# A Multi-Model Study of Energy Supply Investments in Latin America under Climate Control Policy Energy Economics

Kober, T.; Falzon, J. ; van der Zwaan, B.; Calvin, K.; Kanudia, A.; Kitous, A.; Labriet, M.

*Published in:*
Energy Economics

*DOI:*
10.1016/j.eneco.2016.01.005

Energy Economics 56 (2016) 543–551

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

# A multi-model study of energy supply investments in Latin America under climate control policy☆

Tom Kober [a,*], James Falzon [a], Bob van der Zwaan [a,b,c], Katherine Calvin [d], Amit Kanudia [e], Alban Kitous [f], Maryse Labriet [g]

[a] Energy Research Centre of the Netherlands, Policy Studies, Amsterdam, The Netherlands
[b] Johns Hopkins University, School of Advanced International Studies, Bologna, Italy
[c] University of Amsterdam, Faculty of Science, Amsterdam, The Netherlands
[d] Pacific Northwest National Laboratory, Joint Global Change Research Institute, College Park, MD, USA
[e] KanORS-EMR, Delhi, India
[f] European Commission, Joint Research Centre, Sevilla, Spain
[g] Eneris Environment Energy Consultants, Madrid, Spain

ARTICLE INFO

*Article history:*
Received 29 August 2014
Received in revised form 11 January 2016
Accepted 14 January 2016
Available online 25 January 2016

*JEL classifications:*
Q54
F53

*Keywords:*
Climate policy
Low-carbon energy technology
Technology investment costs

ABSTRACT

In this paper we investigate energy supply investment requirements in Latin America until 2050 through a multi-model approach as jointly applied in the CLIMACAP-LAMP research project. We compare a business-as-usual scenario needed to satisfy anticipated future energy demand with a set of scenarios that aim to significantly reduce $CO_2$ emissions in the region. We find that more than a doubling of annual investments, in absolute terms, occurs in the business-as-usual scenario between 2010 and 2050, while investments may treble over the same time horizon when climate policies are introduced. Investment costs as share of GDP, however, decline over time in the business-as-usual scenario as well as the climate policy scenarios, as a result of the fast economic growth of the region. In the business-as-usual scenario, cumulative investments of 1.4 trillion US$ are anticipated between 2010 and 2050 in electricity supply. These investments increase when additional climate policies are introduced: under a carbon tax of 50 $/tCO_2e$ in 2020 growing with a rate of 4%/yr, an additional 0.6 trillion US$ (+45%) of cumulative investment is needed. Climate control measures lead to increased investment in low-carbon electricity technologies, primarily based on wind and solar resources, as well as CCS applied to fossil fuels and biomass. Our analysis suggests that, in comparison to the business-as-usual case, an average additional 21 billion US$/yr of electricity supply investment is required in Latin America until 2050 under a climate policy aiming at 2 °C climate stabilisation. Conversely, there is a disinvestment in fossil fuel extraction and transformation. For oil production, a growth to 130 billion US$ annual investment by 2050 is anticipated in a business-as-usual scenario. Ambitious climate policy reduces this to 28 billion US$. Mobilising the necessary additional investment capital, in particular for low-carbon energy technologies, will be a challenge. Suitable frameworks and enabling environments for a scale-up of public and private investment will be critical to help reach the required low-carbon energy deployment levels.



## 1. Introduction

The research work presented in this article originates from the CLIMACAP-LAMP project[1] which investigates economic, technical and policy implications of climate change control measures in Latin America. The regional definition of *Latin America* as used in this study refers to all countries of central and South America, including the Caribbean countries and Mexico. This article focuses on required financial investments in the energy supply sector, and as such is complementary to other contributions of this special issue, such as van der Zwaan et al. (2016a). An overview of the topics highlighted in the articles of this special issue is provided in van der Zwaan et al. (2016b).

Globally, on average about 1.8% of gross domestic product (GDP)[2] has been invested annually in the energy supply sector between 2000 and 2013, corresponding to 1061 billion US$[3] per year (IEA, 2014a;

☆ The views expressed in this article are purely those of the author and may not in any circumstances be regarded as stating an official position of the European Commission.

* Corresponding author.
*E-mail address:* kober@ecn.nl (T. Kober).

[1] The Integrated Climate Modelling and Capacity Building Project in Latin America (CLIMACAP) is a European Commission funded effort focused on analysing the effects of mitigation strategies in key Latin American Countries (www.climacap.org). The Latin American Modeling Project (LAMP) is a similar effort funded by the U.S. Environmental Protection Agency and the U.S. Agency for International Development. The projects are collaborating to develop a multi-model comparison project focused on mitigation in Latin America. An overview of the project is provided by van der Zwaan et al. (2015). The database of the project can be found at: https://tntcat.iiasa.ac.at/CLIMACAP-LAMPDB/.

