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Energy efficiency in new houses. Heat demand reduction versus cogeneration?

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Abstract

Heat demand reduction and cogeneration are two main options to reduce fuel consumption for space heating and warm tapwater in buildings. This article compares fuel saving and costs of these two options for the case of new Dutch houses. In the calculations, simulation techniques are used to account for diurnal and seasonal variations of both the heat demand level and the operational conditions of cogeneration. The use of a short term thermal storage is considered in order to match heat supply and demand. Heat demand reduction and cogeneration appear to have a considerable fuel saving potential in new Dutch houses. At present Dutch natural gas prices both options are not cost-effective. However, expected investment cost reductions and energy taxes that are under consideration may eliminate this hindrance. These developments would also open possibilities towards combinations of heat demand reduction and cogeneration. Such combinations could make a large contribution to fuel consumption reduction goals in The Netherlands.

Keywords: Energy efficiency; Heat demand; Cogeneration; Houses; The Netherlands; Simulation

1. Introduction

Residential and commercial energy consumption in The Netherlands covers about 30% of total final energy consumption. Most of this energy consumption is used for low temperature heating purposes. In 1991, the share of space heating in total final energy consumption was 21% and the share of warm tapwater heating was 3% [1]. In other European countries, the share of space heating in total energy consumption is comparable or even higher [2]. In The Netherlands, natural gas is the dominant fuel for heating purposes. The most common heating system, with an almost 90% share in new installations, is a central heating system in which the natural gas-fired central heating boiler also provides warm tapwater.

Reduction of natural gas consumption is important to slow depletion of natural gas resources and to prevent emissions of CO₂ and NO_x to the atmosphere. Present Dutch policy goals aim at substantial end-use efficiency improvements in buildings, which means providing the same comfort with less natural gas input. The end-use efficiency goal for the period 1990–2000 is an improvement of 23% in the residential, commercial and service sectors [3]. For the period after the year 2000, further improvements will be necessary, especially when policies

are adopted that aim at stabilization of CO₂ concentrations in the atmosphere.

Important efficiency improvements can be expected from heat demand reduction. In the period 1980–1993 a 50% improvement in the efficiency of space heating in Dutch centrally heated houses has been accomplished, mainly by improving insulation values and boiler efficiencies [4]. Demonstration projects with superinsulated houses have shown the possibility of further substantial reductions in heat demand.

Another important contribution to efficiency improvement in building heating can be expected from cogeneration. The present market share of cogeneration in the Dutch heating market is about 10%, most of which is heat from large scale cogeneration in district heating systems. Dutch electricity producers have proposed a ‘heat plan’, aiming at the expansion of large scale cogeneration. Small scale cogeneration is applied in a number of buildings in the commercial and service sectors, and in some housing projects with block heating. Dutch energy distribution companies have developed plans for a substantial expansion of small scale cogeneration over the next decade.

Heat demand reduction and cogeneration being two main options to achieve reduction goals in Dutch houses, the question arises how these two options compare.

Which of the two options will offer the highest fuel saving? Which option offers fuel saving at the lowest costs? And finally, is a combination of the two options possible to obtain higher fuel savings?

In this article, these questions are tackled for the case of new Dutch houses. The evaluation in this article is based on calculations of fuel saving and costs of various combinations of heat demand level and co-generation system design. In such calculations it is necessary to account for the dynamical, time varying, nature of both the heat demand level and the operational conditions of cogeneration. Heat demand shows both diurnal and seasonal variations under the influence of behaviour patterns of the inhabitants and the meteorological conditions. Cogeneration operational conditions are not static because of varying electricity prices. An additional dynamical element is introduced by considering the use of thermal storage in order to match heat supply and demand.

In this article, heat demand reduction is considered first. The dynamics of heat demand are discussed, followed by a quantitative assessment of heat demand levels and heat demand patterns in new Dutch houses – for present building practice as well as for reduced heat demand levels. Next, cogeneration options are considered, also starting with a discussion of cogeneration system dynamics. A quantitative assessment is made for cogeneration options, both small scale and large scale, applied at different levels of heat demand in new Dutch houses. Fuel saving and costs for heat demand reduction and cogeneration options are compared, and the possibilities of implementation at present fuel prices will be examined. Finally, the influence of developments in investment costs and fuel prices on the implementation possibilities is examined.

2. Heat demand dynamics

The most common method to describe variation of heat demand over time is the simulation method: heat demand is simulated for all occurring conditions by keeping track of all relevant heat flows in discrete time steps over a full year. Various models are available that simulate heat demand in buildings and thus provide time series of heat demand for a specified building in a specified climate. Input of such models consists of meteorological conditions, building characteristics and occupant behaviour. A problem in simulation models is that the input regarding occupant behaviour, like thermostat settings and ventilation rates, is generally unknown. This problem is tackled here by confronting the results of a building simulation model with measured data. This provides a check on the validity of the model, and especially a check on the validity of the model input regarding occupant behaviour.

2.1. The simulation model

The heat demand simulation model we developed for the calculations in this article considers the building as an open thermodynamic system [5]. The system boundary, or building envelope, separates the internal climate from the outside climate. The system is divided into three subsystems or zones, corresponding to different air temperature zones within the building. In domestic buildings, for instance, these are a living-room zone, a bedroom zone and an unheated storeroom zone.

