biomass made fuel gas are similar to flame temperatures of fossil fuels). With gas and oil-fuelled combined cycles, flame temperatures are controlled in ways which enable the use of the full cycle conversion. An example approach is gas dilution with air, water, or steam prior to, or during, expansion in the gas turbine.

A comparison of projected efficiencies for biomass-fuelled GAST systems and efficiencies of coal-fuelled demonstration units is also appropriate (for data see also Figure 28). As observed, the latter’s efficiencies are in the order of only 38%-45%, which is considerably lower than the efficiencies projected for biomass-fuelled systems. Projections reported in Scott and Nilsson (1999), based on experience with coal-fuelled demonstration units, anticipate future efficiencies of 47% and 51% for 365 and 555 MW_e systems respectively. One characteristic of the evaluated coal-fuelled GAST systems is the choice of oxygen as the gasifying medium instead of air (and thus there is a need for air separation - which consumes work). Note that this choice is not motivated by technical considerations (the Piñon Pine project is air-blown (referred earlier on page 159)). Rather, the choice of oxygen-blown gasification is based on an economic evaluation; with oxygen, the gasifier and heat exchangers for heat recovery prior to fuel gas cleaning are cheaper (since they are smaller). The efficiency loss due to power consumption in the air separation unit is 7-9%. Such losses can be avoided with air-blown GAST systems, whether fuelled by coal or biomass. With this argument in mind, one is encouraged to accept the efficiencies for the referred projected biomass-fuelled GAST systems despite

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285/ Bain, Overend and Craig (1998), Craig and Mann (1996), and DeMeo and Galdo (1997).
them being higher than the cited projections for oxygen-blown coal fuelled GAST concepts.

This assessment should be borne in mind when interpreting Figure 28. Efficiencies of biomass-fuelled GAST systems may be higher than those of similar coal-fuelled systems, but they should be lower than efficiencies of natural gas or oil-fuelled CC systems. The designs described in Faaij, Meuleman and Van Ree (1998) have extremely high efficiencies, much higher than those estimated by others. These are not impossible in terms of first principles, but in view of 1) the state-of-the-art and the development of CC technology in general and 2) gasification technology and system integration in particular; they seem to be somewhat optimistic.

Finally, with respect to the course of technology development, it can be concluded that, while GCC takes advantage of the achieved and forthcoming developments in CC technology, it is clear that the R&D priorities of those interested in the GCC concept should focus on the gasification technology and on improving the integration of the gasifier into the GCC system. In view of the large market for gas and oil-fuelled power plants, the development of CC technology will follow its own dynamics.

5.2.3 Efficiency of biomass-fuelled Liquefaction-Combined cycles

What is liquefaction?

Before focussing on the Liquefaction-Combined cycle, a brief introduction is given into the methods of oil manufacture from biomass. There are several ways in which a liquid fuel (bio-oil) can be made from biomass. A high-pressure/medium-temperature technology is hydrothermal liquefaction with a product sometimes known as ‘biocrude’. An alternative process, at low-pressure/medium temperature, is fast pyrolysis. The oil resulting from the latter process is often referred to as ‘bio-oil’. In view of the advanced development stage of fast pyrolysis, and the widespread involvement of technology developers, this section is further restricted to bio-oil manufacture. Fast pyrolysis differs from oil extraction from oil seeds (such as cotton seed and rape seed); both the product and the yields are entirely dissimilar. Whereas the vegetable oil extracted from oil seeds mainly consists of fatty acids, the main constituents of bio-oil are fragments of cellulose, hemicellulose and lignin polymers. Further, whereas oil extraction is limited to the oil already present in plant material, the fast-pyrolysis process converts the entire biomass matter. This is achieved by applying a rapid temperature rise from ambient to about 500 °C. The reaction takes place in the absence of oxygen. In this manner the biomass is split into three components:

- Bio-oil.
- Pyrolytic gas.
- Charcoal.

After completion of the desired reactions, the products are quickly quenched to prevent further reaction. The bio-oil is condensed by cooling, and it contains the majority of the water present in the biomass prior to the reaction, as well as most of the water formed during the pyrolysis reaction. Some water remains in the vapour state and remains in the
pyrolytic gas. The charcoal is also separated out. The mass and energy flows of the fast-pyrolysis process are important in the assessment of the efficiency (and the technical feasibility) of the LCC cycle investigated in this section. However, even the most recent literature on fast pyrolysis does not report mass and energy balances at the level of the constituting chemical compounds and the chemical elements.\textsuperscript{290} Based on the available data it can be concluded that the precise mass distribution, physical characteristics and energy balances are strongly dependent on the processing equipment and processing conditions. It is also clear that a consensus is being developed towards certain bio-oil qualities\textsuperscript{291} and, therefore, towards necessary processing conditions such as temperature levels and reaction periods. At the same time, some variety in processing technologies remains. With some technologies the pyrolysis gas is diluted with air, in others with combustible gases, and in others again they are not diluted at all but recovered in a pure form. Without entering into the details of particular processes, it is possible to prepare a representative (indicative) mass and energy balance on the level of the macroscopic material flows. These are given in Table 31. A more detailed elaboration is given in Appendix D.

If the charcoal is used for heating the plant (as in the process developed by the University of Twente and BTG), then the bio-oil and the pyrolytic gas are available for electricity production. Larger liquefaction plants of this type would be more energy efficient than smaller ones and therefore some of the charcoal would be available as a by-product. On the basis of bio-oil and pyrolysis gas only, the energy efficiency of a liquefaction plant reaches 78%. This is a proven lower boundary. Alternatively, in some concepts (e.g. the one developed by Ensyn), part of the gas is used to provide the plant with heat, thus placing the focus on oil and charcoal production.

\textsuperscript{290} See Bridgewater, Csernink, Diebold \textit{et al.} (1999), Bridgwater and Peacocke (2000), and Meier and Faix (1999).

\textsuperscript{291} These qualities include calorific value and moisture content.
By limiting the potential conversion cycles to these two only, the use of any potential charcoal surplus for electricity production is ignored.

Efficiency

Concepts for the Liquefaction-Combined cycle (LCC) include two options:

- Liquefaction of biomass, immediately followed - on a single site - by further conversion of the bio-oil and the pyrolytic gaseous by-product, in a gas-turbine/steam power plant, into electricity.
- Liquefaction of biomass, followed by on-site conversion of the pyrolytic gaseous by-product in a gas turbine or gas engine. The bio-oil is transported to a large-scale CC power plant for further conversion into electricity.

The essential difference between the two is the transport of bio-oil which takes place in the second option. A future preference for one of the two options might be motivated by economies of scale (an issue to be addressed in Chapter 6). For example, it could be imagined that the liquefaction plant and the gas-to-electricity conversion plant of the second option is relatively small, and the oil-to-electricity conversion plant relatively large (utilising the oil produced at multiple liquefaction plants). Hence the suggestion of a gas turbine or gas engine for the gas-to-electricity conversion plant of option two, even though a combined cycle is conceivable for the small power plant. Solantausta, Bridgwater and Beckman (1996) appear to be the only authors who have carried out a techno-economic study of LCC. They did not consider the option of using the pyrolysis gas in the combined cycle, but limited the fuel conversion to the bio-oil only. Further, they did not incorporate a bio-oil production unit, with the potential of also producing electricity, in their study.

Table 31, Indicative mass and energy balances of biomass liquefaction (assuming non-diluted pyrolysis gas).

<table>
<thead>
<tr>
<th>Mass balance</th>
<th>g/w wood</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>1.00</td>
<td>10%</td>
</tr>
<tr>
<td>Oil</td>
<td>0.68</td>
<td>20%</td>
</tr>
<tr>
<td>Charcoal</td>
<td>0.09</td>
<td>0%</td>
</tr>
<tr>
<td>Gas (undiluted)</td>
<td>0.24</td>
<td>0%</td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
<td>100%</td>
</tr>
</tbody>
</table>

This energy balance does not take work inputs (electricity) into account. This balance assumes a non-diluted pyrolysis gas. It has a net calorific value of about 11 MJ/Nm³. If the gas is diluted with another gas, the associated energy becomes available in a diluted form. In some liquefaction processes (certain fluid bed technologies), the dilution gas is air. Also natural gas has been proposed. Dilution does not necessarily prevent utilisation of the pyrolysis gas in engines or turbines.

Energy balance (NCV)

<table>
<thead>
<tr>
<th>In J/gw wood</th>
<th>Out J/gw wood</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>16400</td>
<td>67%</td>
</tr>
<tr>
<td>Oil</td>
<td>10900</td>
<td>16%</td>
</tr>
<tr>
<td>Charcoal</td>
<td>2600</td>
<td>13%</td>
</tr>
<tr>
<td>Gas (undiluted)</td>
<td>2100</td>
<td>7%</td>
</tr>
<tr>
<td>Heating energy</td>
<td>-500</td>
<td>-3%</td>
</tr>
<tr>
<td>Pyrolysis reaction energy</td>
<td>40</td>
<td>0%</td>
</tr>
<tr>
<td>Radiation from reactor wall</td>
<td>50</td>
<td>0%</td>
</tr>
<tr>
<td>Total</td>
<td>16400</td>
<td>100%</td>
</tr>
</tbody>
</table>

Values may not add due to rounding errors. This balance assumes a non-diluted pyrolysis gas. It has a net calorific value of about 11 MJ/Nm³. If the gas is diluted with another gas, the associated energy becomes available in a diluted form. In some liquefaction processes (certain fluid bed technologies), the dilution gas is air. Also natural gas has been proposed. Dilution does not necessarily prevent utilisation of the pyrolysis gas in engines or turbines.
One study, exploring the technical issues and options for the use of bio-oil in gas turbines, was found (Moses and Bernstein (1994)). In addition to theoretical considerations, and experience with ordinary gas turbine fuels, the study relies on a single experiment with bio-oil in the early 1980s. Since then, no further experiments appear to have been reported. The use of pyrolysis gas in gas turbines appears not to have been investigated at all. The lack of literature on the conversion of bio-oils and pyrolysis gas into electricity by means of LCC systems, makes it necessary to review some of the relevant issues here on the basis of theoretical considerations alone.

There is no principal limitation to the use of bio-oil and pyrolysis gas in gas turbines, or, in other words, gas turbines can be designed such that the use of these fuels is technically feasible. The question then becomes what efficiencies can be reached. It is reasonable to assume that if blades and nozzles are designed appropriately using state-of-the-art knowledge of fluid mechanics and materials engineering, expansion efficiencies will be of the same order of magnitude for each fuel type. However, differences can be expected for the energy inputs required at the compressor side. These inputs concern the pressurised fuel feed as well as the compression of combustion air (the quantities of which may differ for each fuel). The conclusion is that, in principle, specifically optimised gas turbine designs for different fuel types will show varying efficiencies. A more detailed investigation goes beyond the scope of this analysis. Instead, an different approach is chosen by investigating to what extent existing gas turbine designs are capable of accommodating these fuels and what adaptations to existing gas turbine designs would be necessary.

Existing gas turbine designs are generally for distillate oils (aircraft engines), natural gas or lower quality furnace oils (the latter two fuel types are used in industry and central electricity production). Whereas distillate oils and natural gas do not carry or form ashes during combustion, lower quality fuels do, and therefore the gas turbines used for so-called ash-bearing fuels are specifically designed with respect to corrosion resistance of blade and nozzle materials. Also maintenance schedules are specifically adapted. Ash is also an issue in the use of bio-oil and pyrolysis gas in gas turbines. In addition, for the application of these fuels in existing gas turbine concepts, differences in gas flow characteristics (relative to the design fuels) will be important, both in the compressor section and in the expander section of a gas turbine. Due to different gas flow characteristics, the use of off-design fuels in existing equipment may result in changing efficiencies and in re-rating (if capacities are reduced, we speak of derating). In the explorative study reported by Moses and Bernstein (1994) a number of other technical issues relevant to the technical feasibility of employing bio-oil were identified. However, for the evaluation of the conversion efficiency, the focus of this section, they are not relevant. In Appendix E, both ash and gas flow issues are further investigated. With regard to ash, it is concluded that, at this stage, nothing more can be said than that ash

294/ Palmer and Erbes (1994).
295/ The study by Moses and Bernstein (1994) is recommended to those who are interested in further developing the technology of bio-oil and pyrolysis gas fuelled gas turbines. Their review covers a broad range of topics, although no attention is given to the balance of gas flows in the compressor and the expander. The study is also slightly biased in favour of gasifier-produced gas due to the availability of data (a fact which is rightly acknowledged by the authors).
deposition is a potential difficulty. It is unlikely that the solving of this potential difficulty will call for solutions which consume power or otherwise have an impact on conversion efficiency. Neither do the differences in gas flows provide firm indications of a reduced efficiency when utilising bio-oil or pyrolysis gas in an existing turbine. Therefore, the efficiencies achieved in existing gas turbine designs are assumed in the further elaboration of the LCC cycle, below.

At this stage of technology development, equipment manufacturers and scientists are clearly not able to reliably predict the performance of bio-oil and pyrolysis gas in existing gas turbine concepts. From the properties assessed, it is concluded that evaluations of alternative fuels for existing turbine designs should include the following issues:

- The technical feasibility of employing off-design fuels with particular emphasis on:
  - Potential ash deposition and corrosion (including eventual consequences for power plant availability).
  - The matching of compressor loads with expander loads (including consequences for capacity rerating).
- The efficiency of existing gas turbine designs when fuelled with alternative fuels (in view of specific expanded mass flows).

Finally, some energy consumption by the liquefaction plant (a parasitic load) should be incorporated in the efficiency determination of LCC cycles. Such consumption is required for fuel preparation (heat energy for drying, electricity for size reduction) and operation of the liquefaction reactor. The quantities of these energy flows are dependent on the specifications of the biomass intake and on the particulars of the selected liquefaction technology. In the systems analysis carried out in Chapter 6 (Section 6.3), feed-related energy consumption is taken into account. As for the liquefaction reactor, its heat balance has already been discussed earlier. For its electricity consumption, which will depend on the type of reactor, an amount of 0.003 MWhₑ per GJ of biomass intake (on an NCV basis for a feed with a moisture content of 10%, wet basis) is a reasonable estimate. This enables us to make a preliminary estimate of system efficiency for the LCC cycle, for use in the subsequent analysis. This is depicted in Figure 29, and is based on efficiencies reported for natural gas and mineral oil fuelled CC power plants,\(^{296}\) as well as on the energy balance shown in Table 31 and the estimated parasitic load.

5.2.4 Summary

A summary of efficiencies for the CS, the GCC (GAST), and the LCC, concepts is provided in Figure 30. The extreme data for GCC plants given in Faaij, Meuleman and Van Ree (1998) were omitted for the reasons discussed in Section 5.2.2. Note that two data sets are given for the LCC cycle. One concerns electricity production from biomass...
(single site processing), the other electricity production from bio-oil. The latter appears higher since the liquefaction process is placed outside the system boundaries. The reason why, for large capacities, the efficiency for single-site LCC plants is lower than for GCC plants, is the charcoal yield of the pyrolysis technique. Since charcoal cannot be converted in a gas turbine, the overall system efficiency could be enhanced by integrating a pulverised fuel furnace into the steam component. Conservatively, and underestimating the LCC potential, this option is not taken into account in the further analysis.

With each technology a trend is observed, that conversion efficiencies increase with plant capacity. The reason is that higher efficiencies can be achieved economically with larger power plants. This is related to the costs of manufacturing technology and is one of the economy of scale effects. (For example, on a cost per capacity basis ($/MW_c$), it is cheaper to make a large efficient turbine than a smaller turbine of the same efficiency).

A second observation, for each technological concept individually, is the wide range of efficiencies applicable to each power capacity (a scatter along the ordinate). This is understandable. Technologies are flexible to the extent that, for each particular capacity, varying efficiencies are the result of different system specifications. Therefore, efficiencies which do not lay on the trendlines are not incorrect (a number of efficiency data not located on the trendline for biomass-fuelled CS systems refer to existing power plants). The trendlines represent nothing more than a characteristic of an average power plant. One would expect the associated costs for a single plant capacity to vary with the efficiency. At least, that would apply in a rational market, and it is indeed true for the market for biomass-fuelled CS systems which is established up to capacities of about 100 MW_c. The relationship between plant capacity, estimated plant cost, and estimated efficiency, is less clear for technologies which are not yet mature, such as the GCC and LCC concepts. Certainly, if cost estimating would be done on a uniform basis, one would expect a consistent relationship between these three parameters - also in future projections. In practice such a basis has not been established. Particularly with regard to the biomass-fuelled GCC technology this was reported by Bain, Overend and Craig (1998). Obviously, plant costing itself is not the issue here; the point is that if a market for these electricity production concepts develops, then so will rational relationships between capacity, efficiency and costs. So, by adding the trendlines to Figure 30 the following are achieved:

- For any relevant plant capacity, a conversion efficiency is provided which is representative of the capacity concerned.
- Over a range of plant capacities, a coherent relationship (rational in view of plant cost and efficiency) between plant capacity and conversion efficiency is found.

These relationships are employed in the assessments carried out in the following chapter. Since the CS technology is mature, its efficiency trendline represents the existing market. It is possible to build CS power plants with higher or lower efficiencies than indicated for each individual capacity, but then the investment levels will differ from those to which the capacity/efficiency-trendline applies (these cost levels are discussed in Chapter 6, Section 6.2.1). For biomass-fuelled GCC plants, the trendline represents the average of what has been estimated by a number of respected researchers. Unfortunately this cannot be said for the trendline postulated for the LCC concept. Here we are relying on the technical analysis made in this thesis. Hence, for biomass-fuelled GCC and LCC plants, the
indicated trendlines *postulate* a relationship between capacity, efficiency and cost (and costs for these concepts are investigated in the next chapter). Within boundaries determined by technical constraints, and taking into account the consequences on costs, it will be possible to deviate from the postulated capacity/efficiency-trendlines for GCC and LCC plants. The trendlines, however, serve as working hypotheses in the analyses carried out in the following chapter.
In the preceding chapter, several alternative technologies were identified for central biomass-fuelled electricity generation. The ones investigated here are:

- **CS**: Combustion followed by a steam cycle;
- **GCC**: Gasification followed by a combined Brayton-Rankine cycle;
- **Single-site LCC**: Liquefaction followed by a combined Brayton-Rankine cycle for further conversion of the bio-oil and the pyrolysis gas;
- **Multiple-site LCC**: Liquefaction followed by a combined Brayton-Rankine cycle for further conversion of the bio-oil.

The main objective of this chapter is to identify which technology developments are necessary in order to create sufficient opportunities for these concepts to become viable alternatives in the market for central electricity production. Of the above concepts, the CS technology is mature, commercially available and used in many places (see Chapter 5). This technology, therefore, serves as a baseline. In accordance with the methodology elaborated in Chapter 3, the alternative technologies, in order to become feasible, have to perform better than CS, and additionally meet absolute feasibility criteria. The evaluation is carried out in the form of a number of case studies for capacities of 10, 30, 90, 270 MWₑ, all within the range identified earlier (3-300 MWₑ, page 157). These cases were selected in accordance with the preferred numbers of the Renard series.

In view of the methodology detailed in Chapter 3 (see Table 13), technology and site parameters need to be specified. The technology parameters are specified in the relevant sections below, one for each technology. The site parameters are independent of the technology, and therefore discussed first.

### 6.1 SITE PARAMETERS

Some site parameters are specified in Table 32. This selection of parameter values clearly reflects the situation in OECD countries. Of course there may be large fluctuations among these countries in operator costs and the costs of consumables. However, such cost types have only little influence on the total costs of electricity production, as will be seen during the course of the analysis.

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297/ In this alternative, the gaseous by-product of the liquefaction process is used at the presumed small-scale liquefaction plant.

298/ By applying a Renard series, the consecutive capacities in the array show a constant relative ratio to each other (here: 3). Internationally, Renard series are recommended for technical evaluations of broad ranges of such factors as volumes, tolerances and dimensions, and also power capacities. Renard series are standardized under ISO 3:1973 (Preferred numbers - Series of preferred numbers), ISO 17:1973 (Guide to the use of preferred numbers and of series of preferred numbers) and ISO 497:1973 (Guide to the choice of series of preferred numbers and of series containing more rounded values of preferred numbers).
Four more site parameters were distinguished in Chapter 3:

- Unit electricity sale price.
- Unit GHG emission reduction sales price.
- Unit biomass fuel cost.
- Discount rate.

Being true site parameters, these vary strongly from place to place and are treated as true variables in the analysis. Their assumed values are indicated in Table 33.

<table>
<thead>
<tr>
<th>Table 32. Some site parameters for central electricity generation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project life time</td>
</tr>
<tr>
<td>Capacity factor (CF) /a</td>
</tr>
<tr>
<td>Based on:</td>
</tr>
<tr>
<td>Operational period (OP)</td>
</tr>
<tr>
<td>Planned maintenance during OP (PM)</td>
</tr>
<tr>
<td>Availability factor during (100%-PM)*OP</td>
</tr>
<tr>
<td>Load factor</td>
</tr>
<tr>
<td>Not applied (compare Table 13):</td>
</tr>
<tr>
<td>Unit operator costs</td>
</tr>
<tr>
<td>Unit consumable costs</td>
</tr>
</tbody>
</table>

Instead:

<table>
<thead>
<tr>
<th>Capacity (MWa)</th>
<th>10</th>
<th>30</th>
<th>90</th>
<th>270</th>
</tr>
</thead>
<tbody>
<tr>
<td>General operator costs (€/kWh)</td>
<td>0.0055</td>
<td>0.0040</td>
<td>0.0028</td>
<td>0.0020</td>
</tr>
<tr>
<td>General consumable costs (€/kWh)</td>
<td>0.0025</td>
<td>0.0018</td>
<td>0.0013</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

a/ For definitions of the parameters CF, OP, PM and load factor, see Appendix F.

The sales price of pure electricity corresponds to the basic compensation paid in the Netherlands to any electricity producer, irrespective of whether it is for GHG-neutral electricity or not. Also the discount rate of 10% seems a reasonable assumption for the sector in European countries. The range of biomass fuel costs starts with a negative value. This is largely for theoretical reasons, since insights may be gained for such negative prices. Usually, biomass fuel prices are positive.299

The selection of ERU values has, as will become apparent in the course of the analysis, a large influence on the results, and the range of available estimates is quite broad. In Table 34, the actually prevailing value applicable for Dutch domestically produced

299/ See the discussion about fuels, wastes and renewable energy in the Introduction to Part B of this Thesis, p. 113.
GHG-neutral electricity is calculated at 65 €/t CO₂-eq. Other indications of current ERU values can be derived from the Dutch ERU tenders for JI and CDM, opened in the course of 2000 and 2001. The Dutch JI tender for the year 2000 resulted in an average ERU value of 8.75 €/t CO₂-eq. Further indicators for prevailing values can be obtained from the Prototype Carbon Fund managed by the World Bank. In fact, however, we are interested in ERU values applicable after the new technologies have been developed, i.e. about 10 years onwards, followed by the period of new technologies’ economic lifetime. As already stated in Chapter 1, the rational analyst who also assumes that society is perfectly rational and fully informed would base his value estimates on an economic analysis of the global climate change issue. Initial attempts at such an evaluation were made in the early 1990s, and these were further integrated by the IPCC in its Second Assessment Report of 1995. With the Kyoto Protocol (1997), the international ERU market has taken off, and the implications of the Protocol, together with the uncertainties around its implementation, actually make an objective scientific assessment less meaningful in the short term. Among the uncertainties one should consider is the eventual future participation of the USA, and the pool of participants in an ERU market. How the ERU market will develop after 2010 is a matter of speculation, but it is not unreasonable to construct a scenario on the basis of the current perspectives of the Kyoto Protocol, the assumption being that either there will be no ERU market after the end of the current term of the Kyoto Protocol, or there will be a market resembling the current one.