[2] GDP refers to purchasing power parities (PPP) in this article.

[3] Unless stated otherwise, monetary units in this article refer to US$(2005).

http://dx.doi.org/10.1016/j.eneco.2016.01.005
0140-9883/

World Bank, 2013). Ranking energy investment intensity by region reveals that industrialised countries with a high GDP invested proportionally less in energy supply technology, whereas in emerging economies, such as China and India, and fossil-resource-rich regions, like the Middle East and Africa, energy supply investments represent a comparably larger share of GDP. In Latin America, the energy investment share of GDP at 2% is slightly higher than the world average.

Annual investments in energy supply in Latin America represent 9% (99 billion US$) of global annual average energy supply investments between 2000 and 2013 (IEA, 2014a). Referring to Fig. 2 below, roughly 60% of energy supply investments in Latin America were dedicated to oil supply, one fourth to the electricity sector and 14% to natural gas supply. The Brazilian share of energy supply investments between 2000 and 2013 is 43% of the Latin American total, and in the power sector Brazilian investments accumulate to even 60% for this period, with the majority invested in generation units based on renewable energy and the electricity grid (IEA, 2014a). According to PLATTS (2012), 70% (24 GW) of the newly commissioned hydro power capacity in Latin America in the period from 2000 to 2012 was installed in Brazil. Investments in clean energy technology in Latin America represented 6% of the global investments in clean energy technologies of 231 billion US$ in 2012 with Brazil hosting most of these investments (BNEF, 2013). Nonetheless, over the past years there has been an increase in investment activity in clean energy technology outside Brazil, reaching 6.5 billion US$ in 2012 compared to 7.4 billion US$ for Brazil (BNEF, 2013).

The future evolution of energy supply investments, in particular in the context of reducing GHG emissions, has already been researched in several studies. Future investment needs are for instance assessed by Luderer et al. (2009) and McCollum et al. (2013), who undertake their analysis based on a multi-model approach on a global scale, and McCollum et al. (2013) additionally for the main world regions. Recent publications of the International Energy Agency (IEA, 2014a) and the Global Energy Assessment (GEA, 2012) also stress the energy technology investment topic, whilst taking different future climate policy framework conditions into consideration. Bauer et al. (2015) investigate assets related to fossil fuel reserves and changes of these assets resulting from climate change mitigation policy and associated fuel price changes. However, the IPCC (2014) concludes in its 5th assessment report that the “scientific literature on investment and finance to address climate change is still very limited and knowledge gaps are substantial”. Long-term energy supply investments in Latin America under different climate policies have not been investigated extensively in the past.

In this article we quantify future investment requirements in the Latin American energy supply sector until 2050 under business-as-usual and climate change control scenarios, thereby contributing to an understanding of potential future investment pathways for the Latin American energy supply sector. The analysis of investments is conducted by using quantitative assessment tools of the participants of the CLIMACAP-LAMP project. The structure of the paper is as follows. In Section 2 we describe the methodology used for our work, and list the models on which our research results are based. Section 3 reports our main findings in several subsections including (1) investments in the overall energy supply sector, (2) electricity sub-sector supply investments, and (3) investment requirements for specific low-carbon technologies required to achieve greenhouse gas emission reductions, as applied to Latin America as a whole. In Section 4 we discuss the policy implications of our results.

## 2. Methodology

This paper focuses on investments in energy supply needed to meet energy demand in Latin America. In this article investments refer to undiscounted values of capital for planning, construction and commissioning of energy technologies. Although discounting is not undertaken in this analysis, in each period we compare the investments with projected GDP in the same period, thereby providing an economic perspective on the level of investment. In terms of scope, the focus is on energy supply technologies. Investments in end-use demand technologies are not covered by the analysis (we refer to GEA (2012) and IEA (2014a) for a recent assessment of demand side investments on a global scale). Demand side effects, such as energy efficiency improvements of final energy use, impact upon the results insofar as they contribute to the determination of the energy needed to be supplied. However, the investment effort required to introduce those measures is not covered here.

The analysis is based on a multi-model comparison of a set of specific scenarios including four global integrated assessment models, namely GCAM, POLES, TIAM-ECN and TIAM-WORLD. For a brief characterisation of the models we refer to van der Zwaan et al. (2016a), and detailed model descriptions can be derived from publications by their respective modelling teams: GCAM (Calvin et al., 2011); POLES (Kitous et al., 2010; Criqui et al., 2014; Markandya et al., 2014); TIAM-ECN (van der Zwaan et al., 2013a; Keppo and van der Zwaan, 2012; Kober et al., 2014; Rösler et al., 2014) and TIAM-WORLD (Loulou and Labriet, 2008; Loulou, 2008). For information on the models' base year calibrations and the development of the main socio-economic parameters and energy indicators in the business as usual scenario we refer to van Ruijven et al. (2016), and for the analysis of the effects of climate policy measures on the energy sector we refer to van der Zwaan et al. (2016a) and Clarke et al. (2016).