Each zone contains modules, building elements sharing similar properties. The description of these building elements in our model is based on an earlier developed model [6]. Several types of building elements and heat flows can be distinguished:

- Solid constructions are elements through which heat is transferred to the outside or to another zone. This heat transfer is described by a one-dimensional Fourier equation, characterized by a heat resistance and a heat capacity.
- Ventilation is also considered as a heat transfer element, but without heat capacity.
- Internal mass is a heat capacity element that acts as a heat buffer. This mass is divided into a slow and a fast reacting part.
- The indoor air is considered as a heat capacity element that connects all heat flows from the other modules.
- Internal heat load, coming from inhabitants, electric apparatus, cooking etc. is considered as an incoming heat flow into the system. The same holds for solar radiation.

The model is written in the TUTSIM simulation language [7]. Heat flows through the building are calculated in discrete time steps¹. Heat supply into the building is governed by a control unit. At each time step of the simulation, the indoor air temperature per

Table 1
Input and output of the heat demand model

Input	<p>Meteorological data (hourly values): outdoor temperature, solar irradiation per orientation</p> <p>Building specifications (per zone): solar transmittance, heat resistance and heat capacity of building elements</p> <p>Occupant behaviour data (hourly values per zone): thermostat settings, ventilation rate, internal heat production by persons, appliances and warm tapwater use</p>
Output	Heat demand (hourly values per zone)

¹ Input and output of the model is at 1 h intervals, but the time step for the calculations is much shorter, typically 80 s, for stability reasons in solving differential equations.

Fig. 1. Measured and simulated space heating demand patterns for 96 low-rise houses in Groningen, The Netherlands. Average diurnal patterns for four weeks in December 1986.

zone calculated in the previous time step is compared with the thermostat setting. The thermostat setting expresses the temperature required by the inhabitants of the building. According to the difference between required and actual air temperature, a PI control calculates the amount of heat to be supplied to the indoor air. Table 1 gives the input and output of the heat demand model.

2.2. Model adjustment

As mentioned above, a serious problem with heat demand simulation models is that it is difficult to establish the necessary input, especially regarding occupant behaviour. The problem is tackled here by comparing the heat demand data obtained by the model with measured data, and adjusting behavioural characteristics to make the calculated model results match the measured data. The procedure is described in more detail in Ref. [5]. The comparison was made for a project containing 96 single-family houses in the city of Groningen, The Netherlands. The houses were built in 1983, and match closely the housing type used as a reference in most Dutch studies on heat demand reduction. Hourly measurement of heat demand for space heating and warm tapwater as well as measurement of meteorological variables and indoor temperatures were undertaken for this Groningen project in the year 1986 [8]. Data of two weeks of measurements were substituted for data from adjacent weeks to obtain a close agreement of average outside temperature and solar irradiation with the Dutch 30-year average of these variables [9].

Occupant behaviour characteristics that appear to have an important influence on heat demand variations are the ventilation rate and the diurnal variations of thermostat settings. Starting values for these variables were taken from the literature. Establishing the variation in thermostat settings was supported by indoor temperature measurements in the project. Final adjustments were made based on inspection of differences between model calculations and measured data.

Fig. 1 shows aggregated results for December 1986. Model results are in good agreement with measurements. The figure shows a clear difference between day and night, due to lower thermostat settings in the night period.

3. Heat demand in new dutch houses

3.1. Reference

The houses of the project described in the preceding paragraph are taken as the reference housing type used in this article. Application of the 1992 Dutch building practice and building standards on these houses defines the reference heat demand. Calculations with the simulation model described above show a reference heat demand for space heating of 29 GJ/yr. If supplied by a central heating boiler with a 89% efficiency², this heat demand matches a natural gas consumption of

² Efficiencies are with respect to the lower heating value of natural gas, being 31.65 MJ/m³ for the most commonly used natural gas quality in The Netherlands.

1030 m³/yr, in close agreement with the reference value found in other sources [1].

The hourly heat demand for warm tapwater of a single family house is also based on data from the Groningen project [1,9]. The heat demand for warm tapwater is 10.8 GJ/yr, which matches a warm water consumption of about 150 l per day at 40 °C. If supplied by a combi-boiler with a 63% efficiency for warm tapwater production, the natural gas consumption for warm tapwater would be 540 m³/yr, which is in agreement with the Dutch average natural gas consumption for warm tapwater in houses with new tapwater heating installations [1].

3.2. Heat demand reduction options

Heat demand in new Dutch houses has been decreasing substantially over the last decades. The average annual natural gas consumption for a new house built in 1970 was about 3000 m³, three times the 1992 value used as reference for this article. This decrease is accomplished mainly by improving insulation of new houses. Insulation of walls, windows, roof and ground floor of a building decreases heat losses due to conduction, convection and radiation, and therefore reduces the amount of heat that has to be put into the building. For new Dutch buildings, mandatory insulation standards have gradually been tightened since 1975. From 1992 on, these standards require double glazing with a maximum heat loss coefficient (k value) of 3.0 W/(m² K) and constructions in roofs, outer walls and ground floors with a minimum heat resistance (R_c value) of 2.5 (m² K)/W³. These insulation values are used as the basis for reference heat demand.