Some 20 recent studies on the future ERU market were reviewed for UNCTAD by Morozova and Stuart (2001). The target year for which demand and supply curves were determined was 2010. ERU values reported varied between 26-77 1998 US$ (Table 35). This is similar to the range selected for this study (Table 33). The wide range is a result of the uncertainties attached to the Protocol. The equivalent value in terms of €/kWh is also indicated. This is based on the unit-specific emission coefficient $\rho$ as defined in Section 3.2.1. At any moment in time, this parameter is independent of the quantity of renewable electricity produced within a country or by a producer, since it represents the GHG emissions of the replaced electricity that would have been produced from fossil fuels. (Taking the Netherlands in 1998 as an example, Table 34 determines $\rho$ at 0.65 t CO₂/MWh.) Several developments within the electricity sector may result in changes to the unit-specific emission coefficient for fossil-fuel based electricity generation over time, e.g.:

- An increased use of less carbon intensive fossil fuels (natural gas instead of coal);
- An increased use of combined heat and power (CHP);
- An increase in conversion efficiencies for fossil fuel-based generation technologies.

The assumption is made here that the impact of such changes on the value of the unit-specific emission coefficient will be negligible.

One possible refinement to the assessment is to also take into account the fact that biomass fuel transport results in increased GHG emissions. This issue was already raised in

300/ Based on data provided by SEP (1999).
301/ http://www.senter.nl.
302/ Pearce, Cline, Achanta et al. (1995).
303/ See also the discussion on this issue in Section 1.3.2.
Chapter 3, and effectively the quantity of ERUs per unit of electricity produced is reduced. Where relevant the matter is discussed separately in the following sections.

Table 34, Calculation of the ERU value in the Netherlands for 1999/2000.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emission (annual) by Dutch electricity producers /a</td>
<td>38750000 t CO₂/yr</td>
</tr>
<tr>
<td>Fuel mix consumed (on NCV) by Dutch electricity producers /a</td>
<td>510067 TJ/yr</td>
</tr>
<tr>
<td>Electricity production by Dutch electricity producers /a</td>
<td>60000 GWh/yr</td>
</tr>
<tr>
<td>Specific CO₂ emission</td>
<td>0.076 t CO₂/GJ₁</td>
</tr>
<tr>
<td></td>
<td>= 0.65 t CO₂/MWhₑ</td>
</tr>
<tr>
<td>NCV efficiency</td>
<td>42%</td>
</tr>
<tr>
<td>Dutch CO₂ Tax (REB), average returned to GHG neutral producers /b</td>
<td>0.0427 Fl/kWh</td>
</tr>
<tr>
<td></td>
<td>= 0.0194 €/kWh</td>
</tr>
<tr>
<td></td>
<td>= 30 €/t CO₂</td>
</tr>
<tr>
<td>Dutch price of Green Certificates /b</td>
<td>0.05 Fl/kWh</td>
</tr>
<tr>
<td></td>
<td>= 0.0227 €/kWh</td>
</tr>
<tr>
<td></td>
<td>= 35 €/t CO₂</td>
</tr>
<tr>
<td>Total REB + Green Certificates</td>
<td>0.042 €/kWh</td>
</tr>
<tr>
<td></td>
<td>= 65 €/t CO₂</td>
</tr>
</tbody>
</table>

a/ Source: SEP (1998)
b/ Source: Ekogas, trader in Green Certificates (verbal communication, 2000).


<table>
<thead>
<tr>
<th>Domestic abatement</th>
<th>Annex 1 JI and trade</th>
<th>CDM</th>
<th>Permit based global trade</th>
</tr>
</thead>
<tbody>
<tr>
<td>77</td>
<td>37</td>
<td>30</td>
<td>26</td>
</tr>
</tbody>
</table>

Having selected site parameters, the technology parameters are now established in the respective sections dedicated to the evaluation of the various alternative biomass-fuelled concepts.

6.2 GASIFICATION - COMBINED CYCLE CONCEPTS

In this section, the development perspective for biomass-fuelled GCC is investigated by comparing it with biomass-fuelled CS technology. The latter technology is not the subject of the analysis, but merely serves as a reference technology.

6.2.1 GCC technology parameter values

For all the capacities under investigation, the technology parameters are specified below. The most straightforward ones are shown in Table 36.
Sources consulted include a specific investigation into the market for plants offered in the capacity range of 6-30 MWₑ, carried out in close collaboration with dr. ir. P. Onaji (Ahmadu Bello University, Zaria, Nigeria, and BTG) and ir. R. Ellenbroek (BTG), as well as Williams and Larson (1993), Bridgwater (1995), Van den Broek, Faaij and Van Wijk (1995) and DeMeo and Galdo (1997).


For the efficiencies, the trendlines derived in Section 5.2.4 are used. Estimating the investments needed for constructing a CS power plant, since the technology is already available in an established market in the capacity range up to 100 MWₑ, is not too complicated, although some extrapolation to larger capacities is required. Cost data are shown in Figure 31. To make cost estimates comparable, the scopes of the cost items covered should be the same, or, if they are not, they should be normalised. Unfortunately, not all the quoted sources are fully explicit. The data quoted from Van den Broek, Faaij and Van Wijk (1995) and DeMeo and Galdo (1997), as well as the data specially collected, concern installed and commissioned power plants, but exclude land. The systems include biomass storage and handling systems as well as electricity generators, transformers and protection systems. Conventional exhaust gas cleaning equipment, needed to comply with European and USA regulations in the power sector, are assumed. Where the base years of quoted cost estimates differ, they were recalculated to the year 1998 by making use of the Chemical Engineering Plant Cost Index published in the journal on Chemical Engineering. This enabled the establishment of an approximative relationship between plant capacity and cost. As observed, the generally established rule in cost engineering, i.e. that the capacity specific investment costs decrease with a power function of the shape ‘C⁻¹’ (where C is capacity, and s is usually in the range 0.4-1), does apply. Here the value of s is about 0.76.
Consistent cost estimating for the biomass-fuelled GCC concept is more complicated. In the first place a large range of costs are found in the available sources. In principle they do not cover the entire capacity range studied here, and neither are their data based on investigations into established markets. Therefore one should not be surprised that the consistency found with CS technology is not encountered. Moreover, as already noted in Section 5.2.4, a common basis for cost estimating has not been established by the various researchers. However, cost data are available for the first biomass-fuelled GCC pilot projects and also for coal-fuelled GCC demonstration projects. As a first approach therefore, a similar cost vs. capacity relationship as found with biomass-fuelled CS, fitted through measured data points of existing biomass-fuelled GCC projects, is a defensible approach. This yields the estimates shown in Figure 32.

---

307/ Data sources for biomass-fuelled GCC were: De Lange and Barbucci (1998), McGowin, Hughes and Holt (1998a), ARBRE (1998), Salo, Horvath and Patel (1999). Cost data on coal-fuelled GCC power plant are quoted from DOE (2000a) and Holt and Burgt (1999). Cost for natural gas-fuelled combined cycles (NG-CC) originate from Sheard and Raine (1998). In constructing Figure 32 it was assumed that the same system boundaries apply as those for the CS technology indicated above. All data were converted to 1998 € by means of the Chemical Engineering Plant Cost Index.
In this way the following relationships have been established:

- For CS:
  \[ \text{Investment (€)} = 4.85 \times 10^6 \times \text{Capacity (MW}_e\text{)}^{0.763} \]

- For GCC:
  \[ \text{Investment (€)} = 7.42 \times 10^6 \times \text{Capacity (MW}_e\text{)}^{0.763} \]

Just as with the relationships found for efficiencies (Section 5.2.4), one should be aware that they represent average power plants. Deviations from the trendlines will occur. Secondly, one should note that the trendline for GCC projections is based on estimates for first-of-a-kind power plants. Since not a single project has been commissioned, the actual investment costs of such projects are not known. It is not unreasonable to expect that there is scope for cost reductions in the construction of the next generation of biomass-fuelled GCC power plants. What is analysed in the following sections is not so much the magnitude of this scope, but rather the necessary cost reduction in GCC technology for it to become of interest for sustainable electricity production. Once that required cost reduction has been determined, an investigation into the potential for meeting that reduction is obviously of importance.

### 6.2.2 Feasibility conditions for biomass-fuelled GCC

Using the parameters identified here, the results depicted in Figures 33-36 are determined using the algorithm described in Chapter 3.
Figure 33, 10 MW: Feasibility niches for CS and GCC concepts.

Figure 34, 30 MW: Feasibility niches for CS and GCC concepts.
Figure 35, 90 MW: Feasibility niches for CS and GCC concepts.

Figure 36, 270 MW: Feasibility niches for CS and GCC concepts.
Conclusions drawn from Figures 33-36 are summarised in Table 37. They concern both the existing CS technology and the new GCC technology. For example, if ERU values only reach the relatively low level of 30 €/t, it is seen that biomass-fuelled power plants with capacities of 30 MWₑ are only feasible with fuel prices below 11 €/t (equivalent to 0.8 €/GJ). At those fuel prices CS, rather than GCC, is feasible. Overall, it is found that at the current investment levels for the GCC concept, the technology is only feasible for capacities larger than 90 MWₑ, and then with the condition that ERUs become as valuable as 90 €/t.

The evaluation assumes that revenues for avoided GHG emissions are recovered by the electricity producer rather than by the biomass fuel provider. This makes a difference, as elaborated below.

The impact of ERUs on technology preferences

Before analysing potential and required capital cost reductions, the impact of ERU sales - their value and the primary recipient - on technology preferences is investigated. ERU sales are financial cashflows, paid by governments, which in principle may benefit any or all of those involved in the production of ERUs, i.e. producers of sustainable electricity as well as the preceding production chain starting with the biomass producers. To what extent particular actors actually benefit will depend on the primary recipients of ERU revenues as well as on their market position. If governments buy ERUs from electricity producers, part of these revenues will be used to finance the additional capital required for biomass-fuelled electricity generation equipment, and part will be used to purchase biomass fuels. These are, on a primary energy basis (€/GJ), usually more expensive than mineral fuels, and converted into electricity at efficiencies lower than those common for the energy conversion of mineral fuels, thus usually resulting in higher cost per unit of electricity. Part of these revenues may also be used to increase profit margins of the

<table>
<thead>
<tr>
<th>ERU value (€/t GHG)</th>
<th>30</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept</td>
<td>CS</td>
<td>GCC</td>
</tr>
<tr>
<td>Biomass cost #</td>
<td>€/t</td>
<td>€/GJ</td>
</tr>
<tr>
<td>10</td>
<td>-2.4</td>
<td>-0.2</td>
</tr>
<tr>
<td>30</td>
<td>11</td>
<td>0.8</td>
</tr>
<tr>
<td>90</td>
<td>25</td>
<td>2.0</td>
</tr>
<tr>
<td>270</td>
<td>39</td>
<td>3.2</td>
</tr>
</tbody>
</table>

- = Technology not feasible for any biomass cost level (either CS or GCC more attractive).
electricity producers, but this is an event which usually remains hidden. Alternatively, governments may decide to buy ERUs from biomass fuel providers. These may use the revenues to reduce biomass fuel prices to levels affordable by electricity producers, taking into account the energy value, conversion efficiency, and the increased investments required for using biomass fuels. In this case it also remains hidden whether a proportion of the revenues results in additional producer profits (in this case of the biomass producer).

Initially, ERU values are expressed on the basis of the quantity (tonnes) of avoided emissions (€/t GHG). In the electricity sector, in addition to being traded as ERUs, they can have the form of GHG emission rights. Currently, there is a system in several European countries in which ERUs are expressed on an energy basis (€/MWh e). This occurs in situations where environmental taxes may be avoided (such as the Dutch regulatory energy tax, REB) and in markets for Green Certificates. Value conversion is carried out by means of the unit-specific emission coefficient $\rho$ (t GHG/MWh e), introduced in Section 3.2.1, of the avoided use of fossil fuels:

$$\text{Electricity equivalent ERU value (€/MWh e)} = \rho \times \text{ERU (€/t GHG)}.$$  

Whichever method is applied for the settlement of ERUs with the electricity sector - through taxes, emission rights, etc. - this model calculation is required. This implies that any form of ERU settlement with the electricity sector can ultimately be expressed in terms of €/kWh e.

If, on the other hand, a government decides to purchase ERUs from biomass fuel producers, the ERU equivalent value must be expressed on a per tonne of biomass basis (€/t biomass). Conversion then proceeds by means of the following equation:

$$\text{Biomass equivalent ERU value (€/t biomass)} = \rho \times \eta_{\text{NCV, biomass power}} \times NCV_{\text{biomass}} \times \text{ERU (€/t GHG)},$$

where $\eta_{\text{NCV}}$ is the average net energy conversion efficiency of biomass-fuelled electricity generation technology (averaged across the various installed biomass-fuelled power plants). Subsidies to support the cultivation of energy crops do exist in the EU, but their magnitude is derived from the compensation for fallow, rather than from yield (see Section 4.3.1) and the intended use for energy and ERU production. Consequently, they are given on a per hectare basis. (For such conditions, it would be intriguing to determine the price actually paid for an ERU by applying the above equation in the reverse direction. Vollebergh (1997) did such an exercise for biomass-based transportation fuels produced and used in France.)

However, with regard to sustainable electricity production, ERUs may be purchased either from electricity producers, or from biomass fuel providers. Both methods are, unavoidably, framed on model assumptions, although in the first case less parameters need to be estimated and a better accuracy can be achieved. We now consider the two extremes (electricity price support, and biomass fuel price support) to analyse their particular
influence on technology preferences. The fundamentals can be assessed from Figure 37 which, just as an example, applies to a 30 MW case. As a starting position, the pure electricity price, and the pure biomass price, are assumed to be such that neither the CS nor the GCC technology is economically feasible. We effectively assume a Quadrant IV position (Figure 37), but in fact any pure price condition somewhere in the non-shaded range would have been suitable to illustrate the argument. Further parameter values in this example are shown in Table 38.

Table 38. Assumed parameter values selected for preparing Figure 37.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure electricity price (€/kWh)</td>
<td>0.084</td>
</tr>
<tr>
<td>Pure biomass price (€/t)</td>
<td>85</td>
</tr>
<tr>
<td>( \rho ) (t GHG/MWh)</td>
<td>0.65</td>
</tr>
<tr>
<td>NCV Efficiency</td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td>28%</td>
</tr>
<tr>
<td>GCC</td>
<td>39%</td>
</tr>
<tr>
<td>Average across installed biomass-fuelled plants</td>
<td>36%</td>
</tr>
<tr>
<td>NCV(_w) wood (GJ/t)</td>
<td>12.5</td>
</tr>
<tr>
<td>ERU (€/t GHG)</td>
<td>90</td>
</tr>
</tbody>
</table>

One can now observe the following:

- **Absence of price support:** Given the pure electricity price, the maximum affordable biomass fuel price, in the absence of an ERU purchase, is 38 €/t biomass. The preferred technology is CS and in so far as actual fuel prices are lower than 38 €/t, the investor in this technology receives a rent.
- **Electricity price support:** Under the assumed price conditions, an effective electricity price support in the form of ERU purchase, results in a preference for the
GCC technology. The price support indicated in the graph (with the help of an arrow) would make an investment in CS technology also economically feasible, but an investment in GCC is more profitable. Since the indicated price support surpasses the minimum level required (determined by the iso-IRR line for the GCC technology), the investor in GCC receives a rent. If the ERU value would increase, a point is reached where the CS concept is preferred. The same applies if pure price conditions were located in the non-shaded area of Quadrant I, but not if they were located in the non-shaded area of Quadrant III. In the latter case, although at certain price levels the GCC technology is economically feasible, GCC is never preferred over CS - however large the ERU value.

- **Biomass fuel price support:** Under the assumed price conditions, effective biomass fuel price support, again in the form of ERU purchase, results in a preference for the CS technology. The GCC concept will not be selected, even if biomass fuel prices were supported at levels such that the associated IRR surpasses the discount rate. The same would apply if pure price conditions were located in the non-shaded part of Quadrant III. If pure price conditions are in the non-shaded area of Quadrant I, GCC may become feasible as a result of this form of price support, and with an increasing ERU value, the CS concept would eventually become the preferred technology.

Society is interested in the lowest possible costs for electricity and ERUs, which is equivalent to the avoidance of rent received by electricity producers or windfall gains by biomass-fuel producers. To this end any payment mechanism will need careful design, but this matter is not further addressed here.

The above consideration helps to analyse two statements found in techno-economic literature about biomass-fuelled electricity generation concepts, i.e.:

- "An incentive for higher efficiencies has been CO₂ taxes in Scandinavia, which made it possible for more expensive biomass fuels to compete with fossil fuels."³⁰⁸
- "Capital intensive, high efficiency thermal biomass power technologies have difficulties in competing with conventional technology with lower investment cost and lower efficiency. However, environmental taxes ... will improve the competitiveness of new biomass fuelled power plant concepts."³⁰⁹

This first statement is a bit complicated since it says two things:

- CO₂ taxes enable the utilisation of more expensive fuels.
- CO₂ taxes favour high-efficiency technologies.

There is no doubt about the first item. But with regard to the second, it was shown above that a detailed analysis is needed in order to assess whether the introduction of ERU payments do indeed support high-efficiency technologies. It is not always true, but depends on initial pure price conditions and the size of the ERU value. With regard to the statement made by Solantausta, Bridgwater and Beckman, it should be noted that their argument makes the following presumptions:

³⁰⁹/ Solantausta, Bridgwater and Beckman (1995). Based on the full text of the cited paper one may conclude that the authors imply technologies such as GCC in comparison with CS.
Pure price levels render GCC technology unfeasible, but price support may eventually make GCC feasible. This implies that biomass fuel prices are already higher than the intersection of the two iso-IRR lines (here 73 €/t, Figure 37).

Price support makes CS technology economically feasible (after all, one does not compete something which is not feasible in the first place).

Thus, price support is supposed to place the effective price levels within the wedge between the CS/GCC equi-IRR line and the CS iso-IRR line (i.e. the upper part of the feasibility niche for GCC, highlighted in Figure 38). Only within this niche do the feasibilities of CS and of GCC overlap, so that competition may emerge between the two concepts. The principal implication of increased competitiveness is the possibility of increased IRRs on invested capital, which is a respectable aim. Such an increased IRR would be achieved by selecting the more competitive technology for the production of the same products at the prevailing market prices. In the graphs produced (Figures 33-36), the wedge in question is very narrow, and as a consequence, so will be the relevance of the assessment of increased competitiveness. But that is jumping to conclusions. The size of the indicated wedge may differ for different technologies (the LCC concept has yet to be analysed, see Sections 6.3 and 6.4) and, in the case of the GCC concept studied here, the wedge may widen if substantial cost reductions can be achieved by continued development of the GCC concept. This potential for cost reduction is the topic addressed next. However, the focus is not on its implications for increased profitability of capital, implied by Solantausta, Bridgwater and Beckman, as explained below.

![Diagram](image)

**Figure 38.** Division of the GCC feasibility niche.

### 6.2.3 Targeting investment costs for biomass-fuelled GCC

One of the aims with the further development of the GCC technology, through R&D in the laboratories and pilot plants as well as through learning, is the reduction of capital...
involved in constructing GCC power plants. This may occur as a result of the increased effectiveness of designs, but also as a result of increased energy conversion efficiencies with later generations of GCC power plants, provided such increases in efficiency are not coupled with a proportional increase in capital needs. Here we only consider the first cause of capital cost reduction: the increased effectiveness of designs. Rather than predicting the eventual future position of GCC technology in the market on the basis of so-called learning curves established from historical technology developments, such as provided by Grübler, Nakicenovic and Victor (1999), it is the intention to investigate the reverse: to quantify which developments are required and how much has to be learned for the technology to become economically feasible.

For our purpose, however, a technology’s economic feasibility is still too vague a concept. Its meaning is that a technology can be employed under economic conditions acceptable to a producer. However, why should anyone wish to find out at which level of reduced capital cost the GCC technology is economically feasible? After all, the employment of GCC technology is not an aim in itself. Therefore, a more precise objective linked to capital cost reduction has to be selected. Such cost reduction could potentially serve three purposes:

• Increasing the profitability of biomass-fuelled electricity production. This assumes that such production is already economically feasible with the CS technology, and that prices for fuel, electricity and ERUs are not affected by the further development of GCC. Profitability increases as the wedge widens between the CS iso-IRR line and the CS/GCC equi-IRR line (i.e. the upper part of the feasibility niche for GCC, in Figure 38).

• Enabling the production of ERUs at lower costs (Figure 39). This assumes constant fuel prices as well as constant pure electricity prices.

• Increasing affordable biomass fuel prices, the maximum affordable price being defined as the cut-off price above which the production of electricity from biomass does not meet the applicable economic efficiency criteria (Figure 39). Constant ERU prices and constant pure electricity prices are assumed. This action makes GHG emission reduction, by means of biomass-based electricity, economically feasible in more situations.

Not all of these objectives are equally important for a society supporting the further development of the GCC technology.

With regard the profitability of an investment in biomass-fuelled electricity production, a cut-off rate has already been determined as a starting-point in the analysis (i.e the discount rate of 10%). The potential IRR increase, therefore, as a result of lower capital cost levels for GCC technology, is merely an attractive incidental benefit which occurs in situations where favourable biomass prices or ERU values apply. Or, in other words, a target for technology development should not be based on any increase above an IRR cut-off rate already accepted in the market.

Concerning the production of ERUs at reduced costs, one should note that the pursuit of precisely this objective was the reason for the UNDP/World Bank’s GEF programme supporting the 30 MW_e biomass-fuelled GCC project in Brazil (the bank subsumed its support within the operational programme ‘Reducing the long-term costs of
It is an attractive idea, but it assumes that innovative technologies for biomass-fuelled central electricity generation will have a substantial influence on the market prices for ERUs. In the present analysis, the forthcoming ERU market is accepted as a fact, although still uncertain. The search for an investment target is therefore confined to the first issue: an increase in the affordable biomass fuel price.

Prior to establishing technology development targets, an objective must be set for the real indicator, i.e. a desired maximum affordable biomass fuel price which would allow the GCC technology to have a substantial impact. In Section 4.4, the range of biomass prices was estimated at 5-15 €/GJ, and thus the maximum is 15 €/GJ, which is equivalent to 190 €/t₃₀ biomass.