Further improvements in the insulation of buildings are possible. Double glazed windows with a k value down to 1.3 W/(m² K) are commercially available. These windows use low emittance coatings and are filled with inert gas. For walls and roofs, an improvement of the R_c value to 3.0–3.5 (m² K)/W is possible in conventional Dutch construction practice, e.g. in cavity wall constructions by using prefabricated insulated inner walls in combination with insulation in the cavity itself. Mineral wool can be used as insulation material. Alternatives are materials like flax, cellulose or coconut fibre, which are based on renewable resources and have a lower energy content [10].

More heat demand reduction can be attained by tackling ventilation heat losses. Ventilation causes heat losses because warm indoor air is removed and replaced by fresh air at outdoor temperature. Ventilation losses can be decreased by transferring part of the heat content

of the removed warm air to the incoming fresh air in a heat exchanger. This heat recovery is only possible in ventilation systems that control incoming and outgoing air flows. Typical heat exchangers recover about 70% of the ventilation heat. Due to the extra ventilation induced and the remaining infiltration losses, the effective heat recovery is lower in practice.

A last relevant concept in heat demand reduction is the passive solar concept. The most common passive solar application is the direct gain concept. In this concept south facing windows allow sunshine to enter the rooms which are used most frequently, e.g. the living space in dwellings. To prevent overheating, most of the solar radiation must be absorbed and stored by thermal mass in floors and walls. An additional overheating prevention measure is the use of overhangs or blinds to shield windows from solar radiation in the summer.

3.3. Fuel saving and costs

Fuel saving and costs have been calculated for two levels of heat demand reduction: an 'improved insulation' option and a 'minimum energy' option. Table 2 shows the relevant input data for the calculations. Heat demand for space heating has been simulated for the reference heat demand and the two heat demand reduction options with the heat demand model described above. Calculated diurnal space heating demand patterns are shown in Fig. 2. The distribution of heat demand over the year is shown in Fig. 3. Results show that heat demand reduction leads to a shortening of the space heating season. In the 'minimum energy' option, heat demand for space heating is mainly concentrated in daytime and evening hours during 4–5 winter months.

Also shown in Figs. 2 and 3 is warm tapwater heat demand. Warm tapwater heat demand shows a clear diurnal variation, but little seasonal variation. The share of warm tapwater in total heat demand increases substantially when heat demand reduction options are applied.

Table 3 lists annual heat demand and fuel consumption for the three heat demand options. For the 'minimum energy' option, the calculations show a heat demand for space heating of 13.3 GJ/yr, which matches a natural gas consumption of 470 m³/yr, in agreement with measured values in actually realized 'minimum energy' houses that are in the range of 400–500 m³ natural gas annually. Fuel saving compared with reference heat demand is thus 560 m³/yr. Accounting for the extra electricity consumption in the balanced ventilation system, the net fuel saving is 480 m³/yr. The electricity is assumed to be produced by a combined cycle natural gas-fired power station with a state-of-the-art efficiency of 52%.

³ Dutch calculation rules use an average value for boundary layer heat transfer resistances of 0.17 (m² K)/W for windows, walls and roofs, so $k = 1/R = 1/(R_c + 0.17)$.

Table 2
Calculation input of the three heat demand options [1]

Building features	Reference	Improved insulation	Minimum energy
R_c Walls/roof ((m ² K)/W)	2.5	3.0	3.5
R_c Ground floor ((m ² K)/W)	2.0	3.0	3.5
k Windows living room (W/(m ² K))	2.9	1.9	1.9
k Windows other rooms (W/(m ² K))	2.9	2.9	1.9
Effective efficiency heat recovery			0.5
Orientation of windows in living room	E	E	S
Investment costs (Dfl)		1800	6000
Depreciation period (yr)		30	25
Auxiliary electricity consumption (kWh/yr)		0	360

Fig. 2. Heat demand for low-rise houses in The Netherlands. Average diurnal patterns for four weeks in December, three space heating demand options plus warm tapwater.

Also listed in Table 3 are costs per saved m³ natural gas for the heat demand reduction options. This cost indicator is calculated by dividing annualized⁴ investment and maintenance costs by the annual net fuel saving. All costs in this article are in Dutch guilders (Dfl) of 1992⁵. Investment costs and depreciation periods for the heat demand reduction options are listed in Table 2. Costs of extra electricity consumption are calculated on a marginal costs basis, again assuming electricity production from a combined cycle natural gas-fired power station with a 52% efficiency. The marginal costs approach used here [11] divides electricity costs into:

- Costs associated with fuel consumption in a power station. For an assessment of costs per saved m³ it is

not necessary to calculate this cost component, because the fuel consumption of electricity production is treated as part of the net fuel consumption effect of an option. At the 1994 Dutch natural gas price for households, the fuel costs would be 0.103 Dfl/kWh. Because electricity producers pay a lower natural gas price, the actual fuel component in the electricity price is only about 0.05 Dfl/kWh.