From the viewpoint of an investor in a biomass-fuelled electricity plant, the maximum affordable biomass price is defined as the cost level at which the IRR equals the discount rate. Variation of the capital cost of the plant relative to the estimate assumed in the previous section yields the results given in Figure 40. A lower boundary for achievable capital cost reductions is provided by the cost of the natural gas fuelled combined cycle concept (NG-CC), since a GCC unit is ultimately a gasifier coupled to a combined cycle. The upper boundary for capital cost reductions, also given in Figure 40, is determined by the equi-IRR line resulting from the comparison with the CS technology. Capital cost must be reduced to at least this level in order for GCC to become attractive. In accordance with the long-term market expectations for ERUs, the two extremes, 30 and 90 €/ERU, justified in Section 6.1 were assumed.

Figure 39. Effects of reduced capital cost at constant energy conversion efficiency.

**Increasing affordable biomass fuel cost**

310/ Martinot and McDoom (1999).
From Figure 40, it is apparent that the target set for the affordable biomass fuel price cannot be achieved by any lowering of the capital cost of the GCC technology. Under the most favourable scheme of 90 €/t GHG for ERUs, the maximum affordable biomass fuel cost is about 140 €/t₄₅ (11 €/GJ), and that is for the largest capacity investigated (270 MWₑ) and with the condition that the GCC technology would become as cheap as one of its own major components, the combined gas turbine/steam cycle. In other words, the gasifier component would be added at zero costs - an evident lower boundary. Note that an eventual reduction in ERU production, due to increased GHG emissions as a result of biomass transport, is not even taken into account here. The assessment is therefore actually biassed in favour of the GCC technology.

The investment targets summarized in Table 39 are obtained from techno-economic literature. In most of the cases, the authors estimated the investment for the nᵗʰ plant, to indicate that the so-called learning effect has run its course. Authors who instead indicated projection years also assumed maturity of the technology. The data are plotted in Figure 41, together with other relevant data. It is apparent that the anticipated costs are lower than for biomass-fuelled CS power plants, and higher than those for natural gas fuelled CC power plants. Especially the latter is reassuring. It suggests that all the estimates presented here make some sense. However, whether or not these cost estimates are realistic is not the topic of the current section. What is of interest here, is the question as to whether these cost reductions are sufficient to meet the social objectives which can be pursued by developing the GCC technology. In general, 100 MWₑ systems and long-term cost reductions of about 50% are anticipated (median values). From the analysis presented above, it must be concluded that such cost reductions are still insufficient for wide-scale application of the technology under EU conditions.
This is where an analysis of the GCC technology should stop - the fundamental question having been answered: the GCC concept cannot be developed to the extent that it enables the production of electricity and ERUs at economically feasible costs using biomass fuels at cost levels relevant for EU-like economies. This does not imply that all efforts to develop this technology are useless. We come back to this matter at the end of this chapter, where the perspectives for the GCC technology are discussed in a somewhat broader context.
6.3 THE SINGLE-SITE LIQUEFACTION - COMBINED CYCLE CONCEPT

In this section an initial variant of LCC technology is investigated: liquefaction followed by a combined Brayton-Rankine cycle for the further conversion of the bio-oil and the pyrolysis gas. The products of biomass liquefaction are immediately converted into electricity by means of a gas-turbine/steam power plant. There is no sale or external transport of bio-oil beyond the boundaries of the central electricity producer. As in the previous section, the concept is compared with the existing combustion/steam technology (CS).

6.3.1 Parameter values for single-site LCC technology

The same site parameters, discussed in Section 6.1, are applied as in the technology evaluation carried out in the previous section. As for the technology parameters, the same values as applied in the GCC investigation, are assumed for technical lifetimes, the type of biomass and maintenance costs. These are listed in Table 36 (Section 6.2.1). The biomass assumed as feed for the plant has a moisture content of 30% (wet basis). This is perhaps too high for the proper functioning of an LCC plant, and for this reason a dryer may be required. A few considerations are therefore appropriate here.

The biomass feed of a liquefaction reactor needs to be sufficiently dry. All moisture in the fuel ends up as water in the bio-oil. An additional source of water found in bio-oil is reaction water resulting from the pyrolysis process. Experience with liquefaction shows that high a moisture content in the biomass feed may result in phase separation into two fractions, a wet one and a dry one. This is particularly problematic if plant-external transport is involved. For single-site LCC applications it is not self-evident, however, that high-moisture bio-oil would be unworkable for technical reasons. Concerning the technical feasibility per se, two issues need specific investigation when considering high-moisture feedstocks:

• The liquefaction reactor should function with the desired, higher, moisture levels.
• The gas turbine should be capable of employing the wetter bio-oil (this is an issue of flame stability and flame size).

These matters are left for further technical R&D. In the following analysis, the efficiency of single-site LCC technology, as elaborated in Section 5.2.3, is used. This implies that a dryer is installed to reduce the feedstock's moisture content to a level of 10% (wet basis). The dryer can be thermally driven using some of the waste heat from the LCC power plant. Its operation, thus, does not reduce the plant’s efficiency.

The biomass feed, delivered in the shape of wood chips, is not only dried but also has to be ground to particle sizes below 5 mm. Small particles are required to ensure a rapid
temperature increase of the raw material. This process has an energy cost of less than 1% of the originally contained energy ($J_c/J_{in}$, NCV basis).

Unfortunately we cannot call on investment data from first pilot or demonstration projects in order to prepare a preliminary investment estimate. A reasonable approach is to assume the same investment level as applied in the analysis of GCC. In fact any arbitrary cost level would serve our purpose, since it does not affect the absolute cost level below which the technology becomes of interest in serving the social objective discussed earlier (increased affordable biomass fuel cost). Determining that cost limit, after all, is the purpose of this analysis.

6.3.2 Feasibility conditions for biomass-fuelled single-site LCC plants

On the basis of the of the parameter values indicated above, a similar analysis to that carried out earlier is performed. The results are shown in Figures 42-45. Comparing with the GCC concept, the economic feasibility of single-site LCC technology seems equally remote for the smaller capacity of 10 MW$_e$. On the other hand, for the largest capacity of 270 MW$_e$, the economic feasibility of GCC technology appears more promising. This is due to the fact that in this thesis, for the larger capacities a lower energy efficiency is assumed for the LCC$^{314}$ concept than predicted by the quoted literature for the GCC concept. Another reason is the investment level presumed. As such, this result does not imply that either of the two concepts is to be preferred. The analysis goes further to determine the desired investment levels, if the social objective of increased affordable biomass fuel prices is to be achieved.

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$^{313}$ Spliethoff and Hein (1998), and Wagenaar, Pascual, Aa et al. (2000).

$^{314}$ Due to charcoal formation using LCC. The utilisation of this charcoal is not included in the model.
Figure 42, 10 MW: Feasibility niches for single-site LCC in comparison with CS.

Figure 43, 30 MW: Feasibility niches for single-site LCC in comparison with CS.
Figure 44, 90 MW: Feasibility niches for single-site LCC in comparison with CS.

Figure 45, 270 MW: Feasibility niches for single-site LCC in comparison with CS.
As with the GCC concept, it is concluded that capital cost levels for the single-site LCC technology cannot be foreseen such that they would support the use of the expected high cost biomass fuels (Figure 46).

![Figure 46](image)

**Figure 46.** Affordable biomass fuel cost for reduced cost single-site LCC technology. Lower cluster: assumed ERU value = 30 €. Upper cluster: assumed ERU value = 90 €.

It is interesting to note the similarities between the potentials for single-site LCC and GCC (analysed in the previous section), for the smaller capacities of 10 and 30 MW_e (compare Figures 40 and 46). The reason is, simply, that at these capacities, the presumed energy efficiencies of the two technologies are very similar. The differences encountered for larger capacities, is caused by the lower efficiency of single-site LCC plants due to charcoal formation, which this model assumes is not converted into electricity.

### 6.4 THE MULTIPLE-SITE LIQUEFACTION - COMBINED CYCLE CONCEPT

Finally, an alternative LCC implementation mode is studied here: multiple-site LCC. In this variant of LCC technology, a central electricity producer (operating a gas-turbine/steam power plant) buys bio-oil from several manufacturers. On their own sites, these bio-oil manufacturers produce bio-oil for sale, plus electricity which they make from their pyrolysis gas surplus. An essential difference between the single-site LCC concept, and the option investigated here, is the plant-external transport of bio-oil. On an energy basis, the transportation of bio-oil has different costs than the transport of wood chips, the assumed fuel for the previously studied central power plant concepts. There is also another difference; bio-oil can be made from several types of bulky biomass resources, the transportation of which would lead to prohibitive costs for their application in central power plants. In addition to sawdust, these resources include sugar cane bagasse, tobacco
residues, rice husks and certain other feedstocks. So, there are two reasons why the multiple-site LCC technology is potentially attractive:

• It enables the use of cheaper feedstocks;
• Delivery costs are lower.

The examples given for feedstocks, suggest that the technology might result in the involvement of developing countries as a new type of fuel supplier. After all, these are the places where the indicated bulky biomass residues are available. Additionally, the technology might also be of potential interest for other trading schemes, such as fuel trade between the EU15 and C&E Europe, and also intra-EU15 fuel trade, if in certain areas energy crops could be produced at an attractive cost. The uncertainties with regard to the technical feasibility of this concept mainly concern the employment of bio-oil in gas turbines, some issues of which are discussed in Appendix E, and the chemical stability of the oil during storage and transportation. There are also potential disadvantages associated with multiple-site LCC. Among these are the unavoidable production of charcoal and pyrolysis gas, for which there might not be an efficient use. Whether or not such uses will exist cannot be assessed generically, as it will depend on location-specific market circumstances around bio-oil manufacturing sites.

Whereas, in the previous two sections, the alternative new technologies could be compared to their existing counterpart (CS) by virtually placing them at the same location and using the same fuel - for the technology analysed here this does not make sense since it would not reflect the intended production chain. In other words, the difference in feedstock has methodological consequences for the analysis. A proper analysis has to make a distinction between the systems of bio-oil manufacture, and bio-oil utilisation for electricity production. The transportation of bio-oil can be included in either of the two systems, or it could also be considered as a separate item for further analysis. The analysis framework established in Section 3.1, and especially in Figures 14 and 15, should be followed.

A method for the analysis of bio-oil manufacture

In the biomass-to-electricity production chain discussed here, the bio-oil manufacturing process is the link between biomass feedstock and the end-user, in this case power plants fuelled with bio-oil. It is characterized by a number of technology parameters and site parameters, as defined in Table 13 (page 108), and the purpose of the analysis is to determine development targets for the technology parameters of the process. The first and foremost parameter on which the analysis depends is the price level supported by the end-user. Therefore, although the physical process is carried out from biomass feedstock through to the electricity produced, the analysis of the bio-oil manufacturing process should proceed in the reverse direction. First, the affordable bio-oil price should be established and transportation costs should be determined. Only after this should the liquefaction process be investigated. The feasibility indicator used is the unit production cost of bio-oil. This must be lower than the affordable price, after subtracting delivery costs. The first step in this analysis is the identification of the most important technology
parameters, given the state-of-the art of the bio-oil manufacturing process. This is achieved by breaking down the unit production cost.

*The adapted method for the analysis of bio-oil utilisation*

One particular question in the analysis of the bio-oil utilisation technology is, which investment level is acceptable for the adaptation of the combined cycle for the use of bio-oil. This question cannot be addressed if a price for bio-oil is not set. Therefore, an investigation into this issue cannot be carried out simultaneously with the determination of the affordable price level for bio-oil. Hence, it is necessary to temporarily skip the inquiry into the affordable capital cost, and to assume a reasonable investment level for the retrofit of the combined cycle.

As with the GCC and the single-site LCC technologies, where the affordable biomass price was found to be dependent on two issues, i.e. the absolute IRR and the IRR in comparison with the next best alternative, a similar situation occurs with the multiple-site LCC technology. The first of these functions isolates the considered technology from its biomass-based alternatives. Here, the iso-IRR line, defined earlier in Chapter 3, is determined as a relationship between the cost of delivered bio-oil (rather than biomass) and a unit sales price of electricity and ERUs. In Figure 47, this is shown graphically. Its interpretation is that:

- For price conditions below the lines depicted for each individual capacity, the technology is not feasible,
- On the line the IRR reaches the assumed discount rate of 10% and,
- Above the line the IRR is above that level.

For each power capacity, a maximum affordable bio-oil price is defined by the intersection of the combined electricity and ERU sales price and its associated iso-IRR line. Except for the fact that the alternative of biomass combustion (CS) technology cannot be shown in the same graph - since the latter requires the cost of delivered wood chips, rather than that of bio-oil, displayed along the abscissa - there is no fundamental difference between this graph and the ones produced for the GCC and single-site LCC technologies (e.g. Figures 33-36). Below, in Section 6.4.1, the conditions for which the graph was derived are further clarified.

By determining the comparative equi-IRR line - the second function - it is seen how the maximum affordable bio-oil price is not only dependent on the multiple-site LCC technology itself, but also on the alternative technology. The CS technology is assumed to be this alternative. This particular choice is, of course, debatable, since the other technologies considered in the preceding sections (GCC and single-site LCC), might also be successful future alternatives. To enable a comparison of the multiple-site LCC concept with its next best alternative, the ordinate is changed to the cost of wood fuel, delivered at the power plant. As an example, Figure 48 shows such a graph for a 30 MW<sub>e</sub> power plant. The underlying quantitative assumptions of this graph are also discussed in Section 6.4.1. The graph provides various items of information:
The equi-IRR line for the two compared technologies enables the selection of the preferred technology on the basis of the highest achievable IRR, provided fuel prices are available.

It shows cut-off fuel prices for the two individual technologies considered. If fuel prices are higher, then a project employing the particular technology would not achieve the desired IRR. Naturally, cut-off fuel prices depend on the revenues received, and thus on the sales price of electricity and ERUs.

For the particular case depicted in Figure 48, it is seen that CS technology may be preferred if wood chips can be acquired for below 3.8 €/GJ. But even then, if bio-oil is sufficiently cheap, the LCC technology may prove more attractive.

Figure 47. Iso-IRR lines for the bio-oil user with multiple-site LCC technology.
6.4.1 Parameter values for multiple-site LCC plants

Bio-oil manufacture

Bio-oil manufacture could be conceived of as a side-activity for enterprises already involved in other biomass-related business. Examples of such enterprises are sugar industries, saw mills, and rice mills. In such cases, feedstocks would consist of bagasse, saw dust and rice husk. Occasionally, there are alternative uses for these materials, such as paper manufacture out of bagasse. In some instances, sugar factories already produce surplus electricity for delivery to a distribution grid. However, there are many such enterprises for which such opportunities do not exist, and where these materials, as a consequence, have a negative (disposal costs), or a zero, value. Meuleman and Siemons (2001) showed that sugar factories in Uganda face bagasse disposal costs of 8-10 $/t 50, which is equivalent to about 1-1.2 i/GJ. 315 If a bio-oil manufacturing operation is located external to this type of enterprise, the feedstock must be valued positively, even if only transportation is involved. In Chapter 4, it was found that Eucalyptus wood chips, originating from sustainably managed plantations, can be supplied at a cost of 1.9 €/GJ f.o.b Montevideo, and that soya hulls are actually supplied at 50-60 $/t f.o.b. Argentina and Brazil for animal feed. The latter is equivalent to about 4 €/GJ. Both these estimates include transportation, storage and handling costs. The latter one even includes a sales margin achievable on the market for cattle feed. Therefore, feedstock costs can be safely assumed to be within a range of -1 to 4 €/GJ. A positive value of 1 €/GJ is adopted here. In this manner, the influence of this cost item can be easily assessed.

315: The energy equivalent after drying the bagasse.
The raw material types indicated above represent typical feedstocks and the way in which these are produced suggests that plant capacities in the range of 5,000-440,000 t\textsubscript{10} biomass/yr would be quite realistic. The said 440,000 t\textsubscript{10} biomass/yr is in fact the capacity, in terms of bagasse, of one of the largest sugar factories in the world (Kenana, Sudan). One could consider larger scales, but the comparative advantages of the multiple-site LCC technology (avoided transportation of bulky feedstocks, and use of cheap feedstocks) would be lost. The indicated range corresponds to thermal capacities of the order of 3-250 MW\textsubscript{th} (on bio-oil NCV). This range is investigated for the following cases: 7.6, 19, 48 and 120 MW\textsubscript{th} (Renard series R10/4). The mass and energy balance given in Table 31 (page 171) shows that the series corresponds to a feedstock intake of 2.5, 6.3, 15.9 and 39.8 t\textsubscript{10} biomass/h. In Table 40, the ratio between end-user capacities and bio-oil producer capacities is shown. Manageable numbers result: a 19 MW\textsubscript{th} bio-oil plant for example could serve one 10 MW\textsubscript{e} power plant. The data on which these estimates were prepared are justified below, in this section.

**Table 40. Capacities and capacity ratios of bio-oil production and utilisation plant.**

| End-use capacity (MW\textsubscript{e}) | 10 | 30 | 90 | 270 |
| End-use energy efficiency (on NCV) | 46.7% | 49.2% | 51.6% | 54.0% |
| Bio-oil consumption (t bio-oil/yr) | 38,000 | 108,000 | 310,000 | 887,000 |
| Production capacity (MW\textsubscript{th} on oil) | 7.6 | 19 | 48 | 121 |
| Bio-oil production (t bio-oil/yr) | 12,000 | 30,100 | 75,700 | 190,000 |
| Number of liquefaction plants (MW\textsubscript{th} on oil) per electricity plant (MW\textsubscript{e}) | 3.2 | 9.0 | 26 | 74 |
| Liquefaction plant capacity (MW\textsubscript{th} on oil) | 7.6 | 3.2 | 9.0 | 26 | 74 |
| 19 | 1.3 | 3.6 | 10.3 | 29 | 12 |
| 48 | 0.50 | 1.4 | 4.1 | 12 |
| 121 | 0.20 | 0.57 | 1.6 | 4.7 |

In the technology exploration (Chapter 5) it was shown that a technically-optimised biomass to bio-oil conversion efficiency has already been achieved, and is scale independent. Efficiency gains at larger scales do exist, but these rather occur in the area of internal plant energy consumption. This means that larger plants generate proportionally more energy surpluses in the form of charcoal and electricity (the latter generated from the pyrolysis gas produced). As indicated in the introduction to the present analysis, the valuation of those surpluses is entirely site specific. If the bio-oil manufacturing technology was integrated with cane sugar manufacture, then all the residual energy could be used in the sugar production process, and the sugar factory would remain independent of external energy supplies. In such a case, the value of residual energy would be zero. If bio-oil was manufactured from residues of processes which required less energy (such as sawdust and rice husk), then charcoal and electricity could be sold as by-products. If they replace resources which emit GHGs, then these by-products might also qualify for ERUs. These details can have a major influence on the results of a technology assessment of the type being carried out here. At this preliminary stage, however, it is assumed that the value of these potential by-products is zero. Additional site parameter values are reviewed in Table 41. Notably, a relatively high discount rate (25%) and a low capacity factor (81%)
are used, since developing country conditions are assumed in order to make full use of the comparative advantages of multiple-site LCC. Labour and consumable costs are conservatively assumed equal to those estimated for bio-oil manufacture in industrialized countries.

### Table 41. Site parameter values for bio-oil manufacture in developing countries.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project life time</td>
<td>15 years</td>
</tr>
<tr>
<td>Discount rate</td>
<td>25% /yr</td>
</tr>
<tr>
<td>Capacity factor (CF) /a</td>
<td>81%</td>
</tr>
<tr>
<td>Based on:</td>
<td></td>
</tr>
<tr>
<td>Operational period (OP)</td>
<td>52 weeks/year</td>
</tr>
<tr>
<td>Planned maintenance during OP (PM)</td>
<td>15% of OP</td>
</tr>
<tr>
<td>Availability factor during (100%-PM)*OP</td>
<td>95% of (100%-PM)*OP</td>
</tr>
<tr>
<td>Load factor</td>
<td>100% of capacity</td>
</tr>
<tr>
<td>Not applied (compare Table 13):</td>
<td></td>
</tr>
<tr>
<td>Unit operator costs €/man hour</td>
<td></td>
</tr>
<tr>
<td>Unit consumable costs €/unit</td>
<td></td>
</tr>
<tr>
<td>Instead:</td>
<td></td>
</tr>
<tr>
<td>Capacity (MWth on oil)</td>
<td>7.6</td>
</tr>
<tr>
<td>General operator costs (€/t bio-oil)</td>
<td>8.33</td>
</tr>
<tr>
<td>General consumable costs (€/t bio-oil)</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>19.2</td>
</tr>
<tr>
<td></td>
<td>3.32</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>48.2</td>
</tr>
<tr>
<td></td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>121</td>
</tr>
<tr>
<td></td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
</tr>
</tbody>
</table>

a/ For definitions of the parameters CF, OP, PM and load factor, see Appendix F.

We now turn to the so-called technology parameters. The results of a literature survey of cost estimates of liquefaction plants is presented in Figure 49. The range covered is 2-1000 MWth on bio-oil, despite the largest existing biomass liquefaction plant having a capacity of only 4.9 MWth on oil (Pyrovac technology, located in Jonquière, Quebec province, Canada). Of the sources quoted, only BTG, Dynamotive, Ensyn, Pyrovac and VTT have any experience with pyrolysis plant construction and estimating. The variations within the estimates may be explained by the fact that different reactor concepts are concerned. The estimates provided by these sources are all confined to relatively small capacities. ECN and the University of Utrecht have considered substantially larger scales. Such capacities go beyond the range investigated in this study. If the usual scaling factors applicable to this type of processing plant (0.6-0.8) (that is, the factor s, explained on page 183) are taken into account, then the estimates by Van Ree (ECN) and Faaij (University of Utrecht) are about 5-10 times larger than might be expected. The high estimates by ECN, especially at the larger capacities, are a result of ECN’s presumption that, as the technology is made larger, there will be no economy of scale (compare ECN’s estimates with the depicted trendline with a scale factor equal to 1). In the present analysis, BTG’s small-capacity data combined with a 0.76 scaling factor are assumed. This yields the quantitative relationship depicted in Figure 49. The estimated costs include a biomass-feed...

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317/ Calculated from data provided by Roy (1999) and Roy (2000).

318/ Van Ree, Korbee, et al. base their estimate for a pyrolysis plant on a capacity of about 45 MWth on oil, provided to them by stakeholders in the competing technology of biocrude manufacture (HTU), and using a scale factor of 1 (Van Ree, Korbee, Eenkhoorn et al. (2000), p. 116).
dryer, a gas-fuelled electricity generator set with pilot injection, a liquefaction reactor, installation and commissioning, but they exclude buildings and land. A complete list of the assumed technology parameters is shown in Table 42.

### Figure 49, Cost estimates for biomass liquefaction plants (pyrolysis technology).

**Table 42.** Technology parameter values for bio-oil manufacture in developing countries.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment /a</td>
<td>(691453 \times C^{0.76}) £</td>
</tr>
<tr>
<td>Technical lifetime of system components</td>
<td>15 yr</td>
</tr>
<tr>
<td>Bio-oil yield /b</td>
<td>68% g\textsubscript{w}/g\textsubscript{w} biomass</td>
</tr>
<tr>
<td>Fuel calorific values (NCV\textsubscript{w}):</td>
<td></td>
</tr>
<tr>
<td>Bio-oil at 20% moisture (w)</td>
<td>16.20 GJ/t</td>
</tr>
</tbody>
</table>

Not applied (compare Table 13): Number of operators Consumables utilisation

Instead:

- General operator cost (£/t bio-oil) see Table 41
- General consumable costs (£/t bio-oil) see Table 41
- Maintenance costs 2.5% of investment/8000 full-load equivalent hours

<table>
<thead>
<tr>
<th>Working capital</th>
<th>neglected</th>
</tr>
</thead>
</table>

a/ C = Capacity (MW\textsubscript{in} on oil)
b/ Low-ash biomass is assumed (wood, bagasse, etc.). High-ash biomass such as tobacco waste and rice husk give lower yields on a wet basis.

### Bio-oil transport

The cost of sea transport was discussed in Chapter 4. In this analysis a cost of 3 £/GJ (equivalent to 49 £/t bio-oil) is assumed.
Bio-oil conversion into electricity

The same power plant capacities are used as in the previous sections, i.e. 10, 30, 90 and 270 MW. The assessment is carried out for electricity generation located in industrialised countries. Therefore the same site parameters are assumed as in the assessments of GCC and single-site LCC (Tables 32-33).

The respective energy conversion efficiencies of the investigated plant capacities are 47%, 49%, 52% and 54%. These are the same as those of the NG-CC technology, an assumption which was justified in Section 5.2.3. As indicated in the introduction to this section, the total cost of new NG-CC power plants form the basis of the investment estimates. These costs have already been presented in Figure 32 (page 185). For the adaptation to enable the use of bio-oil as a fuel, an assumed percentage is added to the investment for a NG-CC power plant. Without any great justification, this percentage is set at 20% (and if the concept shows potential, then power plant designers are invited to prepare firmer cost estimates). This allowance is assumed to cover all the changes in terms of fuel storage and handling, eventual fuel quality management such as filtering, as well as combustor retrofits. The full set of assumed technology parameters is given in Table 43.

The GHG balance

As discussed in Chapter 3, the ultimate balance of GHG emissions does not only depend on technical issues, but, due to politically-determined allocation difficulties, also on the particular role of the countries involved. In Section 3.1.3, Table 10, five different configurations of these roles were distinguished. To make full use of the comparative advantages of multiple-site LCC, it is assumed here that the biomass fuel providing country, and the electricity producing country, are distinct and that the biomass fuel providing country is a non-Annex I country. A likely outcome of CDM negotiations is that the full national GHG emission balance of the biomass providing country, as a result of bio-oil manufacture will be adopted by the electricity producer’s country. Any advantages
of eventual local substitution of GHG emitters, as a result of local energy substitutions, is not taken into account at this preliminary stage of the assessment. There are also additional GHG emissions associated with bio-oil manufacture since a liquefaction plant needs energy. As explained earlier, the pyrolysis gas could provide more than enough energy, and would be GHG neutral, but in certain configurations fossil energy sources are required. In a worst case scenario, particularly applicable to small plants, all the pyrolysis gas would be utilised in running the liquefaction plant, and a gas engine with pilot injection of diesel fuel would be employed. In fact, not all the pyrolysis gas is needed for this purpose, and larger plants would probably use spark-ignited gas engines or gas turbines. In any case, the mass and energy balances of the pyrolysis process show that, under unfavourable circumstances, diesel fuel injection would still only amount to a consumption of 0.0015 t diesel/t bio-oil and result in an additional emission of 0.005 t CO₂/t bio-oil. This is negligible in view of the avoided GHG emissions in the electricity producer’s country resulting from the utilisation of the bio-oil (for the power capacities considered, the avoided emissions range between 1.2-1.4 t GHG/t bio-oil).

With regard to the determination of additional GHG emissions due to international transport, it was shown that the avoided emissions, by not transporting the fossil fuels replaced, should be deducted from the emissions from the biomass-fuel transport. A difficulty identified was that it is unknown from where the replaced fossil fuels would have originated. A worst case assessment therefore considers only the emissions from bio-oil transport. The emissions reviewed in Table 44 were calculated from data provided by Kaltschmitt and Reinhardt (1997). Note that a typical transportation distance for bio-oil would perhaps be 12000 km (Montevideo - Rotterdam) and that typical additional GHG emissions due to transportation would amount to 0.15 t GHG/t bio-oil. Relative to the avoided emissions due to fossil fuel substitution by the electricity manufacturer, a 10% reduction in emission avoidance is conservative for this assessment.

Table 44, GHG emissions during sea transport.

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
<th>16000</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG emissions (t GHG/t cargo):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk carrier</td>
<td>0.0161</td>
<td>0.0323</td>
<td>0.0645</td>
<td>0.1290</td>
<td>0.2581</td>
</tr>
<tr>
<td>Tanker vessel</td>
<td>0.0081</td>
<td>0.0161</td>
<td>0.0322</td>
<td>0.0644</td>
<td>0.1289</td>
</tr>
</tbody>
</table>

Based on:

<table>
<thead>
<tr>
<th>Emission (g/(t.km))</th>
<th>GHG multiplier /b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bulk carrier /a</td>
</tr>
<tr>
<td>CO₂</td>
<td>15.9</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.0003</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.00072</td>
</tr>
<tr>
<td>GHG potential</td>
<td>16.1</td>
</tr>
</tbody>
</table>

a/ Source: Kaltschmitt and Reinhardt (1997).


6.4.2 Feasibility conditions for biomass-fuelled multiple-site LCC plants

The first results of the analysis have already been shown in Figure 47. At a value of 30 €/ERU, the maximum affordable costs for delivered bio-oil range from 3.86 to 5.73 €/GJ. The lowest value applies to a small end-use capacity of 30 MWₑ, and the highest value to
In the low ERU value scenario, the largest bio-oil production capacity will provide an investigated bio-oil manufacturing capacities and the entire range of end-use capacities. A breakdown of bio-oil manufacturing costs, augmented by the cost of international transport, is also given in Figure 50. The conclusion is that in the high ERU value scenario, of 90 €/t GHG, the technology will be economically feasible for most of the investigated bio-oil manufacturing capacities and the entire range of end-use capacities. In the low ERU value scenario, the largest bio-oil production capacity will provide an economically feasible match with the largest bio-oil utilisation capacity. Further generalised, these results are depicted in Figure 51, where the arrows indicate just one example of an economically feasible combination. From these graphs the following conclusions are drawn:

- The most significant of the assumed supply cost items are bio-oil transportation and plant capital.
- The most significant demand side assumption concerns the value of the ERU.
- For manufacturing capacities smaller than about 20-30 MWth, the bio-oil manufacturing costs are extremely sensitive to scale. This is mainly due to the large capital cost component.
6.4.3 Research and development targets for multiple-site LCC

The potential of the multiple-site LCC technology would be enhanced if it could become economically feasible for a wide range of bio-oil manufacturing capacities. The broadening of this range towards smaller capacities is especially desired, since these enable the use of low value biomass feedstocks available from a variety of small-scale agro-industrial and forestry operations. The economic feasibility at small scales is especially critical if a low-value ERU scenario develops, since the smallest capacity at which the liquefaction technology appears economically feasible, in that scenario, is no smaller than 120 MWth (Figure 51). One would desire feasible scales which are at least one order of magnitude smaller (see the discussion on page 207). Capital cost reductions as a result of learning is the key to this issue. Reducing the capital requirements to levels of 80% and 60% of the assumed values gives the results shown in Figure 52. Such capital cost reductions rapidly decrease the minimum capacities at which the technology becomes economically feasible. The sensitivity to capital cost reduction is due to the weak economies of scale with bio-oil manufacturing costs at larger capacities (flatness of the curve). Since this is not the case with capacities smaller than about 30 MWth, continued capital cost reduction will not reduce the minimum economically feasible size below approximately 20-30 MWth.
Under the assumption that future ERU values will be towards the lower end of the range of 30-90 €/t GHG, R&D targets are assessed as follows:

- Liquefaction technology should be made technically feasible for capacities of 20-30 MW_{th} and above.
- Above these capacities, capacity-specific investment costs need to be below the value of 60% × 690,000 × C^{0.76}/C/MW_{th} (with the capacity C expressed in MW_{th}).

These conclusions are contingent upon an assumed cost of international bio-oil transportation of about 3 €/GJ. One further economic assumption, influencing this conclusion, is the cost of adapting electricity plants to use bio-oil. Both assumptions require further justification.

The eventual availability of multiple-site LCC technology for electricity generation does not exclude the application of conventional CS technology for the same purpose. If solid biomass fuels such as wood chips are locally available at sufficiently low prices then their use in combustion plants can be attractive. Boundary fuel values for a variety of conversion capacities are depicted in Figures 53-56. The probability of obtaining fuel supplies at such prices, and in the quantities required for the respective capacities, is however small due to limitations in the resource base. In fact, as substantiated in Chapter 4, these prices can only be achieved for locally produced residues which do not require transportation. Realisation of the indicated development targets for multiple-site LCC technology, on the other hand, will broaden the region from where biomass fuels can be supplied at affordable costs.
Figure 53, 10 MW: Feasibility of multiple-site LCC in comparison with CS.

Figure 54, 30 MW: Feasibility of multiple-site LCC in comparison with CS.
Figure 55, 90 MW: Feasibility of multiple-site LCC in comparison with CS.

Figure 56, 270 MW: Feasibility of multiple-site LCC in comparison with CS.
6.5 PUTTING THE RESULTS INTO PERSPECTIVE

In this conclusion to the technology assessments made in this chapter, an attempt is made to investigate a number of different angles from which the issues of technology selection, of R&D targeting, and of associated public policy determination, can be viewed. Finally, an economic development perspective is briefly outlined.

6.5.1 Comparison with co-firing

The assessments of the GCC, and the single-site LCC, technologies made here are relative to the CS concept applied in a biomass-dedicated power plant. No comparison was made with co-firing technology for biomass and mineral fuels in large-scale power plants. As discussed in Section 4.2, co-firing, if integrated on the reactor side, combines small effective capacities with high energy conversion efficiencies. This particular advantage is absent in the case of so-called steam-side integration. However, in both cases, co-firing takes advantages of scale benefits in terms of plant management and operation, as well as exhaust gas cleaning. Given those additional plus points of co-firing relative to CS, the assessments made here give a somewhat optimistic perspective of dedicated biomass-fuelled GCC and single-site LCC technology. This all the more underscores the conclusions drawn from the preceding analyses. To what extent this impacts on the assessment of multiple-site LCC is less clear. It is conceivable that bio-oil could be co-fired with mineral fuels in gas turbines and that scale advantages would result in higher affordable bio-oil prices, but this is uncertain. Conversely, bio-oil can be co-fired with coal in conventional coal-fired power plants without any great technical difficulties and with low adaptation costs, much lower than the 20% gas turbine adaptation costs assumed in the previous section. To what extent this will apply to coal-fired power plants of the 2010s and beyond (perhaps coal fired GCC, or supercritical steam) has yet to be investigated.

6.5.2 Market niches for the reviewed technologies

In the assessment carried out in the previous sections, an attempt was made to rigorously limit the evaluations to a public perspective, the guiding principle being to increase affordable biomass fuel prices to such levels that the technologies could find wide-scale application. From that perspective, it was shown that the biomass-fuelled GCC and the single-site LCC technologies do not offer sufficient potential. This, in itself, does not imply that these technologies will never find a role in future sustainable electricity production. However, the conditions under which a particular technology may find an application are less of a public interest, and rather more important to the industries involved in the development of that technology. There are a number of technology-oriented studies that, unlike the current study, specifically aim at assessing the future market position of biomass-fuelled GCC. Examples are Faaij, Meuleman and Van Ree (1998), DeMeo and Galdo (1997), and Craig and Mann (1996). These have already been cited in the previous chapters. One of the economic performance indicators employed in the referred studies is the cost of electricity (COE). ERUs, and the cost of their production, were not considered in these reports. Therefore, these are also left out of consideration.
here for a moment. It is important to note that what is called COE, here, is generally not an indicator of the market price of electricity, especially in economies where biomass-fuelled GCC is not the prime electricity generation technology. Under certain conditions, the COE denotes the unit production cost, as perceived by the producer, and then the difference between sales price and COE indicates the producer’s profit. The conditions for which this applies include that the discount rate employed for determining COE equals that of the producer; that the ratio of equity and outside capital, and the interest rates, apply to the producer in question; and that the biomass fuel cost used reflects the financial costs as seen by the producer. Under independent market prices, minimisation of COE is equivalent to IRR maximisation. In the discussion of Solantausta, Bridgwater and Beckman (1995), Section 6.2.2, it was explained why this was not selected as the guiding principle for the analysis. However, the COE being a function of capital and biomass fuel costs, the current study does provide an instrument to investigate this function and, hence, potential market niches for the reviewed technologies. One possible conclusion from the data given in Section 6.2.3, drawn from the perspective of profit maximisation, is that, for the high ERU value scenario (90 €/t GHG), large scale GCC technology (> 90 MWe) will be more attractive for an investor than the conventional CS technology, even if current capital cost projections apply. At smaller scales, capital cost reductions of 10-15% are needed to out compete the CS technology - again under the high ERU value scenario and from the investor’s viewpoint. A necessary condition for this to occur is that biomass fuels are sufficiently cheap. This emphasises the relevance of the GCC technology - a relevance which incidentally decreases in a low ERU value scenario - potentially replacing the existing CS technology. In terms of increasing the sustainability of the energy economy in the industrialised world though, as argued in this chapter, this is of less importance.

UNDP’s and the World Bank’s involvement in the development of the biomass-fuelled GCC technology is focussed on applications in developing countries, constituting an entirely different market to those investigated in this study. Firstly, developing countries bear no obligations regarding GHG emission reduction under the Kyoto Protocol and, therefore, do not represent future buyers of ERUs. Secondly, not being industrialised to the same extent, or in the same manner, as the OECD countries, they are more agriculturally oriented, with some focus on agri-industries such as sugar, palm oil and rubber manufacture. Biomass is often much cheaper here than in regions such as the EU. Thirdly, their position relative to the local costs of mineral fuels varies widely. It is therefore certainly interesting to investigate whether modern biomass-fuelled electricity generation technology could become a major electricity supply technology in these countries. In such an assessment, the existence of the Kyoto Protocol, and the associated uncertainty with regard to the eventual implementation of a CDM mechanism, makes it relevant to assume two scenarios:

- Absence of CDM: in this case, the industrialised countries obliged under ‘Kyoto’ would decide to deal locally with global warming, and not to pay for GHG emission reductions realised elsewhere. Hence there would be no finance for ERUs produced in developing countries.

• Under CDM: in this scenario, countries would agree to act globally within the framework of a CDM programme with foreign funding. Low ERU values, payable by foreign countries obliged under the UNFCCC, should be assumed (see Morozova and Stuart (2001), referred to in Section 6.1).

There is no scenario related to the UNFCCC and the Kyoto Protocol which would result in high ERU values ever being applied in developing countries, since high ERU values are associated with the absence of CDM. In the first scenario, technologies such as biomass-fuelled GCC could become of interest in developing countries only if they can produce electricity at lower long-run marginal costs than competing technologies suitable for their markets (mainly hydro and conventional mineral fuels), irrespective of ERU values. Concerning the World Bank’s support to the electricity sector, Munasinghe defined the long-run marginal cost “broadly as the incremental cost of optimum adjustments in the system expansion plan and system operations attributable to an incremental demand increase which is sustained into the future”.

The study by McGowin, Hughes and Holt (1998a), carried out for UNDP’s and the World Bank’s GEF-supported biomass-fuelled GCC development project in Brazil, is one of the few examples of a technology assessment carried out in this very context. These authors provide future unit electricity production costs for biomass-fuelled GCC in comparison with a wide range of alternative candidate technologies under typical utility conditions in developing countries. According to Waldheim and Carpentieri (1998), this type of evaluation was also specifically made for the Brazilian market during the preparations of the said Brazilian project. However, a generic technology evaluation must necessarily generalise away from country-specific expansion plans and assume typical parameter values.

Due to the availability of ERU-based finance, the implementation of a CDM scenario could have an impact on the position of GCC and single-site LCC technologies in developing countries. One possible interest, based on which the development of GCC and single-site LCC technologies could be supported, is the potential reduction of ERU production costs. In Section 6.2.3 it was shown that this is the reason why UNDP and the World Bank are involved in the development of the GCC technology. However, any study in which the potential of the biomass-fuelled GCC concept is assessed in view of the reduction in ERU costs could not be identified. If such study is planned, then single-site LCC and multiple-site LCC deserve a similar consideration.

6.5.3 Some elements of a view on the development of biomass based electricity technology

The work by the IPCC, for the UNFCCC, has been trail-blazing for the penetration of ideas about making our economies more sustainable. In view of the complex nature of the IPCC’s assignment, its assessment reports cannot help but be brief on single issues such as biomass energy. This thesis is an attempt to more fundamentally consider and elaborate upon one of the many options reviewed by the IPCC. The IPCC strongly emphasizes biomass-fuelled GCC as the exemplary concept of modern biomass-based electricity

320/ Munasinghe (1979), p. 25.
One of the justifications brought forward is the high expectation of future reductions in the capital costs of implementing this technology. A second, and necessary, assumption made by the IPCC to justify its position, is a low cost estimate for the supply of biomass fuels. The costs quoted by Ishitani and Johansson (1995), for the growing of energy crops in industrialised countries projected for the year 2020, are with a range of about 1.7-2.0 €/GJ, quite low. This is some two to four times lower than cost projections prepared for the EU and quoted in this study (Section 4.3.1). A reason might be that all of the sources quoted by Ishitani and Johansson concern the USA. Based on their two assumptions for capital and fuel costs, the authors estimate that in the near future the technology could successfully compete with modern coal-fired power plants. In my research the hoped for capital cost reductions are neither accepted or rejected. Rather the conviction is disputed that biomass fuels could become available in the required amounts at a sufficiently low cost. As a consequence, it is concluded that one of the necessary conditions for wide-scale implementation of biomass-fuelled GCC technology in EU-type industrialised countries is not satisfied. Therefore, although the technology might occasionally be economically feasible in certain locations, there will be no substantial impact on GHG emission reductions.

With its expectation that biomass-fuelled GCC technology will compete with modern coal fired power plants, the IPCC makes no distinction between markets in developing countries and in industrialised countries. At least in so far as industrialised countries such as the member states of the EU are concerned, the current study draws conclusions which significantly disagree with those by the IPCC. For developing countries, although some first steps have been made - notably by McGowin, Hughes and Holt (1998a) referred to earlier - comprehensive studies, taking into account long-run marginal costs and low value ERU scenarios, have not been identified. Again, one should, in addition to GCC, also consider the potential of single-site LCC and multiple-site LCC technology for these countries. Such studies are relevant because they will show which technology developments are necessary to enable the further expansion of the electricity sector in third world countries in an environmentally sustainable manner - and taking advantage of additional foreign ERU-based finance.

However, developing countries could play a much larger role in GHG emission reduction than that of mere producers of ERUs based on their own avoided use of fossil fuels. They may also become producers of biomass-derived fuels - bio-oil - by means of which industrialised countries can avoid using fossil fuels. In the assessment of the multiple-site LCC technology, in Section 6.3, it was assumed that developing countries, after the technology has become mature and then during its economic lifetime, are able to export biomass-derived fuels at attractive prices. Today that assumption may be reasonable, but one wonders whether by 2010-2030 these countries will still be willing to export biomass-derived fuels at attractive costs, or whether their economies will have developed to the extent that local utilisation of their own biomass potential will have become equally, if not more, attractive. Their ongoing development may thus eventually result in higher biomass

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fuel prices. Whether the multiple-site LCC technology would still be able to find sufficient quantities of low cost biomass feedstocks under that favourable development scenario is not discussed here, since any attempt would necessarily be replete with speculation. Instead it is simply noted that the development of the multiple-site LCC technology provides fascinating opportunities for the further economic development of third world countries as suppliers of biomass-derived fuels. Particularly since one implication of the assessment made here is that none of the technologies reviewed offer sufficient development potential for the application of biomass fuels produced locally within EU-type economies. This conclusion does not change even if the countries obliged under the UNFCCC are forced to implement their GHG emission reduction targets by other means than CDM and worldwide emission trading, i.e. by domestic abatement and intra-Annex I JI. The associated expected rise in ERU values to levels of around 40 or even 90 €/t GHG (see Table 35) would not make a difference. In addressing climate change, developing countries could yet become indispensable partners to industrialised countries.
7 IDENTIFYING A ROLE FOR BIOMASS GASIFICATION IN RURAL ELECTRIFICATION IN DEVELOPING COUNTRIES

7.1 THE PROBLEM

The provision of electricity to households in the rural areas of developing countries is an objective which has been recognized by governments of these countries as well as by donor agencies and international financing institutions. This chapter addresses the potential of certain technical approaches which are being employed, or may be employed, for rural electrification. Rural electrification is characterized as follows:

• The areas are remotely located from large-scale electricity grids.
• The projected electricity consumption shows a need for the installation of small power capacities.\(^{324}\)
• The projected electricity consumption pattern necessitates the operation of installed power capacities at low capacity factors,\(^ {325}\) which means that the installed capacity (and hence the capital invested) is used much less intensively than in the case of medium and large scale power plants.

In addition to the extension of existing electricity grids, the options capable of coping with these technical and economic conditions include:

• The creation of small isolated grids, powered by small generators.
• The provision to individual households of batteries, charged at a central station powered by a small generator.
• The provision to individual households of their own solar powered home systems.

This chapter does not consider the latter option, but is about the type of small scale generators employable in the first two options. Typical scales for these small power generating plants are 10-200 kW\(_e\).

The particular question investigated here is, under which economic conditions could biomass gasification play a role in these small power generating plants? Biomass gasification, as opposed to fossil-fuel driven generators, has the advantage that biomass fuels may be produced locally and therefore more cheaply than fossil fuels. A further reason for considering biomass gasification is its potential to be exploited in a sustainable manner in terms of greenhouse gas emissions. The question of the potential role of biomass gasification is approached from two directions:

• Technology oriented, given typical economic conditions and the state of the art of the gasification technology - What are the prospects for the biomass gasification technology? What will be the influence of changing economic conditions? Are there prospects for advanced developments in biomass gasification technology?
• User oriented, given location-specific economic conditions, and the state of the art of gasification technology - do local conditions favour biomass gasification?

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323/ This chapter, in an adapted form, has been published in the journal Biomass & Bioenergy (Siemons (2001)).
324/ ‘Power capacity’ is defined in Appendix F.
325/ ‘Capacity factor’ is defined in Appendix F.
Whereas the first approach is of relevance to those who determine R&D strategies, the latter addresses the questions usually asked by potential users of biomass gasification technology.

The role of biomass gasification is not a matter of economics alone. There are a number of other issues that determine its potential, economic feasibility being just one of the conditions. However, as one of the key conditions, it needs a particular analysis - the focus of this chapter.

7.2 METHODOLOGY

Within the framework of small-scale power generation, the obvious alternative to biomass gasification is to utilize diesel fuel in an internal combustion engine linked to an electricity generator. The biomass gasification system would consist of a gasifier with gas filter, an internal combustion engine and an electricity generator. The two systems are illustrated in Figure 57.