- Costs associated with investment and maintenance costs of a power station. Annualized costs are 133 Dfl/kW_{el}. These costs are assigned to the hours between 8.00 and 18.00 on weekdays in the months September to April. This leads to a 'peak charge' of 0.076 Dfl/kWh during these 1750 h [1].

Costs per saved m³ are 0.65 Dfl/m³ for the 'improved insulation' option and 0.89 Dfl/m³ for the 'minimum energy' option. This implies that at the 1994 Dutch natural gas prices for households (0.45–0.50 Dfl/m³) these heat demand reduction options are not cost-effective: costs are higher than the financial benefits

⁴ A real interest rate of 5% is used for the annualization of investment costs.

⁵ Costs stated here do not include the Dutch value added tax. 1 Dfl = 0.55 \$.

Fig. 3. Heat demand for low-rise houses in The Netherlands. Average monthly heat demand for three space heating demand options and warm tapwater.

Table 3
Calculation results of the three heat demand options

	Reference	Improved insulation	Minimum energy
Annual heat demand			
Space heating (GJ/yr)	29.0	24.0	13.3
Warm tapwater (GJ/yr)	10.8	10.8	10.8
Annual natural gas consumption using a combi-boiler			
Space heating (m ³ natural gas/yr)	1030	850	470
Warm tapwater (m ³ natural gas/yr)	540	540	540
Net fuel saving (m ³ natural gas/yr)		180	480
Costs per saved m ³ natural gas (Dfl/m ³)		0.65	0.89

of the fuel saving. The influence of possible investment cost reductions and energy taxes on cost-effectiveness will be discussed in the last paragraph of this article.

4. Cogeneration system dynamics

Cogeneration, or combined heat and power (CHP) technology, is the combined production of electricity and useful heat. In electricity generation from fossil fuels, the cooling water and combustion gases contain waste heat that can be recovered for heating purposes. The principle is applied at various scale levels and is used with various electricity generation techniques.

The application of cogeneration systems in building heating has several features, which makes an analysis of variations in time necessary. In the first place, the production of a cogeneration system must follow the variations in heat demand. In case heat demand is lower than cogeneration capacity, the cogeneration unit

will operate under part load conditions or will switch on and off. In case heat demand is higher than cogeneration capacity, a back-up system, generally a boiler, must be used to meet heat demand. A heat storage system can be applied to unlink cogeneration production and heat demand, making it possible to meet peak heat demand with heat from storage and limiting cogeneration capacity. Secondly, the operation of a cogeneration system may be dependent on varying electricity prices. It is financially attractive to ensure operation of the cogeneration system in periods with high electricity prices. A heat storage may be helpful in this respect, because a storage makes cogeneration production in peak electricity price periods possible also when the heat demand is too low.

4.1. The simulation model

To keep track of the time-varying conditions governing the performance of a cogeneration system — combined

Fig. 4(a). The heat supply system. Lines indicate the transfer of heat between components and heat load. Heat and mass flow is in the direction of the arrows. The dashed line shows the heat flow in case no storage is present.

Fig. 4(b). Physical lay-out of the heat supply system for small scale cogeneration in a block heating network. The cogeneration unit is a small electricity generation unit (capacity typically under 1 MW_e). Cogeneration unit, boiler and storage generally are located in one building, near the heat demand.

Fig. 4(c). Physical lay-out of the heat supply system for large scale cogeneration in a district heating network. The cogeneration unit is a medium sized electricity generation unit (capacity typically in the range 25–250 MW_e). The distance from the cogeneration unit to the heat demand typically is a few km. The boiler and the storage may be located near the heat demand.

with a heat storage and a back-up boiler – a simulation model SIHS (simulation of integrated heat-supply systems) has been developed, based on the TUTSIM simulation language. The model calculates heat flows in a heat supply system from hour to hour⁶, over a full year.

Fig. 4(a) shows the system components of the SIHS heat supply system, and the way heat flows between them. The heat supply components are a cogeneration unit, a hot water storage, and a conventional or condensing boiler. The cogeneration unit delivers its heat to the storage system. The heat demand is divided into a warm tapwater part and a space heating part. Heat transportation and distribution losses are taken as part

of the heat demand to be met by the supply system. The heat transfer medium is water. Fig. 4(b) and (c) schematically represents the physical lay-out of the heat supply system for small scale and large scale cogeneration.

The complete SIHS model also incorporates other heat supply components not shown in the figure: solar collectors and heat pumps. A detailed description of the full model and an account of model testing is given in Ref. [1]; a more brief description can be found in Ref. [12].

4.2. Component description

The performance of components, and the dependence of this performance on system parameters like water temperatures and mass flows, can be described by simple mathematical relations. Important features are:

- The cogeneration unit operates at full capacity, in an on/off mode. The electrical and thermal efficiencies of the cogeneration unit are assumed to be independent of the cogeneration inlet temperature, which implies a fixed ratio between heat output and electricity output. A mass flow control is present to maintain a specified outlet temperature of the cogeneration system. On/off control strategy is discussed in a next paragraph.
- The hot water storage is modelled as a cylindrical stratified water tank. In the model, the tank is divided into N sections of equal volume. Each section is considered as fully mixed and the amount of heat in the section is determined by one section temperature. Heat transfer between the sections is by mass transport only. Because this model assumes that turbulence or diffusion between sections is absent, a large number of sections represents a high level of stratification. Lowering the number of sections represents decreasing stratification. The use of one section represents the case of a fully mixed storage. Only the top and bottom sections of the storage are connected to other components of the system. Mass flow in and out of storage is maximized. Heat loss through the walls is determined by a heat loss coefficient k .
- The boiler has a capacity that exceeds the maximum heat demand. The boiler serves as a back-up heater. Control of the boiler allows its operation to be limited to periods when none of the other heat supply components can meet the heat demand or the required minimum supply temperature of the heat demand. Separate heating of both parts of the heat demand is an option. A mass flow control maintains specified heat demand return temperatures.

Input and output of the SIHS cogeneration/storage model is given in Table 4.

⁶ Input and output of the model is at 1 h intervals, but the time step for the calculations is generally 1/4 or 1/2 h for systems that incorporate a hot water storage, for stability reasons in solving differential equations.

Table 4
Input and output of the SIHS cogeneration/storage model

Input	Heat demand data (hourly values): space heating demand, warm tapwater heat demand System configuration data: storage volume, capacity of cogeneration unit Component specifications: efficiency parameters of cogeneration unit, heat loss parameters of storage Control variables: variables governing flow controls and on/off controls
Output	Fuel consumption and electricity output (annual values)

4.3. Control of cogeneration unit

On/off control of the cogeneration unit has two objectives. A first objective is to limit boiler heating during peak heat demand. This objective will be met by loading the storage as much as possible in periods with low heat demand, e.g. night-time hours. A second objective is to make maximum use of high electricity prices. As these high electricity prices occur during daytime, this objective will be met by loading the storage during daytime hours, and unloading as much as possible during night-time hours. This last objective conflicts with the first objective, which implies that control strategy is not a straightforward matter, and optimization of control is necessary. To make optimization possible, two control variables are introduced.

The main control variable is a target value for the storage charge fraction. The storage charge fraction f_s is defined as the actual heat content of storage E_s ,

divided by the maximum heat content of storage $E_{s,max}$. Cogeneration on/off control is governed by f_{sg} , the target value for the storage charge fraction. This target value can be set to $f_{sg}=1$ during hours of high electricity prices, which means that the cogeneration unit is turned on until storage is loaded to a heat content $E_s=E_{s,max}$. During hours with low electricity prices the target value is set low, which means that a heat demand is preferably met with heat from storage, without operation of the cogeneration unit. The target value f_{sg} can be related to the electricity price, and may therefore not only depend on the hour, but also on the season and on the day-type (weekend-day or weekday).

A second control variable can be helpful to minimize boiler heating. This is $T_{s1,min}$, a minimum temperature of the 'hottop': the highest part of the storage. By keeping this hottop at a temperature somewhat above the minimum supply temperature of the heat demand, at all times, much boiler heating can be avoided. Optimization, e.g. to maximize financial benefits of the cogeneration system, will show the best values for f_{sg} and $T_{s1,min}$.

In Fig. 5, the functioning of the on/off control of a cogeneration unit using the target value of the storage charge fraction is shown. During the first part of the day shown in Fig. 5, the heat demand is met with heat from storage, without operation of the cogeneration unit. This leads to a steady decrease of the storage charge fraction. At 7.00 hours, the target value for the storage charge fraction is set at 0.5, corresponding to a rise in electricity price. The cogeneration unit is switched on and off, keeping storage loaded at about half the maximum heat content. At 9.00 hours, the target value for the storage charge fraction is set to

Fig. 5. Control of cogeneration output for a cogeneration system supplying heat to 200 low-rise houses. Cogeneration capacity 400 kW_{th}, storage volume 40 m³.

1, corresponding to a peak load electricity price. Now the cogeneration unit is switched on continuously, load-ing storage. After another period of on/off switching in the afternoon, the cogeneration unit is again off during evening and night-time hours, when the electricity price is low. This control strategy thus concentrates cogeneration production to only a few hours to make maximum use of high electricity price.

5. Cogeneration in new Dutch houses

In Dutch building heating, two typical applications of cogeneration prevail: small scale cogeneration is applied on the block heating level and based on a gas motor; large scale cogeneration is applied in district heating systems and based on the combined cycle technique (see Fig. 4(b) and (c)).

On the small scale level, in gas motors used for cogeneration, heat can be recovered from the cooling water and the exhaust gases. Typically about 30–35% of the energy input is converted to useful electrical power and about 50–55% to useful heat. Electrical capacities for small scale cogeneration units range from 50 to 1000 kW. Current applications of small scale cogeneration for building heating in The Netherlands

are primarily in commercial and service buildings. Small scale cogeneration covers about 1% of the heating market.

On the large scale level, the typical electricity generation technique is a combined cycle installation: a gas turbine followed by a steam turbine, the steam being produced with the heat from the exhaust gases of the gas turbine. Heat is recovered from the steam cycle. At a typical capacity of 50 MW, the electrical efficiency is 43% combined with a thermal efficiency of 46% [1]. In 1993, 10% of Dutch houses were connected to a district heating network.