The differences between the diesel and the gasification options are primarily characterized by their investment and operating costs (Table 45). Hence the choice between the two options is a conventional investment decision. The tools to evaluate such decisions are strongly developed, enabling a subtle and differentiated solution. The aim of this assessment, however, is to draw general conclusions and to develop generally applicable tools - tailored to producing easily applied rules of thumb. Therefore the following issues are ignored: the role of inflation, profit taxes, loan gearing, and project development costs. Further, the nature of the technologies considered is such that multi-year start-up does not
play a role. In view of the objectives of this analysis, therefore, an annuity method for capital cost determination may be sufficient.

**Table 45. Approximate characterization of diesel and biomass gasification alternatives.**

<table>
<thead>
<tr>
<th></th>
<th>Biomass gasification system</th>
<th>Diesel system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Operating cost</td>
<td>Often low</td>
<td>Often high</td>
</tr>
</tbody>
</table>

The parameters determining the economic feasibility of biomass gasification for rural electrification can be distinguished into those determined by the location where (and the user - by whom) the technology will be employed (the site parameters); and those determined by the technology (the technology parameters). The technology parameters are:

- Investment.
- Technical lifetime of system components.
- Energy conversion efficiency and calorific values of the fuels.
- Operator costs.
- Consumables utilisation (cost).
- Maintenance costs.

These technology parameters may differ depending on power capacity, and perhaps even for different countries or regions, but once they have been established the feasibility of biomass gasification depends on the following site parameters:

- Discount rate.
- Capacity factor.
- Biomass fuel price.
- Diesel fuel price.

The appropriate discount rate is a matter of the enterprise considering the investment. Utilities usually assume a discount rate of 10%-15% (Jechoutek (1992)), depending on the particular economic conditions under which they operate. A private enterprise, on the other hand, may set its discount rate at 30% or higher. Also the capacity factor is location specific. It is strongly determined by the presence of local industries and commercial services or hospitals. In their absence, electricity consumption is limited to household use only, thus lowering the capacity factor. Finally, in developing countries, fuel prices are different from one country to another and from one region to another. This particularly applies to biomass fuels, but transport distances may also result in a range of prices for fossil fuels within one country.

The calculation model developed for the analysis is built-up as shown in Table 46. The symbols in this table have the following meaning:

- **R** Annuity of the gasifier investment (R: reactor),
- **GasE** Annuity of the gas engine (GasE: gas engine),
- **DE** Annuity of the diesel engine (DE: diesel engine),
- **Gen** Annuity of the electricity generator (Gen: generator),
H Annuity of the Hand factors\textsuperscript{326} for piping, isolation, electrical wiring, instrumentation, controls, software and assembly,

BF The cost of biomass fuel,

DF The cost of diesel fuel,

LB The cost of lubricants used for the biomass gasifier system,

LD The cost of lubricants used for the diesel system,

MB Maintenance cost applicable to the biomass gasifier system,

MD Maintenance cost applicable to the diesel system.

\textbf{Table 46. The calculation model.}

<table>
<thead>
<tr>
<th>Cost item</th>
<th>Production cost (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biomass gasifier system</td>
</tr>
<tr>
<td>Capital cost (annuity)</td>
<td></td>
</tr>
<tr>
<td>Gasifier</td>
<td>R</td>
</tr>
<tr>
<td>Gas engine</td>
<td>GasE</td>
</tr>
<tr>
<td>Diesel engine</td>
<td>DE</td>
</tr>
<tr>
<td>Generator</td>
<td>Gen</td>
</tr>
<tr>
<td>Hand factors</td>
<td>H</td>
</tr>
<tr>
<td>Working capital</td>
<td>x</td>
</tr>
<tr>
<td><strong>Operational cost</strong></td>
<td></td>
</tr>
<tr>
<td>Operator</td>
<td>x</td>
</tr>
<tr>
<td>Biomass</td>
<td>BF</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>DF</td>
</tr>
<tr>
<td>Lubricants</td>
<td>LB</td>
</tr>
<tr>
<td>Maintenance</td>
<td>MB</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td>TB</td>
</tr>
</tbody>
</table>

\textit{x}: neglected (cost are assumed equal for the two options)

TB and TD are the respective total production costs, representing the long-run marginal cost for providing electricity to newly established isolated distribution grids (the term was introduced in Section 6.5.2, with a reference to Munasinghe (1979)). TI is the incremental production cost of electricity produced with the gasifier system relative to the diesel system. All costs are expressed on a product basis (€/kWh).

\textit{Completing the model with data}

For the determination of capital costs, a project duration of ten years was assumed. The value of the investments at the end of year 10 was assumed to be zero. Generally, the depreciation period was set equal to the project duration. However, the technical lifetime of some of the system components may be shorter than the project duration. In this case reinvestment is required and, accordingly, the depreciation period was set to the appropriate technical life. Capital cost items could be extended further by the interest cost of working capital. The nature of the projects considered is such, however, that such costs may be neglected in the comparison. The same applies to the cost of the required operators - they are assumed to cancel out in the comparison. Major operational cost items are fuel and lubricants. Fuel costs are determined by energy conversion efficiency as well as by the specific fuel prices (€ per litre or tonne).

\textsuperscript{326} After the cost estimation method developed by W.E. Hand.
Elaboration and interpretation

If the resulting incremental costs (€/kWh) are zero or negative, the additional capital invested in the gasifier project yields a return rate which is equal or higher than the discount rate. Hence, the biomass gasification option is economically feasible. Whether or not this is the case depends in the following manner on the site parameters:

- **Discount rate:** Due to the relative differences in capital involvement in the two options, a low discount rate favours the biomass gasification option.
- **Capacity factor:** The capacity factor may influence unit production costs in two opposing directions. The negative feedback of the more intensive capital utilization (lower production costs) may be offset by decreased depreciation periods for those capital goods which have a shorter technical lifetime than the project duration. The influence of the capacity factor is strongest with the more capital intensive alternative (biomass gasification).
- **Biomass fuel price and diesel fuel price:** Since these directly affect the operating costs, the total incremental cost of the biomass gasifier system increases with increasing biomass fuel price, or decrease with increasing diesel fuel price.

The calculation algorithm is further elaborated by deriving sets of site parameters with which the incremental costs for the biomass gasifier system are equal to zero. Where these sets apply in reality, the biomass and diesel alternatives are equally attractive. Elsewhere there will be an economic preference for one of the two options. The sets of site parameters are reproduced in two-dimensional diagrams, one type of which is illustrated in Figure 2. The line separating the two ‘feasibility niches’ in this figure in an equi-IRR line as defined in Chapter 3. Since, as specified above, there are four independent site parameters, there are six two-dimensional diagrams indicating conditions of equal costs. The graphs thus produced are used to address the questions raised above.
The graphs are determined according to the procedure described in Section 3.3. An appropriate equations is:

\[
[diesel \ fuel \ price]_{\text{breakeven}} = [diesel \ fuel \ price \times (1 \ % TI/DF)]_{\text{assumed}},
\]

where the assumed diesel fuel price is the price with which TI and DF have been determined according to the calculation procedure explained above. This means that the diesel fuel price is implicitly present in the two parameters TI and DF. This is a relevant remark since the equation given suggests, erroneously, that the breakeven diesel price would be directly proportional to the diesel price. In fact it is independent of that price.

Another equation, yielding the same equi-IRR functions, is:

\[
[biomass \ fuel \ price]_{\text{breakeven}} = [biomass \ fuel \ price \times (1 \ & \ TI/ BF)]_{\text{assumed}}.
\]

Again, the fuel price (here the biomass fuel price) is also implicitly present in the other two parameters (here TI and BF) such that the fuel price is independent.

Finally, two remarks should be made about the type of economic evaluation carried out here. 1) The analysis is on the project level from the viewpoint of the private investor. Hence market prices, rather than border prices or shadow prices, are used. 2) With the development of the so-called flexible tools (Joint Implementation, Clean Development Mechanism, emission trading) avoided greenhouse gas emissions can be valued in monetary terms and transferred to the private investor in a project. The effects of this particular type of internalisation are investigated later in Section 7.5.3.
7.3 ELABORATION FOR THREE TYPICAL POWER CAPACITIES

The power capacities concerned with rural electrification - in so far as the feeding of isolated grids or of battery charging stations is concerned - range from 10 to about 200 kW. In this investigation, three cases, representing typical capacities for which distinctive economies of scale may be expected to apply (i.e. 10, 40 and 160 kW) are examined. For the 10 kW system, the fuel for the biomass gasifier system is charcoal. For 40 kW either wood or charcoal could apply, and for 160 kW wood is assumed.

7.3.1 The technology parameters

Investments

Biomass gasifiers are offered by a small number of manufacturers. 14 were reported by Reed and Gaur (1999), of which only a few were able to guarantee the performance of their equipment, mainly due to lack of experience. Given the few suppliers, and the few projects implemented, the analysis, which is aimed at the assessment of the future of biomass gasification technology, should not be limited to cost quotations of systems offered to date. An understanding of the cost breakdown of the investments is as important, if not more so. Nevertheless, it makes sense to review investment costs which appear in current and past markets.

On the basis of the ‘small-scale biomass gasifier monitoring programme’ carried out by UNDP and the World Bank, Stassen (1995) reports the investment data reviewed in Table 47 (see also Knoef and Stassen (1997) for a more elaborate review). The programme was carried out between 1983 and 1990. The gasifiers monitored originated from a number of countries. Bridgwater (1990) reviewed the investment costs for a range of essentially larger capacities (i.e. 0.1-10 MW) than the capacities investigated here. His analysis is therefore not immediately suitable for this study.

Table 47. Investment costs of monitored gasifier systems (US$/kW), after Stassen (1995).

<table>
<thead>
<tr>
<th>Cost item</th>
<th>10 kW</th>
<th>30 kW</th>
<th>100 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasifier incl. filter and gas cooler</td>
<td>217-1001</td>
<td>225-1035</td>
<td>159-880</td>
</tr>
<tr>
<td>Gas engine</td>
<td>466</td>
<td>300</td>
<td>185</td>
</tr>
<tr>
<td>Generator, incl. electrical controls</td>
<td>402</td>
<td>259</td>
<td>160</td>
</tr>
<tr>
<td>Total</td>
<td>1085-1869</td>
<td>784-1594</td>
<td>504-1225</td>
</tr>
</tbody>
</table>

In this analysis the cost estimates presented in Table 48 were used. These apply to turn-key gasifier systems, ex manufacturer. Thus transportation costs are excluded. Neither has a start-up and training component been included. This does not imply that such costs would be negligible. They are to be included as a further refinement. The cost analysis given in Table 48 is an attempt to create some coherence between the cost estimates for

---

327/ Gasifier systems monitored were located in Indonesia, the Philippines, Brazil, Vanuatu, Mali, Seychelles and Burundi.
different gasifier systems and their alternative (diesel gensets). The system components in the various systems are distinguished. Generally, for each component use is made of scale factors in the range 0.4-0.7, depending on the type of component. In small gasifier systems, mechanised fuel preparation, storage and feeding units are not required. Charcoal gasification reactors are substantially cheaper than wood gasification reactors, due to the more complicated construction of the latter. Engine derating (which takes place when petrol engines are converted to run on gaseous fuels) essentially results in higher costs for gas engines in comparison with diesel engines. Finally, all the components have to be integrated into one system. The associated costs are reflected in the Hand factors. It is shown that in larger gasification systems substantially higher integration costs are involved. The resulting prices fit reasonably well within the ranges given by Stassen (1995), particularly at the lower capacity range. For higher capacities, prices were verified with Kara Energy Systems (Reinders (2000)).

Table 48. Gasifier system investment costs used in this study (€/kWe).

<table>
<thead>
<tr>
<th>Cost item</th>
<th>Capacity (kWe) and fuel</th>
<th>10 charcoal</th>
<th>40 charcoal</th>
<th>160 charcoal</th>
<th>10 diesel</th>
<th>40 diesel</th>
<th>160 diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic equipment (BE)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasifier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel preparation</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fuel storage</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Fuel feeder</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Reactor</td>
<td>460</td>
<td>264</td>
<td>660</td>
<td>500</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dust filter</td>
<td>100</td>
<td>60</td>
<td>240</td>
<td>180</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tar filter</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gas cooler</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Gas engine</td>
<td>370</td>
<td>160</td>
<td>160</td>
<td>70</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Diesel engine</td>
<td>-</td>
<td>300</td>
<td>-</td>
<td>-</td>
<td>120</td>
<td>-</td>
<td>50</td>
</tr>
<tr>
<td>Generator</td>
<td>420</td>
<td>420</td>
<td>180</td>
<td>180</td>
<td>80</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>Total basic equipment</td>
<td>1,300</td>
<td>720</td>
<td>714</td>
<td>1,290</td>
<td>300</td>
<td>1,800</td>
<td>130</td>
</tr>
<tr>
<td>Hand factors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piping, isolation</td>
<td>26</td>
<td>-</td>
<td>14</td>
<td>26</td>
<td>-</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>Electrical wiring</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>54</td>
<td>-</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>108</td>
<td>-</td>
</tr>
<tr>
<td>Controls, software</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>108</td>
<td>-</td>
</tr>
<tr>
<td>Assembly</td>
<td>65</td>
<td>-</td>
<td>36</td>
<td>64</td>
<td>-</td>
<td>18</td>
<td>-</td>
</tr>
<tr>
<td>Transport to site</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Erection on site</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Training</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Production start-up</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Insurance</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total investment</td>
<td>1,391</td>
<td>720</td>
<td>764</td>
<td>1,380</td>
<td>300</td>
<td>2,124</td>
<td>130</td>
</tr>
</tbody>
</table>

Hand factors as % of BE

<table>
<thead>
<tr>
<th></th>
<th>2%</th>
<th>-</th>
<th>2%</th>
<th>2%</th>
<th>-</th>
<th>2%</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical wiring</td>
<td>0%</td>
<td>-</td>
<td>0%</td>
<td>0%</td>
<td>-</td>
<td>3%</td>
<td>-</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>0%</td>
<td>-</td>
<td>0%</td>
<td>0%</td>
<td>-</td>
<td>6%</td>
<td>-</td>
</tr>
<tr>
<td>Controls, software</td>
<td>0%</td>
<td>-</td>
<td>0%</td>
<td>0%</td>
<td>-</td>
<td>6%</td>
<td>-</td>
</tr>
<tr>
<td>Assembly</td>
<td>5%</td>
<td>-</td>
<td>5%</td>
<td>5%</td>
<td>-</td>
<td>1%</td>
<td>-</td>
</tr>
</tbody>
</table>
Technical lifetimes

Hard information on the technical lifetimes of the various system components is not available, and hence estimates have to be made. Whereas it is reasonable to suppose that gasifiers can be easily made with technical lifetimes equal to the project duration, this does not apply to every candidate gas engine. The technical lifetime of a mass-produced retrofitted petrol engine (in the 10 kW<sub>m</sub> range) is 2000 full-load equivalent hours (Lambregtse (2000)). Other engines which might be employed are second-hand overhauled and retrofitted car engines. These engines prior to their overhaul for a gasifier project generally have already had a technical lifetime of about 3000 full-load equivalent hours; and it is probably reasonable to assume another 5000 full-load equivalent hours during their use in a gasifier project, since the overhauled engines would be utilised under considerably less stressful conditions. However, as shown Section 7.3.2, the applicable capacity factors may easily result in annual operational loads of about 3000-5000 full-load equivalent hours or more, and the approach of considering retrofitted new or second-hand engines would necessitate frequent reinvestments. Although this is not impossible to organise, the more expensive alternative of using new gas engines, sturdy enough to have a lifespan of up to 30,000 full load equivalent hours, is considered instead. The same is assumed for the generators. The issue of retrofitted equipment is considered further when interpreting the evaluation results (Section 7.5).

Other technology parameters

Energy conversion efficiencies and the calorific values of the fuels are reviewed in Table 49, along with consumables and maintenance cost.

Table 49. Technology parameter values for the various cases.

<table>
<thead>
<tr>
<th>General technology parameter values</th>
<th>Charcoal</th>
<th>Wood</th>
<th>Diesel fuel</th>
<th>Density diesel fuel (t/m&lt;sup&gt;3&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net calorific value, wet basis (GJ/t)</td>
<td>28</td>
<td>14</td>
<td>43</td>
<td>0.70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case specific technology parameter values</th>
<th>Capacity (kW&lt;sub&gt;e&lt;/sub&gt;) and fuel</th>
<th>10</th>
<th>40</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>charcoal</td>
<td>wood</td>
<td>wood</td>
<td></td>
</tr>
<tr>
<td>Energy conversion efficiency (% on NCV&lt;sub&gt;w&lt;/sub&gt;)</td>
<td>Biomass gasifier system</td>
<td>12.5%</td>
<td>16%</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>Fossil-fuelled alternative</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>Maintenance (% of equipment cost /8000 full load equivalent hr)</td>
<td>Biomass gasifier system</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>Fossil-fuelled alternative</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Lubrication ($/kWh)</td>
<td>Biomass gasifier system</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Fossil-fuelled alternative</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
</tr>
</tbody>
</table>
### 7.3.2 Three site parameters: capacity factor, biomass prices and diesel fuel prices

In this section capacity factor, and biomass and diesel fuel prices are considered. Meunier (1990) reports capacity factors between 6% and 50% (where the 50% is exceptionally high due to the use of street lighting) achieved with rural electrification in five Asian countries: Bangladesh, India, Pakistan, Philippines, and Thailand. For likely capacity factors, typical conditions for rural electrification are analysed in Table 50. If households alone are provided with electricity, a capacity of 7% appears to be typical. Higher values may be achieved if additional applications are found. If commercial or industrial activities are also served, the capacity factor may reach a value of 35%. If a battery charging service was to be provided with electricity from the generating system, a capacity factor as high as 55% could be achieved since case battery charging could be continued overnight. Note that the systems considered here envisage one single generator set. Under some circumstances it may be preferable to install a second, diesel, engine for peak load provision and back-up. The load factor of the gasifier system could then be increased. For example, in the case of the second application in Table 50 (households plus commercial or industrial services), from 50% to 90%. As a result, the capacity factor would increase from 35% to 60%.

#### Table 50. Capacity factors for various modalities of rural electrification.

<table>
<thead>
<tr>
<th>Option for use of isolated grid</th>
<th>Unit</th>
<th>Households only</th>
<th>Households plus commercial or industrial services</th>
<th>Households plus battery charging service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter values</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational period (OP)</td>
<td>week/year</td>
<td>52</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>day/week</td>
<td>7</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>hour/day</td>
<td>4</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Planned maintenance during OP (PM)</td>
<td>% of OP</td>
<td>0%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Availability factor during (100%-PM)*OP</td>
<td>% of (100%-PM)*OP</td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Load factor</td>
<td></td>
<td>50%</td>
<td>50%</td>
<td>80%</td>
</tr>
<tr>
<td>Calculated values</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity factor (CF)</td>
<td></td>
<td>7%</td>
<td>35%</td>
<td>55%</td>
</tr>
<tr>
<td>On-stream time (OST)</td>
<td>hour/year</td>
<td>1,310</td>
<td>6,066</td>
<td>6,065</td>
</tr>
<tr>
<td>Full-load equivalent hours</td>
<td>FLE hour/year</td>
<td>655</td>
<td>3,033</td>
<td>4,852</td>
</tr>
</tbody>
</table>

The diesel fuel prices considered are financial prices, i.e. the prices as they are observed by the end user, including taxes and subsidies. In 1998, the average diesel fuel price in Sub-Saharan Africa was 0.4 US$/l (The World Bank, Transport Division and International Energy Agency, 1998). The maximum price found was in Burundi (0.8 US$/l), the lowest in Zimbabwe (0.2 US$/l). For developing countries in Asia and the Pacific region, the World Bank Transport Division reports a substantially lower average of 0.2 US$/l, a maximum of 0.3 US$/l (Bangladesh) and a minimum of 0.04 US$/l (Indonesia). Developing countries in the Americas show an average of 0.4 US$/l, a maximum of 0.6 US$/l (Grenada), and a minimum of 0.2 US$/l (Ecuador). Levies and taxes are a substantial cost component of diesel fuel prices as observed by end users. These are
different in various countries and for various applications. Levies and taxes imposed on diesel fuel intended for commercial, non-transport, purposes are often lower than those charged on transport fuels. It is therefore interesting to compare the above quoted data with the outcomes of a pricing model reported by Berg, Boot, Dykstra et al. (1997). The model yields ex-factory diesel prices, calculated for large refineries, and thus provides a fair indication of the lowest non-subsidised diesel cost excluding levies, taxes and transport costs (a typical result is also included in Table 51).

Public databases with more or less complete reviews of biomass fuel prices do not exist. A number of reports published by the World Bank, various governments, and the FAO provide some details of these prices but they are not available in a systematic manner. Wood is a rural fuel, and hence consumer prices are a good indicator for this study. This is different to charcoal, which, although produced in the rural areas, is a fuel used in urban settlements. Biomass fuel prices for Ghana, Indonesia, Mali and Vanuatu are given in Table 51.

<table>
<thead>
<tr>
<th>Country</th>
<th>Charcoal a/</th>
<th>Wood b/</th>
<th>Diesel fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>€/t €/GJ</td>
<td>€/t €/GJ</td>
<td>€/l €/GJ</td>
</tr>
<tr>
<td>Ghana</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production Zone</td>
<td>60</td>
<td>2.11</td>
<td>15</td>
</tr>
<tr>
<td>Accra</td>
<td>120</td>
<td>4.21</td>
<td>30</td>
</tr>
<tr>
<td>Indonesia</td>
<td>93</td>
<td>3.30</td>
<td>16</td>
</tr>
<tr>
<td>Mali</td>
<td>85</td>
<td>2.99</td>
<td>27</td>
</tr>
<tr>
<td>Vanuatu - Tanna</td>
<td>146</td>
<td>5.12</td>
<td>37</td>
</tr>
<tr>
<td>Diesel Fuel ex refinery (Rotterdam) b/</td>
<td></td>
<td></td>
<td>0.17</td>
</tr>
</tbody>
</table>

b/ At crude oil price of 18 US$/barrel, 1 US$ = 0.90 €. Calculated according to Berg, Boot et al. (1997).

### 7.4 CALCULATION RESULTS

The results of the model calculations are presented in Figures 59-70, for the three sizes of system. The graphs show that if the capacity factor is below 30% then it strongly influences the economic feasibility of the gasification options. Above a value of 30%, capacity factors have little influence. Two extremes are therefore used (i.e. capacity factors of 10% and 50%) to illustrate the conclusions.
Figure 59, 10 kW Charcoal: Equi-IRR lines (comparing charcoal gasification and diesel fuelling) for varying capacity factors and diesel fuel prices calculated at an IRR of 10%.

Figure 60, 10 kW Charcoal gasification: Equi-IRR lines (comparing charcoal gasification and diesel fuelling) for varying fuel prices calculated at an IRR of 10%.

Figure 61, 10 kW Charcoal gasification: Equi-IRR lines (comparing charcoal gasification and diesel fuelling) for varying fuel prices calculated at an IRR of 25%.

Figure 62, 40 kW Charcoal: Equi-IRR lines (comparing charcoal gasification and diesel fuelling) for varying capacity factors and diesel fuel prices calculated at an IRR of 10%.