The next paragraphs will present calculations of fuel saving and costs for cogeneration at these two scale levels, applied at different levels of heat demand for new Dutch houses.

5.1. Small scale cogeneration

The small scale cogeneration option is considered for a project size of 200 houses, connected by a block heating network. The network supplies heat for both space heating and warm tapwater. Technical features of the cogeneration system and the heat distribution system are listed in Table 5.

Table 5

Parameters for cogeneration, heat storage and heat distribution applied to new Dutch houses [1]

	Small scale cogeneration	Large scale cogeneration
Project size (number of houses connected)	200	20000
Heat distribution parameters:		
Heat loss in distribution network (GJ/yr/house)	3	5
Heat loss in tapwater heat exchanger (GJ/yr/house)	4.4	4.4
Minimum supply temperature (°C)	70	70
Return temperature (°C)	40	40
Auxiliary electricity consumption (kWh/GJ)	2	2
Cogeneration system parameters:		
Thermal efficiency cogeneration unit (–)	0.54	0.46
Electrical efficiency cogeneration unit (–)	0.34	0.43
Outages cogeneration unit (%)	4	4
Maximum outlet temperature cogeneration unit (°C)	90	90
Other system parameters:		
Heat loss coefficient storage walls (W/(m ² K))	0.5	0.5
Ambient temperature storage (°C)	10	10
Maximum mass flow into storage (m ³ /h)	16	4000
Thermal efficiency boiler (–)	0.89	0.89
Financial parameters:		
Heat distribution investment costs (Dfl/house)	3000	3915
Cogeneration investment costs (Dfl/kW _{el})	1700	1600
Storage investment costs (Dfl/m ³)	1000	350
Heat distribution depreciation period (yr)	25	25
Cogeneration/storage depreciation period (yr)	15	25
Heat distribution operational costs (Dfl/yr/house)	48	48
Cogeneration operational costs (Dfl/kWh _{el})	0.02	0.015

A conventional boiler is used as back-up heater. The boiler not only serves as a back-up in case of outages, but also provides part of the heat during periods of peak heat demand in winter. Careful choice of the cogeneration capacity is important: a small capacity leaves a large part of the heat demand to be supplied by the boiler, which limits fuel saving; a large capacity implies that the full capacity is only used during a small number of days in winter time, which means that the costs will be high because of the large capacity costs of cogeneration units. An optimal cogeneration capacity has to be found, defined here as the cogeneration capacity for which total costs of investment, maintenance and fuel consumption are minimal.

The derivation of the optimal cogeneration capacity is shown in Fig. 6. For a cogeneration system without storage (solid line in the figure) annual fuel saving at a capacity of 520 kW_{th} is 33% of reference natural gas consumption for space heating plus warm tapwater, equivalent to 520 m³ natural gas per house. As in the calculations of fuel saving for heat demand reduction, fuel savings here are net fuel savings. Net fuel savings account for the fuel consumption associated with the electricity produced by the cogeneration system. This electricity is assumed to replace electricity produced by a combined cycle natural gas-fired power station with an efficiency of 52%. Net fuel savings also account for heat losses and auxiliary electricity consumption in the heat distribution network.

Fig. 6 shows that at a 520 kW_{th} capacity, costs per saved m³ are at a minimum of 0.98 Dfl/m³ natural gas. Costs are all non-fuel costs associated with the cogeneration system: annualized investment and maintenance costs of the cogeneration and heat distribution system, minus replaced investment and maintenance

costs in central electricity production based on a combined cycle power station. The minimum in the cost curve implies that at a natural gas price of 0.98 Dfl/m³ natural gas, the optimal cogeneration capacity of 520 kW_{th} would offer equal costs and benefits and would therefore be cost-effective. At higher natural gas prices, a larger cogeneration capacity would be optimal.

Also shown in Fig. 6 are fuel saving and costs for a cogeneration unit in combination with a heat storage (dashed lines in the figure). This storage is a cylindrical stratified hot water tank, located near the cogeneration unit. Minimum costs of fuel saving are 0.96 Dfl/m³ natural gas for a cogeneration capacity of 550 kW_{th} and a storage volume of 40 m³. Annual fuel saving for this cogeneration/storage system is 540 m³ per house: 35% of reference natural gas consumption. For the optimal system configuration, control strategy was optimized using the control variables mentioned in the previous paragraph. Control is aimed at preferential cogeneration production in periods with high electricity prices: the hours between 8.00 and 18.00 on weekdays in the months September to April. Optimal values for the control variables are listed in Table 6. Even with optimal control, adding the storage turns out to give only a small improvement of results compared with a cogeneration system without storage.

Table 6 summarizes the results for small scale cogeneration with heat storage, for configurations optimized to minimize costs per saved m³. Also shown in the table are results for cogeneration options in combination with 'minimum energy' heat demand. In that case, fuel saving of an optimal cogeneration/storage system decreases to 330 m³ natural gas per house because of lower heat demand. Total fuel saving of heat demand reduction plus cogeneration increases to 810 m³

Fig. 6. Fuel saving and costs for small scale cogeneration, optional hot water storage. Heat demand is for 200 houses, space heating demand at reference level plus warm tapwater.