Figure 63, 40 kW Charcoal gasification: Equi-IRR lines (comparing charcoal gasification and diesel fuelling) for varying fuel prices calculated at an IRR of 10%.

Figure 64, 40 kW Charcoal gasification: Equi-IRR lines (comparing charcoal gasification and diesel fuelling) for varying fuel prices calculated at an IRR of 25%.
Figure 65, 40 kW Wood: Equi-IRR lines (comparing wood gasification and diesel fuelling) for varying capacity factors and diesel fuel prices calculated at an IRR of 10%.

Figure 66, 40 kW wood gasification: Equi-IRR lines (comparing wood gasification and diesel fuelling) for varying fuel prices calculated at an IRR of 10%.

Figure 67, 40 kW wood gasification: Equi-IRR lines (comparing wood gasification and diesel fuelling) for varying fuel prices calculated at an IRR of 25%.

Figure 68, 160 kW Wood: Equi-IRR lines (comparing wood gasification and diesel fuelling) for varying capacity factors and diesel fuel prices calculated at an IRR of 10%.

Figure 69, 160 kW wood gasification: Equi-IRR lines (comparing wood gasification and diesel fuelling) for varying fuel prices calculated at an IRR of 10%.

Figure 70, 160 kW wood gasification: Equi-IRR lines (comparing wood gasification and diesel fuelling) for varying fuel prices calculated at an IRR of 25%.
7.5 INTERPRETATION

7.5.1 Preliminary assessment

The conditions under which biomass gasification would become economically feasible are discussed below.

General

The feasibility of biomass gasification is very site specific due to large differences in prevailing fuel prices at various locations. Attempts to increase the economic viability of biomass gasifiers by employing them for base load (i.e. at capacity factors higher than 50%), with diesel gensets supplying the peak load, will not be successful: the best achievable economic conditions are already achieved with a capacity factor of 50%. Increasing it further does not substantially affect the comparative feasibility of gasification.

10 kW\textsubscript{c} charcoal gasification

The graphs (Figures 60, 61) show that in Vanuatu charcoal gasification at a capacity of 10 kW\textsubscript{c} could be economically feasible if a capacity factor of at least 50% was achieved. However, even at such a high capacity factor, an IRR of 25% cannot be attained. It is further clear that charcoal gasification is not economically feasible in Ghana, Indonesia and Mali, even with very large capacity factors.

40 kW\textsubscript{c} charcoal and wood gasification

Comparing Figures 62 and 65 reveals that the gasification of wood is somewhat more sensitive to the capacity factor than the gasification of charcoal. This is due to the relatively larger requirement for capital in wood gasification. Just as with the 10 kW\textsubscript{c} system, the fuel price conditions prevailing in Indonesia and Mali prevent the economic feasibility of a 40 kW\textsubscript{c} gasification plant. The situation in Vanuatu is different. Here, charcoal gasification projects could be feasible if capacity factors higher than 10% can be achieved. However, the applicable discount rate needs to be 10% or lower. Wood gasification at a capacity of 40 kW\textsubscript{c} is less attractive than charcoal gasification. The best situation for wood gasification is provided by Vanuatu, but capacity factors need to be substantially higher than 10% to make an attractive project.

160 kW\textsubscript{c} wood gasification

Especially with capacity factors below 40%, the economic feasibility is very sensitive to the number of kilowatt-hours produced from a 160 kW\textsubscript{c} wood gasification plant (Figure 68). Figures 69 and 70 show that in Vanuatu a feasible project achieves a capacity factor of 50%. In Ghana, Indonesia and Mali 160 kW\textsubscript{c} wood gasifiers are not economically feasible.
7.5.2 The investment level

The sensitivity to investment level is examined with the 160 kW case (see Figures 71-72). Naturally, the sensitivity to the investment requirement is greatest at low capacity factors. Even a decrease in costs by 30% is not sufficient to make wood gasification a feasible option if the capacity factor does not reach a level of about 50%. Around this value, a change in the investment by plus or minus 30% can be decisive (consider Vanuatu, Figure 72).

![Figure 71](image1.png)

**Figure 71.** Equal cost lines for different investment levels at a capacity factor of 10%.

![Figure 72](image2.png)

**Figure 72.** Equal cost lines for different investment levels at a capacity factor of 50%.

To investigate where cost reductions could be achieved, the investment breakdown shown in Figure 73 was used. The major cost component, in all four gasification cases considered, is the gasifier. This item could certainly be produced at lower costs. Whether the potential for cost reductions is limited to 30% is not investigated here. It seems especially to be a matter of production volume.
It is sometimes claimed that investment costs for gasifier systems may be drastically reduced by employing cheaper gas engines. An alternative to the brand new gas engine, as assumed for the 10 kW case, would be to utilize a second-hand overhauled 30 kWm car engine, converted from petrol to gas fuel. (Note that the retrofitting of an internal combustion engine from a liquid fuel to a gaseous fuel results in capacity derating. This will have an impact on capacity-specific investment costs (€/kW).) Also in the case of the 40 kW gasifier systems an overhauled and retrofitted car engine (in this case originally 60 kWm) would be technically feasible. The costs of this type of engine are estimated at 230 and 100 €/kWm, for the 10 kWm and 40 kWm engines respectively. This is substantially cheaper than the costs of new gas engines (370 and 160 €/kWm in the calculations). However, the influence on the total investment is small (between 4% and 10%, relative to the original investment), and therefore, the use of such engines is not the first step in decreasing capital costs to a level which makes gasifier projects economically feasible.

Whereas the cost estimates employed so far in this thesis are basically for one-off custom-built systems, the principal way to achieve major cost reductions is through the large-scale production of gasifiers. Large-scale gasifier production requires a large market, which in turn means that the range of applications must be wide. They should therefore include applications with the usual low capacity factors of about 10%. At the same time, gasifiers need to be attractive to local private entrepreneurs in developing countries. Therefore, high discount rates of around 25% should be assumed in determining allowable investment levels. Such levels, determined using the typical fuel prices applicable in Vanuatu, are given in Table 52. Drastic cost reductions are thus required. If instead of private entrepreneurs, utilities are the investors in rural electrification, then a discount rate of 10%
may be assumed. As a result of the lower discount rate, slightly higher investments are acceptable. Table 52 also shows the costs of the gas engine and the generator, which are unaffected by developments in the cost of gasifier construction. The available margin for reducing the cost of the gasifier concerns the cost of the Base case minus the gas engine and the generator; and this margin seems quite small.

Table 52. Allowable investments (€/kWc) at two discount rates (30% and 10%) and a capacity factor of 10%.

<table>
<thead>
<tr>
<th>Capacity and fuel</th>
<th>Vanuatu Base case, of which gas engine</th>
<th>of which generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>10 kWc, charcoal</td>
<td>870</td>
<td>960</td>
</tr>
<tr>
<td>40 kWc, charcoal</td>
<td>450</td>
<td>730</td>
</tr>
<tr>
<td>40 kWc, wood</td>
<td>700</td>
<td>1030</td>
</tr>
<tr>
<td>160 kWc, wood</td>
<td>630</td>
<td>930</td>
</tr>
</tbody>
</table>

7.5.3 Fuel prices: the cost of sustainability

It is often argued that due to growing oil scarcity, diesel fuel prices will rise over the forthcoming decades. Such a development would definitely create more favourable conditions for biomass gasification at locations to which national electricity distribution grids will not be extended. Another reason why diesel fuel may be economically valued at a higher price, is the emission of carbon dioxide during the combustion of fossil fuels. Each tonne of combusted diesel oil results in an emission of 3.21 tonnes of carbon dioxide, or, with a density of 0.8 t/m³, in an emission of 2.57 kg CO₂/l. From the data provided by the IPCC in its 1996 guidelines (IPCC (1996)), it can be inferred that contributions to other GHG emissions in the shape of CH₄ and N₂O emissions from diesel fuel use are negligible. If biomass fuels were grown in parallel to their use, the use of biomass fuels instead of diesel oil would effectively prevent all these GHG emissions. This would also apply if charcoal replaced diesel oil, but the use of charcoal would set particular constraints on the technology by which the charcoal is produced. Technically, zero emission charcoal production is possible. The IPCC remarks that traditional charcoal making is a large emitter of fugitive CH₄, and hence special caution is required here.

In Section 6.1 from recent Dutch JI projects, ERU values were estimated at about 10 €/t GHG. Also a longer term (2010) market expectation of 30 €/t GHG was quoted for a global trade scenario. Even higher ERU values of up to 90 €/t GHG were indicated, but these would apply in a restricted ‘domestic only’ emission reduction market in which developing countries did not participate. Therefore, we assume ERU values to range from 10-30 €/t GHG. Eventually, the associated values might be passed-on to rural electrification projects in some way or another. In the instance of avoided diesel fuel combustion, the range of ERU values is equivalent to 0.026-0.077 €/l diesel fuel. The result of applying a value to avoided CO₂ emissions (under the assumption that this value can be made payable in some way) is that the lines drawn in the graphs (Figures 59-70)

---

move downwards towards lower diesel fuel prices by values of 0.025-0.076 €/l. Compared to prevailing diesel prices, in most places, this shift is negligible. The conclusion can only be that current and projected ERU values will have no impact on the general observations made in this chapter about the role of biomass gasification in rural electrification.

Whether or not the global climate is at stake, sustainability of biomass supplies is a necessity for successful biomass gasification projects. This requires sufficiently high prices in order to set up and maintain sustainable production systems. With the exception of the biomass prices quoted for Vanuatu, it is not known to what extent the prices for biomass fuels referred to in this chapter meet this criterion.

7.6 CONCLUSIONS

To analyse the prospects of biomass gasification for the electrification of rural areas in developing countries, an annuity model to calculate production costs was developed. In order to create an equal basis of comparison, proper account has been taken of the differences in technical lifetime of certain components of the technical systems evaluated. The evaluation method distinguishes two types of parameters: technology and site parameters. The analysis tool, thus provided, yields discriminating conclusions about the feasibility of biomass gasification in different circumstances. The second basis for the analysis is a set of applicable technology parameters, including a coherent costing model. The evaluation methodology is also proposed as an assessment tool for quick scans of project feasibility.

Both the economic evaluation tool, and the costing model, are simplified to such an extent that only long-term global conclusions can be drawn. Project development costs, costs for transport of equipment, as well as taxes and some other refinements, are not incorporated in the evaluations.

It is shown that the value placed on avoided CO₂ emissions has a negligible impact on the feasibility of biomass gasification projects.

The capacity range considered (10-200 kWₑ) is treated by an investigation into three cases (10, 40 and 160 kWₑ). For the 10 kWₑ case, the fuel considered is charcoal. Both wood and charcoal are investigated for the 40 kWₑ capacity, and for the largest case (160 kWₑ) wood fuel is investigated. The analysis shows the following:

• Prevailing fuel prices and investment levels suggest that for small scale charcoal gasification (10-40 kWₑ) the conditions for economically feasible projects are easier to satisfy than for slightly larger scale wood gasification projects (40-160 kWₑ). Especially for the larger capacities of around 160 kWₑ, one factor is that, on a capacity basis, investments (€/kWₑ) are substantially larger. This is due to the need for fuel preparation, storage and feeding devices.
• It is not ruled out that there may be sites where biomass gasifier systems can be installed and operated in an economically viable manner, even at today’s cost levels.
for gasifier systems. However such sites will only represent a small niche, and they are difficult to locate.

- Although charcoal is more expensive than wood (on an energy basis) it can out compete wood as a fuel for gasification systems at capacities below 40 kW. One reason is the lower specific investment (€/kW) required for charcoal gasifiers.
- A large market for biomass gasifiers could exist if a drastic cost reduction is achieved by the manufacturing industry. Allowable cost levels are indicated. Probably the larger 160 kW systems will remain too expensive.

Discount rates are low if the public sector becomes involved. This sector may regard the 10-40 kW charcoal gasification option as potentially attractive if conditions in the relevant country are favourable (these conditions primarily concern fuel prices).

Mass production of biomass gasifiers, resulting in considerable cost reductions, would create opportunities for the technology. Further consideration of mass production needs a justification on the basis of a fuel price inventory covering a large number of countries.
APPENDIX A
A MATHEMATICAL PROOF OF PROPERTIES OF ISO- AND EQUI-IRR LINES

In this appendix, properties of the iso-IRR line and equi-IRR line, defined in Chapter 3, are mathematically investigated. Of especial interest is the dependence of these lines on parameters such as the discount rate, conversion efficiency and the investment required to install a particular technology in a plant. Thus, we have to consider parameter values away from the equilibrium conditions of a market. In Chapter 3 the parameters along the abscissa and ordinate were the unit costs of raw materials (UPCbiomass fuel) and of the product (here UPCelectricity), understood as market prices, so that the resulting net benefits of an investment yielded its IRR. Here, since we are considering a range of parameter values, also away from market prices, it is more appropriate to use an adapted terminology: that is discount rate (DR) instead of IRR, and unit manufacturing cost (UMC) instead of unit product price or product cost. In the analysis below, we therefore use the terms iso-DR and equi-DR lines, instead of iso-IRR and equi-IRR lines.

We start with a mathematical expression for the unit manufacturing cost (UMC). This is a function linking annualised capital (A), unit raw material cost (URC), and the conversion efficiency (η):

$$UMC = c_1 \times \frac{URC}{\eta} \times \frac{A(K)}{Q} \times c_2,$$

where K is the investment in the capital good involved, Q is the annual product quantity, and c₁ and c₂ are parameters that are independent of annualised capital, annual production, unit raw material cost and conversion efficiency. For example, c₁ might reflect the arithmetical conversion between product quantities, unit raw material costs, and conversion efficiency. Suppose that the product manufactured is electricity, so that UMC has the dimension of US$/kWh_e. If URC has the dimension of US$/t, and if η has the dimension of kWh_e/kWh_th, then c₁ has the dimension t/kWh_th, which is an inverted calorific value. The parameter c₂ may reflect labour and maintenance costs, expressed on a unit product basis.

The annuity of capital varies linearly with the capital investment K, and the discount factor A:

$$A = \frac{DR}{1 + (1 \times DR)^{t/2}}$$

so that:

$$UMC = \frac{c_1}{\eta} \times URC \times \frac{K}{Q} \times A \times c_2.$$
UMC depends linearly on URC with a gradient in the URC-UMC space of \( \frac{\partial (UMC)}{\partial (URC)} \), \( \frac{c_1}{\eta} \).

With a constant discount factor \( A \), the line described by Equation 5 in this space is an iso-DR line. In a simplified form this line is represented by the following equation:

\[
UMC = a \times URC \% b \times A \% c,
\]

with:

\[
a = \frac{c_1}{\eta}, \quad b = \frac{K}{Q}, \quad c = c_2.
\]

Two competing technologies (H and L) are capable of converting the same raw material into the same product, but their conversion efficiencies (\( \eta_H \) and \( \eta_L \)) differ, their fixed capital (\( K_H \) and \( K_L \)) differs, and other cost parameters (\( c_{2H} \) and \( c_{2L} \)) also differ. Thus, they have different unit manufacturing costs, UMC, according to the following equations:

\[
UMC_H = a_H \times URC \% b_H \times A \% c_{1H},
\]

and

\[
UMC_L = a_L \times URC \% b_L \times A \% c_{1L}.
\]

with:

\[
a_H = \frac{c_1}{\eta_H}, \quad a_L = \frac{c_1}{\eta_L}, \quad b_H = \frac{K_H}{Q}, \quad b_L = \frac{K_L}{Q}, \quad c_{2H}, \quad c_{2L}.
\]

Equations 7 represent the individual iso-DR lines for the respective technologies. Note that the parameter \( c_1 \) is equal for the two technologies (any distinction in the dependence of UMC on the unit raw material costs is represented by the difference in conversion efficiency). As a starting point assume that \( \eta_H > \eta_L \) and that \( K_H > K_L \). This situation is illustrated in Figure 74.
Since conversion efficiencies, $\eta$, are not equal, the two iso-DR lines intersect: there exists a value for URC (denoted by URC*) for which UMC_H equals UMC_L (a common value: UMC*). For varying discount rates - or discount factors $A$ - the set of values for (URC*, UMC*) make up the equi-DR line in the URC-UMC space (see Figure 74). The general expression for this line (for varying discount factor $A$, and hence varying URC*) is formed by:

$$ UMC^\dagger = a^\dagger \times URC^\dagger \times b^\dagger, \quad (9) $$

where $a^*$ and $b^*$ are functions of the parameters $a_H, a_L, b_H, b_L, c_H, c_L$ (defined in Equation 8), but are independent of discount factor $A$. To find expressions for $a^*$ and $b^*$, we apply the condition that UMC_H = UMC_L to Equations 7:

$$ a_H \times URC^\dagger \times b_H \times A \times c_H = a_L \times URC^\dagger \times b_L \times A \times c_L. \quad (10) $$

Based on Equation 10, the discount factor $A^*$ (with an asterix since referring to the intersection point) is now expressed as a function of URC:

$$ A^\dagger = \frac{(a_H \times a_L)}{(b_H \times b_L)} \times URC \times \frac{(c_H \times c_L)}{(b_H \times b_L)} \quad (11) $$

Substituting this expression into one of the Equations 7, we derive:

$$ UMC^\dagger = \frac{(a_L b_H \times a_H b_L)}{(b_H \times b_L)} \times URC \times \frac{(b_H c_L \times b_L c_H)}{(b_H \times b_L)} \quad (12) $$
using the definitions of the parameters \( a_H, a_L, b_H, b_L, c_H, c_L \) (Equation 8), UMC* becomes:

\[
\text{UMC}^* \times c_1 \times \left( \frac{K_H \times K_L}{K_H \times K_L} \right) \times \text{URC} \times \frac{(K_H \times c_{2H} \times K_L \times c_{2L})}{(K_H \times K_L)} \quad (13)
\]

By substituting Equation 11 into one of the Equations 7, an expression for URC* - the abscissa of the intersection point - can be derived, but this is not of interest here.

The gradient of the equi-DR line in the UMC-URC space equals:

\[
\frac{d(\text{UMC}^*)}{d(\text{URC})} = c_1 \times \left( \frac{K_H \times K_L}{K_H \times K_L} \right) \times \frac{(K_H \times c_{2H} \times K_L \times c_{2L})}{(K_H \times K_L)} \quad (14)
\]

Next, we investigate the dependence of this slope on the investment in the high-efficiency technology H. How does it change if \( K_H \) is lowered as a result of technology development and learning (ceterus paribus the fixed capital \( K_L \) of the low-efficiency technology and the conversion efficiencies)? For the analysis, \( K_H \) and \( \eta_H \) are expressed relative to \( K_L \) and \( \eta_L \) as follows:

\[
K_H = k \times K_L; \quad \text{and} \quad \eta_H = e \times \eta_L,
\]

\[ \text{with } k > 0 \text{ and } e > 1. \quad (15)\]

The value restrictions for parameter \( k \) and parameter \( e \), mean that \( \eta_H > \eta_L \) and that \( K_H \) may be smaller or larger than \( K_L \), but not negative. Substitution of these equations into Equation 14 yields:

\[
\frac{d(\text{UMC}^*)}{d(\text{URC})} = \frac{1}{\eta_L} \times c_1 \times \frac{(K_H \times c_{2H} \times K_L \times c_{2L})}{(K_H \times K_L)} \quad (16)
\]

The slope of the equi-DR line is clearly independent of the absolute levels of the fixed capital \( K_H \) and \( K_L \), but rather dependent on their ratio \( (k) \). Conversely, the inclination remains dependent on the absolute conversion efficiency levels. As a starting position, it was assumed that \( K_H > K_L \), or \( k > 1 \). In addition to this limitation on parameter \( k \), two more values of \( k \) are now considered, while maintaining parameter \( e \) constant at a value above unity, namely: \( k = 1 \); and \( 0 < k < 1 \).

If \( k > 1 \), the numerator in Equation 16 is positive or negative, depending on the sign of the expression \((- k \times e + 1)\). Actually it is negative, since both parameters \( k \) and \( e \) are larger than unity, so that their product is larger than unity too. At the same time, the denominator of Equation 16 is negative, since \( k > 1 \). As a result, the inclination \( d(\text{UMC}*)/d(\text{URC}) \) is positive, and the equi-DR line is located in the first quadrant as displayed in Figure 74.

If \( K_H \) now falls towards \( K_L \) - a possible result of technology development and learning - \( k \) approaches unity from above. Both the numerator and the denominator of
Equation 16 remain negative, but the denominator tends to zero from below. Close to zero, as $K_{II}$ approaches $K_L$, the differential approaches $+4$: that is, the equi-DR line runs parallel to the ordinate.

A single answer cannot be provided for situations where $0 < k < 1$ (or $0 < K_{II} < K_L$). The denominator of Equation 16 is clearly positive, but whether or not the numerator is positive or negative depends on the relative magnitude of $k$ and $e$. If parameter $k$ is just below unity, the product $k.e$ is greater than 1 since the parameter $e$ is larger than infinitesimally close to unity. Hence, for these values of $k$, the differential is negative with an equi-DR line pointing into the second quadrant. However, if the parameter $k$ continues to fall below unity, a point is reached where $k.e = 1$. In this situation, the equi-DR line runs parallel to the abscissa. In the graph of iso-DR lines this event can be seen as the value of parameter $k$ for which $UMC^*=UMC^*$, where $UMC^*$ is the ordinate of the pivot point, the existence of which is proven below. If parameter $k$ is reduced still further, so that $k.e < 1$, the differential becomes positive: the equi-DR line points into the third quadrant.

Finally, we prove that the equi-DR line contains a point $(URC^{**}, UMC^{**})$ which remains constant for varying investments $K_{II}$. This point can be called a pivot point, as it appears that a reduced $K_{II}$ makes the equi-DR line pivot around this position. For this demonstration, two investment levels for Technology $H$ are considered: $K_{II1}$ and $K_{II2}$. Using Equation 13, the equations describing the two equi-DR lines, that compare these technologies with Technology $L$, are:

$$UMC_{II1} = c_1 \times \left( \frac{K_{II1}}{\eta_L} \frac{K_L}{\eta_{II}} \right) \times URC \% \left( \frac{K_{II1}, c_2L \ & \ K_L, c_2H}{(K_{II1} \ & \ K_L)} \right)$$

and

$$UMC_{II2} = c_1 \times \left( \frac{K_{II2}}{\eta_L} \frac{K_L}{\eta_{II}} \right) \times URC \% \left( \frac{K_{II2}, c_2L \ & \ K_L, c_2H}{(K_{II2} \ & \ K_L)} \right)$$

Naturally, the parameters $\eta_{II}$ and $c_2H$ are equal for the two cases of Technology $H$. The intersection point of the two equi-DR lines - which exists, since inclinations change with the investment $K_{II}$ - is defined by the condition that $UMC^*_{II1}=UMC^*_{II2}$. Applying this condition to Equations 17, yields:

$$URC \left( \frac{1}{c_1} \frac{1}{\eta_L} \frac{1}{\eta_{II}} \right) = UMC \left( \frac{1}{c_1} \frac{1}{\eta_L} \frac{1}{\eta_{II}} \right)$$

Strikingly, the intersection point of the equi-DR lines is independent of the level of fixed capital (which proves our point), and depends only on the conversion efficiency and the independent fixed cost parameters. Substitution of the result for $URC^{**}$ (Equation 18) into
Equation 11 gives the accompanying discount factor $A^{**}$. All terms cancel out; or $A^{**}$ equals zero, independently of all parameters.

An illustration is given in Figure 75. The data used for its preparation (listed in Table 53), are taken from a technology evaluation for 2 MW$_e$ biomass-fuelled CS plants in Bolivia (Pelaez, Canedo, Goitia et al. (2002)).

![Graph of Equi-DR lines with varying investment](image)

**Figure 75.** Demonstration of the pivot point for equi-DR lines with varying investment.

**Table 53.** Parameter values used for generating Figures 74 and 75 (Source: Pelaez, Canedo, Goitia et al. (2002)).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Technology H</th>
<th>Technology L</th>
</tr>
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<tr>
<td>$C_1$</td>
<td>0.000288</td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>0.131</td>
<td></td>
</tr>
<tr>
<td>$Q$</td>
<td>13,500,000 kWh$_e$/yr</td>
<td>3,130,000 US$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>25.7%</td>
<td>11.8% kWh$<em>e$/kWh$</em>{th}$</td>
</tr>
<tr>
<td>$K$</td>
<td>6,260,000</td>
<td>3,130,000 US$</td>
</tr>
<tr>
<td>$C_2$</td>
<td>0.0129</td>
<td>0.0104 US$/kWh$_e$</td>
</tr>
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Based on principal parameter values:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Annual production</td>
<td>13,500</td>
</tr>
<tr>
<td>NCV of biomass fuel</td>
<td>12.5 GJ/t</td>
</tr>
<tr>
<td>Economic life time</td>
<td>15 yr</td>
</tr>
<tr>
<td>Discount rate</td>
<td>10% /yr</td>
</tr>
<tr>
<td>Labour, maintenance, consumables</td>
<td>0.0129</td>
</tr>
</tbody>
</table>
APPENDIX B
ENERGY BALANCES OF THE WORLD AND OF THE OECD

The following energy balances were derived from tables prepared by the IEA. In the reviews given below the sign convention was used that energy consumption is reported as positive values. Negative energy consumption implies a net production. Thus the consumption of energy carriers utilised by the electricity production sector is reported with positive values. The production of electricity and heat by this sector is given with negative values.

Unlike the energy balance for the OECD, the balance for the World does not distinguish the production of heat and electricity. They are included in the energy carrier ‘Other’.
### ENERGY SUPPLY AND CONSUMPTION IN THE WORLD, 1998 (Mtoe)


<table>
<thead>
<tr>
<th>Energy Carrier</th>
<th>Coal</th>
<th>Crude Oil</th>
<th>Petroleum Products</th>
<th>Gas</th>
<th>Nuclear</th>
<th>Hydro</th>
<th>Combustible Renewables &amp; Waste*</th>
<th>Other**</th>
<th>Total</th>
</tr>
</thead>
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<td><strong>SUPPLY</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indigenous Prod.</td>
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<td>3610.43</td>
<td>-</td>
<td>1949.43</td>
<td>637.26</td>
<td>221.09</td>
<td>1062.85</td>
<td>42.32</td>
<td>9741.06</td>
</tr>
<tr>
<td>Imports</td>
<td>358.5</td>
<td>1982.9</td>
<td>654.03</td>
<td>451.92</td>
<td>-</td>
<td>-</td>
<td>0.63</td>
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<td>3483.77</td>
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<td>-</td>
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<td>-17.25</td>
<td>-</td>
<td>-</td>
<td>0.03</td>
<td>-</td>
<td>-59.43</td>
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<td>3597.73</td>
<td>-86.47</td>
<td>1927.89</td>
<td>637.26</td>
<td>221.09</td>
<td>1062.42</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-125.08</td>
</tr>
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<td>-</td>
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<td>-1.52</td>
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<td><strong>CONSUMPTION (Figures &lt; 0 are net productions)</strong></td>
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<td>Electricity Plants</td>
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<td>336.14</td>
<td>633.29</td>
<td>221.09</td>
<td>21.57</td>
<td>-1048.48</td>
<td>1621.56</td>
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<td>28.99</td>
<td>240.44</td>
<td>3.96</td>
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<td>47.03</td>
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<td>-</td>
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<td>-</td>
<td>0.96</td>
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<td>0.17</td>
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<td>154.43</td>
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<td>Liquefaction</td>
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<td>-3.46</td>
<td>8.22</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11.42</td>
</tr>
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<td>-</td>
<td>-</td>
<td>42.03</td>
<td>-</td>
<td>54.31</td>
</tr>
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<td>9.6</td>
<td>200.5</td>
<td>194.66</td>
<td>-</td>
<td>-</td>
<td>0.45</td>
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<td>1.22</td>
<td>18.77</td>
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<td>-</td>
<td>0.47</td>
<td>123.92</td>
<td>154.67</td>
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<td><strong>Total final consumption by other sectors:</strong></td>
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<td>0</td>
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<td>-</td>
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<td>186.39</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td><strong>Total consumption</strong></td>
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<td>1921.73</td>
<td>637.25</td>
<td>221.09</td>
<td>1061.24</td>
<td>40.28</td>
<td>9532.85</td>
</tr>
</tbody>
</table>

* Combustible Renewables & Waste final consumption has been estimated based on TPES.

** Other includes geothermal, solar, electricity and heat production, wind, etc.

TPES: Total primary energy supply (TPES) is made up of indigenous production + imports - exports - international marine bunkers ± stock changes. For the World Total, TPES excludes international marine bunkers.
## ENERGY SUPPLY AND CONSUMPTION IN THE OECD, 1998 (Mtoe) (Source: Key World Energy Statistics from the IEA [http://www.iea.org/statist/keyworld/keystats.htm](http://www.iea.org/statist/keyworld/keystats.htm)).

<table>
<thead>
<tr>
<th>Energy Carrier</th>
<th>Coal</th>
<th>Crude Oil</th>
<th>Petroleum Products</th>
<th>Gas</th>
<th>Nuclear</th>
<th>Hydro</th>
<th>Combustible Renewables &amp; Waste*</th>
<th>Electricity</th>
<th>Heat</th>
<th>Geothermal, solar, etc.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
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<td><strong>SUPPLY</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indigenous Prod.</td>
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<td>1046.05</td>
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<td>874.91</td>
<td>553.58</td>
<td>111.08</td>
<td>168.64</td>
<td>-</td>
<td>0.35</td>
<td>30.05</td>
<td>3790.32</td>
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<tr>
<td>Imports</td>
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<td>-</td>
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<td>0</td>
<td>-</td>
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<td>-23.18</td>
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<td>0.81</td>
<td>0.35</td>
<td>30.05</td>
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<td>-0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Statistical Diff.</td>
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<td>-2.82</td>
<td>2.01</td>
<td>-8.02</td>
<td>-</td>
<td>-</td>
<td>-0.12</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-13.02</td>
</tr>
<tr>
<td><strong>CONSUMPTION (Figures &lt; 0 are net productions)</strong></td>
<td>(Includes electricity and heat production)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity Plants</td>
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<td>553.55</td>
<td>111.08</td>
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<td>-702.95</td>
<td>-</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
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<td>0.08</td>
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<td>0</td>
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<td>663.49</td>
<td>45.11</td>
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<td>-</td>
<td>-</td>
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<td>553.59</td>
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<td>29.22</td>
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</tr>
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</table>

* Combustible Renewables & Waste final consumption has been estimated based on TPES.
** Other sectors include Agriculture, Commerce and Publ. Services, Residential, Non-specified.

TPES: Total primary energy supply (TPES) is made up of indigenous production + imports - exports - international marine bunkers ± stock changes. For the World Total, TPES excludes international marine bunkers.
APPENDIX C
SECONDARY REFERENCES

Studies cited by Munasinghe (1993) on option values of environmental goods (See Chapter 1)


Studies reviewed by Stirling (1997) on external costs of energy systems (See Chapter 2)

Numbers refer to those in Figure 12.

4 EPRI, 1987 (further details not provided by Stirling).
8 CEC, 1989 (further details not provided by Stirling).
16 Koomey, 1991 (further details not provided by Stirling).
22 Hohmeyer et al., 1992 (further details not provided by Stirling).
23 Externe, 1993 (further details not provided by Stirling).
26 Fankhauser, 1993 (further details not provided by Stirling).
30 Eyre, 1995 (further details not provided by Stirling).
31 European Commission, 'Externe: externalities of energy' Volumes 1--6, EUR 16520-16525 EN, Brussels, 1995
Studies reviewed by UCE, UU-NW&S, RIVM et al. (2000) on the biomass supply potential (See Chapter 4)

Battjes, J.J. (1994). Global options for biofuels from plantations according to IMAGE simulations (IVEM-Studentenrapport 77), Interfacultaire Vakgroep Energie en Milieukunde (IVEM), Rijksuniversiteit Groningen, Groningen.


APPENDIX D
DETERMINATION OF THE ENERGY EFFICIENCY OF ELECTRICITY PRODUCTION SYSTEMS

D.1 COMPARISON OF AMERICAN AND EUROPEAN EFFICIENCY DETERMINATION APPROACHES

The ISO system of norms does not provide standardized methods for energy analysis. Concerning the efficiency of systems, as well as of unit operations, various definitions are in use. In the first place there is a distinction between net and gross efficiency. The former is defined with reference to the net calorific value of a fuel, whereas the latter is defined with reference to the gross calorific value. Hence:

\[ \eta_N' = \frac{\dot{W}_{\text{net electricity}}}{m_{\text{fuel}} \times NCV_p} \]

and

\[ \eta_G' = \frac{\dot{W}_{\text{net electricity}}}{m_{\text{fuel}} \times GCV_p} \]

These equations apply irrespective of the fuel basis (i.e. wet, dry or ash free) as long as they are employed consistently. Depending on fuel moisture and hydrogen content, the differences between the net and gross efficiencies may be substantial. A clear specification of the type of efficiency is therefore important. Whether a system is evaluated using net or gross efficiencies, the net electricity output and the fuel input are the same. From Equation 19, therefore, it follows that the relationship between the two efficiency definitions is:

\[ \eta_W = \eta_G \times \frac{GCV_p}{NCV_p} \]

Thus, the net and gross efficiency can be derived from each other if the net and gross heating values of the fuel are known. This implies, strictly speaking, that conversion from net to gross efficiency, and vice versa, can only be performed at specific levels of fuel moisture content for which an efficiency is known (with for wood, the ratio of \( GCV_p/NCV_p \) varies from about 1.07 with 0% moisture content to about 1.34 if the moisture content is 60% (wet basis)).

This discussion is relevant because engineers from the USA tend to use the gross efficiency (also some British engineers, see Fenton (1977)) whereas continental European engineers usually employ the net efficiency. The use of the gross efficiency means that all the energy associated with the condensation of water vapour in the exhaust gas appears as a loss if this condensation energy is not recovered. In contrast, if the net efficiency is employed, the absence of such energy recovery is accepted as inevitable and not considered relevant. This explains why USA-based energy analyses (oriented towards the
gross efficiency) make mention of efficiency increases as a result of fuel drying. European energy analysis would rather conclude that energy availability (rather than efficiency) increases with fuel drying. In this thesis a net efficiency basis is adopted throughout.

It should be noted that the above relationship between net and gross efficiencies (Equation 20) only applies if the work inputs into the system (e.g. for feedwater pumps and exhaust gas fans) are subtracted from the gross work produced (here $W_{\text{total electricity}}$) and included in the numerator of the efficiency definition. To account for plant internal electricity consumption, therefore, the net system efficiency is preferably expressed as:

$$
\eta_N = \frac{W_{\text{net electricity}}}{W_{\text{total electricity}}} \times \eta_{\text{plant electricity consumption}}
$$

Work inputs are not always so treated. There is a tendency among engineers to place electrical work inputs inside the denominator of the efficiency definition, i.e. as follows:

$$
\eta_N = \frac{W_{\text{total electricity}}}{W_{\text{fuel}} \times NCV_p} \times \eta_{\text{plant electricity consumption}}
$$

If defined so, net and gross efficiencies can no longer be derived from each other. Only if work inputs are small in comparison with the fuel inputs, can reasonable approximations still be made. When comparing literature sources and manufacturers’ data, special care is therefore required with regard to the following:

- Are the provided efficiencies net or gross efficiencies?
- Are work inputs included in the denominator or the numerator of the efficiencies indicated?

**D.2 ENERGY EFFICIENCY OF COMBUSTOR-STEAM TURBINE SYSTEMS**

The efficiency of systems consisting of boilers integrated with steam turbines can be derived from the combination of two data sets: (i) the efficiency of the system components and (ii) the specific manner in which the system components are integrated. For the expression of the net aggregated efficiency, I postulate a cycle efficiency, $\eta_{\text{cycle}}$, such that:

$$
\eta_{\text{system}} = \frac{\eta_{\text{net boiler}} \times \eta_{\text{net turbine}} \times \eta_{\text{generator}} \times \eta_{\text{cycle}}}{\eta_{\text{parasitic}}}
$$

The reason for this approach is that although all the efficiency losses can be attributed to either the boiler, the turbine, the generator, or the plant’s own power consumption (the parasitic load), the efficiency of the entire system is not determined by the subsequent multiplication of the efficiencies of the system components (boiler, the turbine, the generator, parasitic load). This is due to the particular manner in which the boiler and
turbine are integrated (the steam cycle). As is shown in the following paragraphs, where the various efficiencies are discussed, the expression for the system efficiency can be elaborated into the following expression:

$$\eta_{\text{system}} = \eta_{\text{boiler}} \times \eta_{\text{M, turbine}} \times \eta_{\text{generator}} \times \frac{\eta_{\text{S, cycle}} \times \eta_{\text{S, turbine}}}{\eta_{\text{S, cycle}} \times \eta_{\text{S, turbine}}} \times \eta_{\text{parasitic}} \times \eta_{\text{S}}.$$ 

where $\eta_{\text{S}}$ is the so-called isentropic efficiency of the turbine and steam cycle respectively.

**Net boiler efficiency**

In the boiler, the fuel combusts, and the resulting heat is transferred to a heat carrier consisting of water and steam. In the approach chosen here, the net boiler efficiency is defined as:

$$\eta_{\text{boiler}} = \frac{\dot{m}_{\text{water/steam}} \times \Delta h_{\text{water/steam}}}{\dot{m}_{\text{fuel}} \times \text{NCV}_p}.$$ 

At the level of the boiler, the approach taken here disregards work inputs into the boiler (needed for electrically-driven boiler auxiliaries such as stoking equipment, combustion air fans, exhaust gas fans, and feedwater pumps), and instead takes these into account in the parasitic efficiency, $\eta_{\text{parasitic}}$, discussed below. If auxiliaries are steam driven (which is often, but not always, the case with devices such as feedwater pumps), then the work input into the boiler is not taken into account at all, but rather the net flow of steam available for the power generation unit is taken as in the definition of boiler efficiency. Note that boiler efficiencies can be expressed on either the net (NCV$_p$) or gross (GCV$_p$) calorific value of a fuel. For conversion between the two, the relationship derived in Section D.1 can be applied. As with complete energy systems, USA sources generally also employ the gross efficiency for boilers.

In general, energy losses from boilers are made up of the following:

- The sensible heat in the exhaust gas,
- Radiative and convective heat transfer through and from the boiler wall,
- Unburnt fuel in the ash,
- Unburnt fuel in the exhaust gas,
- The sensible heat in the ash,
- The sensible heat in blow-down water.

Since considering the net efficiency, losses due to incomplete energy recovery by condensation of exhaust gas moisture are disregarded here, but rather taken into account in the determination of the energy input into the boiler. Of the above list, the sensible heat in the exhaust gas is usually the largest. This is dependent on the exhaust gas quantity and temperature. The exhaust gas quantity, in turn, is directly proportional to the air factor, which can be defined as the total quantity of air relative to the stoichiometrically required quantity of air (expressed on a molar basis). Another important loss is unburnt fuel in the ash (it is expressed in the combustion efficiency, which is the ratio of actually burnt fuel
to total fuel input). The net efficiency of boilers is therefore most sensitive to three parameters, i.e.:

- The air factor,
- The combustion efficiency,
- The exhaust gas temperature.

The first two parameters are determined by the combustion technology employed in a specific boiler. The other parameter which determines the loss due to sensible heat in the exhaust gas (the exhaust gas temperature) does not depend on the combustion technology, but on the design and size of the heat exchanger.

Rather than measuring the terms indicated in the definition given above - useful boiler outputs and inputs - boiler efficiency can be established by determining boiler inputs and losses:

\[ \eta_{\text{boiler}} = \frac{1}{1 + \frac{\text{Energy losses}_{\text{NCV}_p}}{m_{\text{fuel}} \times NCV_p}} \]

Not surprisingly, this is called the losses method. It is not fully compatible with the approach chosen here (since work flows from directly steam driven auxiliaries are not dealt with in the defined manner), however it does provide a simple tool for judging the reliability of data supplied by manufacturers. A model to quickly estimate the maximum achievable efficiency for a given air factor makes the following assumptions:

- The fuel burns completely,
- The sensible heat in the ash is zero,
- The sensible heat in blow-down water is zero,
- Radiative and convective heat transfer through and from the boiler wall is set at a practical level related to the fuel input (based on net calorific value), ranging from 1-3% for the various boiler sizes considered in this study.
- For the exhaust gas temperature, manufacturer’s data are assumed.

For a specific set of parameters, Figure 76 gives an example of the sensitivity of boiler efficiency to air factor.
Figure 76. Example of the sensitivity of boiler efficiency to the air factor. Main parameters assumed: Fuel = wood; Moisture content = 40% (w.b.); Exhaust gas temperature = 130 °C). Source: this thesis.

**Mechanical turbine efficiency and generator efficiency**

In the power generation unit, the thermal energy, carried by the steam is partially converted into shaft work by a turbine in which the steam is expanded. A generator, converts this work into electricity. The mechanical efficiency of the turbine accounts for mechanical losses (shaft friction) and should not be confused with the isentropic efficiency of the turbine. The mechanical efficiency is defined as:

$$\eta_{M, \text{turbine}} = \frac{W_{\text{turbine}}}{h_{\text{steam at inlet}} - h_{\text{steam at exhaust}}}$$

Generally, about 95% of the released steam expansion enthalpy is converted into electricity in the subsequent generator. For completeness sake the efficiency of the generator is given as:

$$\eta_{\text{generator}} = \frac{W_{\text{total electricity}}}{W_{\text{turbine}}}$$

Shaft friction and generator losses generally amount to about 5% in total. The losses associated with the entropy production by the expanding steam are covered in the cycle efficiency.
The cycle efficiency

In terms of Second Law analysis, the cycle efficiency concerns the entropy produced during:

- The evaporation process inside the boiler,
- Steam expansion inside the turbine.

In a condensing steam cycle, the entropy is removed from the heat carrying medium by means of the condenser. It is transferred into the environment as a heat flow at low temperature. For a simple steam system, the cycle efficiency is defined as:

\[
\eta_{\text{cycle}} = \frac{h_{\text{turbine exhaust}} - h_{\text{turbine inlet}}}{h_{\text{turbine inlet}} - h_{\text{feedwater pump inlet}}}
\]

A Mollier diagram illustrates the meaning of the various symbols (Figure 77). The cycle efficiency of a simple steam system can be increased by using steam reheating and regenerative feedwater pre-heating: techniques which require 1) additional heat exchangers and 2) steam extraction and re-injection from and into the turbine at medium pressures.

![Mollier diagram of a simple steam system](image)

Figure 77. Mollier diagram of a simple steam system.

The steam cycle efficiency is dependent on:

- The steam inlet conditions (pressure and temperature),
- The steam exhaust conditions (pressure (P), temperature (T) and dryness fraction (X)),
- The isentropic efficiency of the steam turbine.

With regard to the steam exhaust conditions: either the pressure or the temperature is fixed depending on the purpose of the plant. CHP plants are usually designed such that the exhaust pressure is set, whereas in power-only plants, with a condensing cycle, the exhaust
temperature is fixed. The other two parameters (P and X, or T and X) constituting the steam exhaust conditions are determined by the isentropic efficiency of the turbine. The isentropic turbine efficiency reflects the entropy production during steam expansion. It is defined as:

\[
\eta_{S, \text{turbine}} = \frac{h_{\text{turbine inlet}} - h_{\text{turbine exhaust}}}{h_{\text{turbine inlet}} - h_{S, \text{turbine exhaust}}},
\]

where \( h_{S, \text{turbine exhaust}} \) is the steam’s enthalpy at the turbine exhaust pressure which would have occurred if the steam expansion was isentropic. Figure 78 illustrates this concept.

**Figure 78.** Mollier diagram for steam expansion in a turbine.

Using this definition of the isentropic turbine efficiency it is now possible to also define an isentropic cycle efficiency as follows:

\[
\frac{1}{\eta_{S, \text{cycle}}} = \frac{1}{\eta_{\text{cycle}}} + \frac{1}{\eta_{S, \text{turbine}}},
\]

So that the cycle efficiency, postulated in Equation 21 becomes:

\[
\eta_{\text{cycle}} = \frac{\eta_{S, \text{cycle}} \times \eta_{S, \text{turbine}}}{\eta_{S, \text{cycle}} \times \eta_{S, \text{turbine}}}
\]

*The parasitic efficiency*

Finally, the parasitic efficiency takes account of the entire electricity consumption of the system itself (such as electricity for fuel preparation, feedwater pumps and exhaust gas fans, and flue gas cleaning equipment). It is defined as:
It is necessary to provide clarity as to which electricity consuming operations are included within the system boundaries to determine meaningful efficiency.

D.3 SYSTEM BOUNDARIES USED TO DETERMINE THE MASS AND ENERGY BALANCE OF A LIQUEFACTION PLANT

The following considerations guided the preparation of the mass and energy balance given here:

- In the liquefaction process, some energy is required to subject the biomass to a sudden temperature shock of about 500 °C. Energy is also required to balance heat losses through the reactor wall.
- The reaction heat released during pyrolysis is insufficient to make up for those heat flows. Existing liquefaction plants use some of the energy contained in the pyrolysis gas or the charcoal to meet these two types of heat consumption.
- The potential for improved heat integration, and thus the maximisation of saleable product quantities from a bio-oil production plant, was not taken into account.

The associated uncertainties were avoided by placing the primary products outside the system boundaries of the balance. The energy balance was closed by determining the quantity of the pyrolysis gas by difference. Together with the measured composition and the net calorific value of the pyrolysis gas in BTG’s pilot plant (Venderbosch and Wagenaar (2001)), the mass balance was established.

Data used:

<table>
<thead>
<tr>
<th>Calculation of cooling and heating energy</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass cooled (oil, gas, charcoal)</td>
<td>1.00 g/g_w wood</td>
</tr>
<tr>
<td>of which water</td>
<td>0.14 g/g_w wood</td>
</tr>
<tr>
<td>c_p (anything but water vapour)</td>
<td>1.1 J/(g K)</td>
</tr>
<tr>
<td>c_v water vapour</td>
<td>2.2 J/(g K)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calculation of condensing energy</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total water condensed</td>
<td>0.135 g/g_w wood</td>
</tr>
<tr>
<td>Total dry oil condensed</td>
<td>0.540 g/g_w wood</td>
</tr>
<tr>
<td>Specific condensing energy water</td>
<td>2256 J/g water</td>
</tr>
<tr>
<td>Specific condensing energy dry oil</td>
<td>500 J/g oil</td>
</tr>
<tr>
<td>Condensor efficiency</td>
<td>100%</td>
</tr>
</tbody>
</table>
Figure 79. System boundaries chosen for determining the mass and energy balance of a biomass liquefaction plant.