Table 6

Calculation results for cogeneration/storage configurations, optimized to minimize costs per saved m³ natural gas

	Small scale cogeneration		Large scale cogeneration	
	Reference	Minimum energy	Reference	Minimum energy
Optimal configuration:				
Thermal capacity cogeneration unit	550 kW _{th}	380 kW _{th}	66 MW _{th}	45 MW _{th}
Storage volume (m ³)	40	30	9000	8000
Target value storage charge fraction f_{sg} ^a	0.2/0.6/0.4	0.2/0.3/0.5	0.3/0.4/0.3	0.3/0.4/0.4
Minimum hottop temperature (°C)	75	75	75	75
Results, cogeneration only:				
Fuel saving (m ³ natural gas/yr)	540	330	930	580
Costs per saved m ³ (Dfl/m ³)	0.96	1.33	0.59	0.84
Results, cogeneration plus heat demand reduction:				
Fuel saving (m ³ natural gas/yr)		810		1060
Costs per saved m ³ (Dfl/m ³)		1.07		0.86

^a Values of f_{sg} are for the periods 23.00–8.00, 8.00–18.00, 18.00–23.00 hours, respectively.

natural gas, at combined costs of 1.07 Dfl/m³ natural gas.

Small scale cogeneration appears to be not cost-effective if compared with the 1994 gas price for households (0.45–0.50 Dfl/m³ natural gas). Even with the 1994 level of Dutch subsidies for small scale cogeneration and natural gas price discounts for cogeneration application, a small scale system is not profitable for a prospective investor. Accordingly, application of small scale cogeneration in new housing blocks is very rare. The dominating factors in costs are the heat distribution costs. Applications of small scale cogeneration in offices or other large buildings, that do not suffer from high heat distribution costs, are profitable and currently more common in The Netherlands.

5.2. Large scale cogeneration

The large scale cogeneration option is considered for a project size of 20 000 houses, connected by a district heating network. The network supplies heat for both space heating and warm tapwater. Technical features of the cogeneration system and the heat distribution system are listed in Table 5.

Like in the case with small scale cogeneration, a conventional boiler is present to serve as a back-up in case of outages and to provide peak heat demand. Optimization of the cogeneration capacity is shown in Fig. 7, for a cogeneration system with and without storage. A striking difference with the small scale system is that the addition of storage now turns out to give a substantial improvement of results. Economies of scale in heat storage cause lower costs per m³ storage volume for large systems. This makes relatively large storage volumes possible, which in turn enables some oversizing of the cogeneration system because of the attractiveness to produce mainly in electricity peak hours.

At the optimal configuration with storage, only 3% of the heat is produced by the back-up heater. The use of storage in combination with high cogeneration capacities is in accordance with current practice in Dutch district heating systems.

Another difference with small scale cogeneration is that fuel saving is substantially higher: the higher electrical efficiency of large scale cogeneration implies that more fuel is saved in central electricity production. Because of the higher fuel saving, costs per saved m³ natural gas are lower.

Table 6 lists results for cogeneration systems with storage, optimized to minimize costs per saved m³. For a large scale cogeneration/storage system applied at reference heat demand the annual fuel saving is 930 m³ natural gas per house, 59% of reference heat demand, at costs of 0.59 Dfl/m³ natural gas. For the combination of cogeneration with heat demand reduction to the 'minimum energy' level, combined fuel saving is 1060 m³ natural gas, at combined costs of 0.86 Dfl/m³ natural gas.

Large scale cogeneration appears to be not cost-effective if compared with the 1994 gas price for households (0.45–0.50 Dfl/m³ natural gas). However, the operation of a cogeneration system under present Dutch conditions may be profitable because the price of natural gas for cogeneration application is lower (approximately 0.20 Dfl/m³ natural gas for the system size under consideration here), while the value of the heat is based on the higher price that applies to households.

6. Results and future developments

6.1. Overview of results

We return to the central question posed in the introduction: comparing the two options — heat demand

Fig. 7. Fuel saving and costs for large scale cogeneration, optional hot water storage. Heat demand is for 20 000 houses, space heating demand at reference level plus warm tapwater.

reduction and cogeneration — which one offers the highest fuel saving, which one offers the fuel saving at the lowest costs, and how do fuel saving and costs of combinations of both options compare with separate application. Simulation techniques with an empirical basis have been used in this article to answer these questions for one specific sector in the heating market: new Dutch single-family houses. Results of the calculations are summarized in Table 7.