Table 54. Indicative mass and energy balance of biomass liquefaction (based on data provided by Meier and Faix (1999), and Venderbosch and Wagenaar (2001)).

<table>
<thead>
<tr>
<th>Mass balance</th>
<th>g_{ inlet} / g_{ outlet} wood</th>
<th>\mu_{ inlet}</th>
<th>g_{ inlet} / g_{ outlet} wood</th>
<th>\mu_{ outlet}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>1.00</td>
<td>10%</td>
<td>Oil</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Charcoal</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gas</td>
<td>0.24</td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy balance (NCV)</th>
<th>J_{ inlet} / g_{ outlet} wood</th>
<th>Out</th>
<th>J_{ inlet} / g_{ outlet} wood</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>16409</td>
<td>Oil</td>
<td>10945</td>
<td>67%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Charcoal</td>
<td>2598</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gas</td>
<td>2141</td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cooling + condensing energy</td>
<td>1168</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Heating energy</td>
<td>-534</td>
<td>-3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pyrolysis reaction energy</td>
<td>40</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radiation from reactor wall</td>
<td>50</td>
<td>0%</td>
</tr>
<tr>
<td>Total</td>
<td>16409</td>
<td>Total</td>
<td>16409</td>
<td>100%</td>
</tr>
</tbody>
</table>

Input data:

Feedstock wood
Feedstock \mu_{ wood} = 10%
Feedstock NCV_{ wood} = 16409 J/g
Oil yield 60% g dry oil/g dry wood
Charcoal yield 10% g charcoal/g dry wood
Gas yield 26% g gas/g dry wood
Oil \mu_{ wood} = 20%
Oil NCV_{ wood} = 16203 J/g
Charcoal \mu_{ wood} = 0%
Charcoal NCV_{ wood} = 30000 J/g

Pyrolysis gas composition:
- CO: 0.456 g/g gas
- CO2: 0.456 g/g gas
- CH4: 0.075 g/g gas
- C2H4: 0.014 g/g gas
- NCV_{ wood} of the pyrolysis gas = 9000 J/g gas

Cooling \Delta T = 475 K
Heating \Delta T = 485 K
APPENDIX E
TECHNICAL ISSUES ON BIOMASS-FUELLED ENERGY CYCLES

This appendix concerns selected items regarding the conversion of biomass fuels into electricity. The focus is on:

- Flame temperatures for biomass fuels.
- Gas flows in gas turbine applications for biomass-derived fuels (fuel gas from gasified biomass, bio-oil and pyrolysis gas).
- Ash issues in gas turbine applications for bio-oil and pyrolysis gas.

E.1 FLAME TEMPERATURES FOR BIOMASS FUELS

Flame temperatures are relevant in understanding the thermodynamics of energy conversion cycles and also for the specific adaptation of system components such as combustion chambers. The elevated temperatures of flames, relative to the temperatures of fuels and combustion air, are a result of the energy released during a chemical reaction, the quantities of resulting reaction components and their specific heat, and the heat transfer from the flame to its environment. Flame temperatures can be measured, but they can also be calculated - which is important for process engineering. A first order approach in flame temperature calculation is to determine the adiabatic flame temperature. In this approach, it is assumed that the energy released from the chemical reaction is entirely absorbed by the reaction products, and is not transferred, by radiation or conduction, to the reactor wall, nor, by convection, is it dissipated to surrounding gases. These effects can subsequently be incorporated in a secondary analysis. The chemical reactions occurring in the system, not surprisingly, determine the resulting temperature. In the analysis presented below, it is assumed that the following reactions occur during combustion:

- Carbon is fully converted, with oxygen, into CO₂. Neither CO nor soot are formed.
- Hydrogen is fully converted, with oxygen, into H₂O. Hydrogen does not react with carbon to form hydrocarbons, nor with sulphur or nitrogen to form acids.
- Sulphur is fully converted, with oxygen, into SO₂.
- Nitrogen is released as N₂.
- Minerals present in the fuel are not reacted into combustion products. Mineral oxides remain oxides, and mineral elements not bound with oxygen are released in their pure form. This assumption results in only minor errors for low-ash fuels including most types of biomass.

The combustion air is assumed to be dry. It is further assumed that the product gases do not dissociate into products such as hydroxyl radicals, hydrogen atoms and oxygen atoms. Such occurrence of dissociation would result in a negative feedback mechanism leading to somewhat lower adiabatic flame temperatures than calculated here. Nolan (1977) reports that dissociation is negligible for flame temperatures below 1800 K. The calculated temperatures are, in fact, occasionally higher; in these cases the assumption results in inaccuracies which may require correction for more precise estimates. The pressure is assumed to be constant so, for the specific heats of the reaction products, the values at constant pressure (c_p) may be used. This may affect the validity of the model for gas turbine applications. A final simplification is the assumption of constant specific heats for
the various gases, over the entire applicable temperature range. Actually, specific heats vary with temperature, for example, the \( c_p \) of CO\(_2\) varies from 1.05 to 1.30 J/(g.K) between 550 and 3000 K. In the same temperature range, that of water vapour varies from 1.9-2.6 J/(g.K). The mass and energy balance of a stationary flame leads to the following formula for the adiabatic flame temperature:

\[
T_a = \frac{N\text{CV}_p}{\prod(X) \times c_p(X)} \% T_1,
\]

where \( N\text{CV}_p \) is the fuel’s net calorific value at constant pressure (J/g fuel), \( \prod(X) \) is the specific quantity of product gas X formed per unit of fuel (g X/g fuel), \( c_p(X) \) is the specific heat of product gas X (J/g X. K) and \( T_1 \) is the feed temperature. The range of product gases, X, includes all compounds released after the reaction, including those compounds not taking part in the reaction, such as excess O\(_2\) and N\(_2\) carried with combustion air, as well as the water present as fuel moisture.

The calculation procedure can be applied to both solid and gaseous fuels, including fuel gases resulting from gasification. In this particular application of the model, the feed temperature of the fuels, as well as combustion air, is set at 25 °C, which is the standard reference temperature used in the determination of calorific values (see ISO 1928 (1976)). The temperatures of fuel gases that result from gasification are usually higher, even after gas cleaning. With this constraint, and the simplifying assumptions in the model, the calculated flame temperatures will certainly differ from the actual temperatures occurring in specific applications. However, this approach serves to show fundamental differences and similarities between fuels of entirely different natures, i.e. of fossil fuels, biomass, and biomass-derived fuels such as fuel gas, pyrolysis gas and bio-oil. It also enables an evaluation of the influence of fuel moisture and excess air on flame temperatures when using these fuels.

Necessary fuel parameters are the chemical fuel composition (in terms of the major constituting elements for primary fuels, and of the gaseous compounds for fuel gases) as well as mineral and moisture contents. The fuel parameter values used are summarised in Table 55. The data for wood are typical values, but vary from species to species. Also the parameters employed for bio-oil and pyrolysis gas represent typical parameter values, but can vary. Methane is a well defined gas and may also be considered to represent natural gas. The analysis of fuel oil disregards the presence of sulphur and mineral matter. The data given for coal, reflect the coal type utilised by Campbell, McMullan and Williams (2000) in their analysis of gasifier systems, i.e. Pittsburg 8. The calorific values of fuel gases resulting from gasification, also summarised in Table 55, result from the parameter values assumed for the respective fuel gases and the calorific values of the pure gases CO, H\(_2\) and CH\(_4\) (so, strictly speaking, they are not input data). Table 56 shows general process-specific parameter values. Generally accepted data such as the calorific values of the pure gases CO, H\(_2\) and CH\(_4\), the general gas constant, as well as normal conditions for gases are not justified further.
Results of the model calculations are given in Figures 80-81. Moisture content has a strong influence, and it is a parameter which varies widely with coal and several biomass types. Also the air factor has a substantial effect. To optimise the efficiency of steam cycles, one attempts to operate combustors at air factors only slightly above unity. This principle does not directly apply to gas turbines, and so a relatively broad range of air factors are evaluated. It is observed that, over the range of air factors and moisture contents analysed, flame temperatures are all above actual utilisation temperatures. Combustion chambers of turbines for example should be designed such that actual temperatures are below about 1450 K. It is striking that, although the calorific values of the fuels vary considerably, flame temperatures are relatively similar. On its own, therefore, the calorific value of a fuel is not an indicator of its flame temperature. Neither is the relatively low calorific value of biomass and biomass derived fuels sufficient reason for assuming that systems fired with these fuels would perform less efficiently.
There are several reasons why the flame temperatures of lean fuels such as biomass and biomass-derived fuels, are so high. One is that they contain oxygen bound in a manner that allows it to react further and so, as a result, less nitrogen, a constituent of the combustion air, has to be heated. This statement can be easily verified by assuming pure oxygen
instead of air as the combustion medium in the mass balances necessary to evaluate the
above equation for the adiabatic flame temperature (page 268). It is then found that the
high-calorific fuels show much higher flame temperatures than the low-calorific fuels.
Another parameter important in flame temperature determination is the hydrogen content.
Upon combustion, hydrogen forms water vapour, which has a high specific heat.

E.2 GAS FLOWS IN GAS TURBINE APPLICATIONS

In Figure 82(a) the principal flow sheet of a natural gas fuelled gas turbine is given, and
it forms the basis for the design of systems which enable the use of biomass-derived
gaseous fuels in gas turbines. Possible system layouts, suitable for the use of these gases,
such as pyrolysis gas and gas resulting from biomass gasification, are given in Figure 83.
Figure 83(a) applies to atmospheric liquefaction plants and atmospheric gasifiers coupled
to gas turbines, and Figure 83(b) applies if the gasification reactor is pressurised. It is
sometimes contemplated that also alternative systems can be used. For example, a
pyrolysis gas could perhaps be premixed with combustion air and compressed by a single
compressor. The typical system given in Figure 82(b) concerns a gas turbine fired with
mineral fuel oil, and it also applies if bio-oil is used. The diagrams only show the major
mass flows, and ignore the possible injection of water or steam for cooling or capacity
increase, and of additional air for cooling.

A compressor section is integrated within the same machine, and either driven by the same
expander which also drives the electricity generator, or driven by a separate expander
running independently of the main expander which drives the electricity generator. In the
latter configuration the main expander is also referred to by the term ‘power turbine’, and
the expander driving the compressor by the term ‘compressor turbine’. Whereas the first
configuration is common for gas turbine generator sets with constant loads, the latter is
needed with variable loads. The reason is that electricity generation requires a constant
speed of the power turbine, even if generator load varies. Load variation requires mass
flow adaptation for fuel and combustion air, which then is made possible by separating the
compressor turbine from the power turbine. The configuration of the freely spinning
compressor turbine is also common for aeroderivatives applied in power plants.

330/ Aeroderivatives are aircraft gas turbines adapted for stationary operation.
If existing turbines, designed for conventional mineral fuels, are considered for other fuel types, the thermodynamical issues to be addressed include:

- Are compressor capacities large enough to provide the required flows of fuel and combustion air?
- Are the required flows of fuel and combustion air large enough to prevent compressor surge?
- To what extent are exhaust gas flows, expressed on an energy basis, similar to those for design fuels? If they are larger, and the same conversion efficiency applies, the turbine capacity is derated; and if exhaust gas flows are smaller, the turbine capacity increases. Note that this argument is only valid if compressor capacities, when fuelled with off-design fuels, are in balance with the expander section, that is if the first two questions are answered affirmatively.

These complicated issues can only be dealt with properly by taking into account the tuning of the air factor to the desired flame temperature, the potential need for air or water injection for cooling, as well as steam injection for capacity regulation. An extensive summary of modelling steps is provided by Palmer, Erbes and Pechtl (1993).

Typical indicators for gas turbine performance are gas flows expressed as mass flows on an energy basis (kg/MJ). A mistake often made in evaluating the use of biomass-derived fuels in various conversion systems designed for mineral fuels (including boilers, reciprocating engines, and also gas turbines), is to assume that the calorific value of biomass-derived fuels, which is considerably lower than those of most mineral fuels, results in strongly deviating mass flows of combustion products. For example by Palmer and Erbes (1994) (p. 1), approvingly cited by Solantausta, Bridgwater and Beckman (1996) (p. 73), who state that “to maintain the same firing temperature in a gas turbine combustor with LHV fuel as with natural gas, more fuel has to enter the combustor and consequently more mass flow passes through the turbine expander.” However, just like flame temperatures (as discussed in the previous section), energy-specific mass flows are much more similar to those of mineral fuels than one would expect on the mere basis of calorific values. For a number of biomass fuels this is shown in Table 57. The calculations
are a result of simple mass and energy balances. Where inflows and outflows do not precisely match, this is a result of calculation inaccuracies and roundings. On a chemical elements level, all molar balances were closed with an error of 0.00%. The major input parameters were the elemental composition of the fuels, their calorific values and the gas compositions on the level of chemical compounds. The shown data are typical, but the absolute values are sensitive to the selected parameter values (given in Table 55, p. 269).

Admittedly, these calculations do not take into account the refinements proposed above for a proper turbine analysis, however, it is apparent that mass-specific calorific values, if taken on their own, are of little meaning for turbine evaluations. A lower calorific value, which applies to biomass derived fuels, merely implies a larger fuel mass flow into a combustion chamber but says nothing about mass flows of combustion air and exhaust gas. In the comparison of bio-oil, for example, with natural gas (methane) and mineral oils (fuel oil), the effect of the lower calorific value of bio-oil (16,000 against 44,700 and 40,000 J/g respectively), is largely compensated by the lower mass flow of combustion air, and the exhaust gas flow is not proportionally affected by the fuel’s calorific value. The exhaust gas flow is larger than for methane and fuel oil; not negligibly, but only by 2%-6% (Table 57). The reason is the same as why flame temperatures of biomass and biomass derived fuels, discussed earlier, are close to those of fossil fuels: biomass fuels contain substantially more partly reacted oxygen than their fossil counterparts and, as a result, less nitrogen gas (part of the combustion air) has to be processed. A proper investigation thus takes calorific values, elemental fuel composition as well as required air quantities into account.

A particularly relevant conclusion from the indicative mass flow estimates is that the mass flows of the biomass-derived fuel gasses considered (pyrolysis gas and fuel gas from wood gasification) are an order of 5 to 10 times larger than the mass flow of a design fuel like natural gas. At the same time, combustion air requirements are considerably smaller. These are serious indications that compressor surge may be a critical issue, and that specific arrangements are needed for feeding the turbine with low-calorific fuels. Possible solutions are the premixing of combustion air and fuel, the charging the compressor with gasification air, and the operation of gasifiers at a pressure somewhat above the turbine feed pressure. These issues are not further investigated here.

### Table 57 Specific gas flows (kg/MJ) on NCVₚ for various fuels in gas turbine applications.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Fuel gas flow</th>
<th>Combustion air flow</th>
<th>Exhaust gas flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>0.022</td>
<td>0.459</td>
<td>0.482</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>n.a.</td>
<td>0.438</td>
<td>0.463</td>
</tr>
<tr>
<td>Bio-oil</td>
<td>n.a.</td>
<td>0.429</td>
<td>0.491</td>
</tr>
<tr>
<td>Pyrolysis gas</td>
<td>0.111</td>
<td>0.347</td>
<td>0.458</td>
</tr>
<tr>
<td>Fuel gas from wood gasification (wet gas)</td>
<td>0.202</td>
<td>0.338</td>
<td>0.539</td>
</tr>
</tbody>
</table>

Assumptions:
The fuel parameters given in Table 55 (p. 269), and an air factor of 1.2 (mole/mole).
E.3 ASH IN PYROLYSIS PRODUCTS USED IN GAS TURBINE APPLICATIONS

Ash is the solid residue of a fuel after it has been combusted, and the combustion products cooled such that any condensable solid matter has been precipitated. It is either present in the fuels prior to combustion, or it is formed as a reaction product during the combustion process. Ash formation and its subsequent deposition on blades and nozzles is a well-known occurrence in gas turbine applications where low-grade types of fuel oil are employed. It may create several technical difficulties, such as the occurrence of harmful vibrations, and leads to capacity derating and corrosion. Naturally, the experience of the gas turbine manufacturing industries is with ash types which occur with currently utilized ash-bearing fuels. As can be inferred from Kaufman (1996), these ash types are typically compounds (oxides and sulphates) of sodium, potassium, magnesium, vanadium, sulphur and oxygen. It should be noted that the sodium does not necessarily originate from the fuel, but, under marine conditions, may also be introduced into a gas turbine together with the combustion air. Neither is the magnesium always present in the fuel, as it may even be used as an additive to inhibit vanadium deposition (silicon additives are sometimes used for the same purpose). Ash types associated with bio-oil and pyrolysis gas differ from those with low-grade mineral oils. Ash-forming chemical elements are already present in the original biomass out of which the bio-oil and pyrolysis gas are made. Such elements are either found in the biomass matrix (sodium, potassium, calcium, magnesium, phosphorous, sulphur, silicon, and some others) or in contaminations such as soil (for example, silicon and aluminium) which may be included in a biomass fuel delivery. It is crucial how these elements are redistributed over the three reaction products made during the liquefaction process - bio-oil, pyrolysis gas and charcoal. Few studies on pyrolysis report on ash-forming elements in pyrolysis oil,333 and none report on these elements in pyrolysis gas. The most relevant elements appear to be the alkali metals namely sodium, potassium and magnesium. Also present in significant amounts are iron, aluminium, silicon, calcium and zinc. Sulphur and phosphorus are also present in measurable quantities. However, the concentration of sulphur is too low to bind the sodium and potassium as corrosive sulphates. The amount of vanadium and lead is less than 1 mg/kg. Particularly when considering gas turbine applications, the following ash properties should be assessed for the ash types resulting from bio-oil and pyrolysis gas combustion:334

• The formation of corrosive sulphates or other corrosive compounds.
• The formation of sticky particles during the expansion process (resulting in hazardous vibrations and capacity derating).

A first attempt to establish proposed specifications for ash forming agents in bio-oil for use in gas turbines was made by Diebold, Milne, Csernik et al. (1999). These authors adopted the maximum allowable alkali metal content (sodium plus potassium) of 0.5 mg/kg, according to the ASTM specifications, for gas turbine fuels as a suggested upper level for bio-oil. Three comments are appropriate here:

• Rather than on a mass basis, any derived norm should be determined on an energy basis. Overall, it is the specific deposition quantity in terms of mg/MJ which will indicate the ash deposition over time. If this approach is adopted, this would imply
that, on a mass basis, a minimum specification for bio-oil would be more than twice as strict than one for mineral oils (since a bio-oil’s calorific value is less than half that of the usual mineral oils).

- It is unknown whether the types of ashes produced from bio-oil have similar detrimental effects on gas turbine components. Since the sulphur content of bio-oil and pyrolysis gas is very low, the formation of corrosive sodium and potassium sulphates is limited by the sulphur concentration rather than the alkali metal concentrations. This suggests that less restrictive specifications with regard to alkali metals could be applied than with fossil fuels.

- Some gas turbine manufacturers\(^{335}\) indicate that they are capable of providing machines which accommodate significantly higher levels of alkali contamination than specified by the ASTM norm.

The first two observations have already been made by Moses and Bernstein (1994). With regard to ash deposition, the technical difficulties are essentially smaller than or, at worst, equal to those occurring with the employment of gasifier-produced gas since the ash forming elements are the same in quantity and type, as they originate from the same biomass feedstock. The solutions pursued with GCC technology involve cooling of the gas to below 540 °C to enable the filtration of the precipitated ashes. As shown in Section 5.2.2, this has consequences for the efficiency of the GCC system. It is still a matter of conjecture to what extent the ash forming elements are transferred into either the bio-oil or into the charcoal by-product. In so far as transferred into the charcoal, the ash forming elements do not pose any problems for turbine applications of bio-oil. Ash forming elements could be transferred into the bio-oil in the form of water-soluble salts (e.g. NaCl), but a transfer of vaporised oxidation products into the pyrolysis gas is very unlikely. This is because ash formation as a result of oxidation can only occur on the basis of the oxygen already present in the biomass feed; the liquefaction reaction takes place without air. At the current stage of technology development there is insufficient experience to determine the best strategies for mutually adapting pyrolysis fuels and gas turbines. Such strategies may include: prevention of carry-over of ash forming elements into bio-oil and pyrolysis gas, selection of adapted nozzle and blade coatings, and regular turbine washing. The latter will inevitably affect power plant availability.

APPENDIX F
QUANTIFYING ELECTRICITY PRODUCTION BY POWER PLANTS

The electricity produced by power plants is analysed using the following definitions:

**Capacity (power capacity)**

The maximum power output that a plant is capable of producing (W)

**Capacity factor**

(Here used as *annual* capacity factor) The quantity of energy produced by a power plant during one calendar period (here a year) divided by the theoretical maximum quantity of energy produced by the power plant during that period (expressed as a fraction or as a percentage).

\[
\text{Annual capacity factor} = \frac{\text{Energy produced during one year}}{\text{Capacity} \times 8760 \text{ hours}} \quad [\text{Wh/Wh}]
\]

**Load factor**

The quantity of energy produced by a power plant during the period that it is operational divided by the theoretical maximum quantity of energy produced by the power plant during that same operational period (expressed as a fraction or as a percentage).

\[
\text{Load factor} = \frac{\text{Energy produced during operational period}}{\text{Capacity} \times \text{operational period}} \quad [\text{Wh/Wh}]
\]

Note that the periods during which the power plant is not operational are not counted as part of the operational period.

The technologies considered produce electricity of equal quality and quantity. Generally both the quality and quantity of electricity production are defined using the following parameters:

- The net electric power capacity (C) (MW) (The term ‘net’ indicates that the capacity available for delivery to the grid is concerned, i.e. excluding capacities for internal plant power consumption).
- The planned annual operational period (OP) (h/yr).
- The planned maintenance period during OP (PM) (h/yr).
- The availability factor during OP-PM (AF) (dimensionless, h/h), expressing the occurrence of expected but unplanned stoppages.
- The load factor (LF) (dimensionless, kWh/kWh), expressing the amount of electricity produced during operational hours, relative to the installed capacity.

Together these parameters indicate the maximum power at which electricity becomes available and the annual quantity of electricity produced, i.e. according to the following equation:

---

336/ If the *combined* production of heat and electricity (CHP) would be considered, the parameter set needs extending.
In a more condensed manner, these six parameters can be combined using:

- The net electric power capacity (C) (MWₑ) and
- The capacity factor (CF) (dimensionless, kWhₑ/kWhₑ),

where CF combines OP, PM, AF and LF and is defined as:

\[
CF = \frac{OP \times (1 \& PM) \times AF \times LF}{8760}
\]

Naturally, information about the equality of services provided is lost if electricity production technologies are only characterised using these two parameters, instead of the six listed above. In this thesis the focus is on electricity production technologies for which these parameters are expected to be similar.
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