Heat demand reduction by improving building design to the demonstrated 'minimum energy' level offers an annual saving of 480 m³ natural gas: a 46% saving compared with the 1030 m³ natural gas used for space

heating in the reference situation that represents current Dutch building standards. It must be added here that the heat demand level in this reference situation is already relatively low: only one third of the 1970 level for new houses. Annual fuel saving of cogeneration — applied in block or district heating systems incorporating warm tapwater heat demand — is in the range 540–930 m³ natural gas per house, the highest saving applying to a large scale 20 000 houses application that benefits from the relatively high electrical efficiency of a combined cycle cogeneration unit. When cogeneration is applied in houses with heat demand reduced to the 'minimum energy' level, heat demand reduction and

Table 7

Optimal fuel saving and costs for some fuel saving options in new Dutch houses. Reference fuel consumption is 1030 m³/yr natural gas per house for space heating and 540 m³/yr natural gas per house for warm tapwater. Costs are stated for both 1992 investment cost levels and for reduced investment cost levels

	Fuel saving ^a (m³ natural gas per house)	Costs ^b 1992 level (Dfl per saved m³ natural gas)	Costs ^b reduced level (Dfl per saved m³ natural gas)
Heat demand reduction:			
Improved insulation	180	0.65	
Minimum energy	480	0.89	0.63
Small scale cogeneration/storage	540	0.96	0.84
Large scale cogeneration/storage	930	0.59	0.49
Small scale cogeneration plus minimum energy	810	1.07	0.78
Small scale cogeneration part only	330	1.33	1.00
Large scale cogeneration plus minimum energy	1060	0.86	0.63
Large scale cogeneration part only	580	0.84	0.63

^a Fuel savings stated in the table are net fuel savings, accounting for fuel consumption associated with electricity consumed by heating/ventilation installations — or produced by cogeneration units. Electricity production is assumed to be based on new natural gas fired power stations.

^b Costs are all non-fuel costs of an option, accounting for costs in electricity production and heat distribution.

cogeneration fuel savings cannot simply be added together: total savings are in the range 810–1060 m³ natural gas per house. The simple addition of fuel savings from heat demand reduction and cogeneration does not hold for two reasons. Firstly, a lower heat demand implies lower cogeneration heat production and therefore lower cogeneration fuel saving. Secondly, heat distribution losses become relatively more important with lower heat demand, which causes the percentage fuel saving of cogeneration to decrease.

Looking at costs per saved m³ natural gas, it appears that the considered options are not cost effective at the 1994 Dutch natural gas price for households (0.45–0.50 Dfl/m³). Cost effectivity is approached most by the ‘improved insulation’ option – with limited fuel saving – and the large scale cogeneration option – offering the highest fuel saving of the options considered here. A combination of heat demand reduction and cogeneration clearly puts cost-effectivity under even higher pressure. The reason for the higher costs per saved m³ of such combinations is that, as mentioned above, the fuel saving of cogeneration decreases with lower heat demand, while investment costs – especially costs for heat distribution – do not decrease proportionally. Though subsidies and gas price discounts for cogeneration may improve the profitability of the options considered here, financial aspects seem to be a hindrance for further implementation of fuel saving options in new Dutch houses. It is interesting to see if there are developments that could eliminate this hindrance.

6.2. Developments

A first relevant development consists of investment cost reductions for heat demand reduction techniques and for heat distribution systems. Table 7 lists the effects on costs per saved m³ of some on-going or expected investment cost reductions [13]: reduction of investment costs for heat demand reduction on the ‘minimum energy’ level to 4200 Dfl/house and a 25% investment cost reduction for heat distribution systems. Though the effects of such investment cost reductions are considerable, it appears that the considered options are still not cost-effective at the 1994 Dutch natural gas price for households.

A second development consists of energy price increases. Many authors have argued that present energy prices do not reflect the full environmental costs of the use of energy sources, although attempts to quantify these environmental costs may lead to diverging results [14,15]. In The Netherlands, an energy tax leading to a 50–100% increase in natural gas prices has been considered recently [16], and the Dutch government has announced the introduction of such a tax [3]. As can be read from Table 7, a 50% price increase – leading to a natural gas price for households of about

0.70 Dfl/m³ – in combination with the expected investment cost reductions would make all options except small scale cogeneration cost-effective.

6.3. Heat demand reduction versus cogeneration?

The option of large scale cogeneration combines high fuel savings with relatively low costs per saved m³. This would make the choice between heat demand reduction and cogeneration easy were it not for the limitations of large scale cogeneration. The application of large scale cogeneration is limited to areas with concentrated heat demand. Above that, the application of cogeneration has an upper limit equal to the total required electrical power capacity for a region. Small scale cogeneration seems to be more suited for application in larger buildings where heat distribution costs and heat losses are low, and is also limited to total required electrical power. This means that there are many situations where heat demand reduction must be considered.

So it seems that every option considered here has its own application area. But moreover, there are several arguments why combinations, especially combinations of large scale cogeneration and heat demand reduction, are an attractive option. The most important argument is that such combinations offer the highest fuel saving. Considering the limited total cogeneration capacity, combination of cogeneration and heat demand reduction implies that more or larger district heating areas can be developed. Combining options makes the highest contribution to reduction goals in The Netherlands. As we have seen, cost-effectivity can be a problem for separate as well as combined application of heat demand reduction and cogeneration. But developments like investment cost reductions and energy price increases by energy taxes appear to eliminate this hindrance.

We may conclude that both options deserve further application and development. Further developments can be expected in heat demand reduction as well as in efficient heat supply. Extreme low heat demand for space heating can be accomplished by the use of new insulation techniques like aerogels or vacuum systems. On the supply side, cogeneration based on non-fossil fuels like biomass and hydrogen produced from renewable energy sources may become an option. Another possibility is to make use of heat produced by solar or geothermal energy. Improving efficiency in building heating seems to be a continuing process of both demand and supply improvements.

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