Two out of the four models involved in this study, namely TIAM-ECN and TIAM-WORLD, belong to the family of optimisation models, where investment decisions are the results of cost-optimality criteria. TIAM-ECN and TIAM-WORLD determine investments under a long-term planning horizon with perfect foresight. GCAM is a market equilibrium model with a myopic perspective where prices are adjusted until supplies and demands are equal. POLES is a simulation model in which investments follow the development of energy technology deployment regardless of cost-efficiency paradigms. In addition to the models' methodological differences, investment costs of energy technology also differ. This study abstains from harmonising energy technology data across models and rather regards different assumptions on future costs representative of the uncertainties today's decision makers face regarding future investments.

We perform our analysis around four main scenarios, which consist of one business-as-usual scenario and three climate policy scenarios, shortly described below. The climate policy scenarios represent three different policy measures which translate into different levels of GHG mitigation stringency for Latin America. The climate policy measures are applied to all world regions, with a globally harmonised carbon tax on all GHG emissions in the high $CO_2$ price scenario and a perfect cap and trade system in the 450 concentration scenario. In the 50% abatement (FF&I) scenario the emissions cap is applied to Latin America on the one hand and to the rest of the world on the other hand, with trade of emission certificates only within these two groups. For more detailed descriptions of these scenarios we refer to van Ruijven et al. (2016) and Clarke et al. (2016), for the baseline and three climate policy scenarios respectively, in this special issue.

| | |
|---|---|
| Core baseline: | (1a) Business-as-usual scenario with climate and energy policies enacted prior to 2010. |
| High $CO_2$ price: | (2c) Scenario with a carbon tax of 50 $/t$CO_2$e in 2020, which grows at a rate of 4%/yr. |
| 50% abatement (FF&I): | (2 g) Scenario with a emission reduction of $CO_2$ from fossil fuel combustion and industry. This reduction increases linearly from 12.5% below 2010 level by 2020, to 50% below 2010 level by 2050. |
| 450 concentration: | (3c) Scenario with globally cost-optimal allocation of emission certificates to reach a stabilisation of the global mean temperature increase at 2 °C compared to pre-industrial level. |

## 3. Results

In the Core baseline the $CO_2$ emissions from fossil fuel combustion and industry increase between 2010 and 2050 by a factor in the range of two to three, reaching 3 $GtCO_2$ in 2050 in the case of TIAM-WORLD and 4.5 $GtCO_2$ in the case of TIAM-ECN (Fig. 3). Imposing emission reduction measures according to the assumptions of the three climate policy scenarios results in different reactions across models.

Under the scenario High $CO_2$ price, three out of four models show long-term $CO_2$ emissions roughly between 1.5 and 2.1 $GtCO_2$ in 2050, whereas in one model the carbon price is sufficient for a complete decarbonisation of the energy sector. In the 50% abatement (FF&I) scenario the defined emission trajectory affects different $CO_2$ avoidance costs across models ranging from about 100 US$ up to 500 US$ in 2050. All models report higher $CO_2$ emissions until 2050 in the 450 concentration scenario compared to the 50% abatement (FF&I) scenario. When comparing these two scenarios it should be considered that the climate policy measure of the 450 concentration scenario applies to all GHG emissions and the emissions cap in scenario 50% abatement (FF&I) to $CO_2$ only. This has an impact on the long-term price of carbon which is, for some models, higher in the 450 concentration scenario compared to the 50% abatement (FF&I) scenario.

### 3.1. Energy supply investments

In this section we outline the aggregate projected investment needs for Latin America for the energy supply sector. Referring to Fig. 4, which displays cross-model averages and the bandwidth across the models, energy supply investments in the Core baseline scenario are projected to increase from average annual investments of 100 billion US$ in 2010[4] to around 150 billion US$ in 2030 and further to 240 billion US$ by 2050. As the figure shows, there is some uncertainty associated with these projections (ca. +/− 10% in 2020, increasing to about +/− 30% in 2050). On average across models, cumulative supply investments between 2010 and 2050 of 7.0 trillion US$ are required to meet energy demand in the absence of climate policy regulation. If climate policy measures are imposed, higher absolute investments are required for the period 2010 to 2050, with an increase of cumulative investments of 5% (+ 320 billion US$) in the 50% abatement (FF&I) scenario and 3% (+ 190 billion US$) in the 450 concentration scenario. The High $CO_2$ price scenario results in less than 1% (70 billion US$) cumulative additional investments in that period compared to the Core baseline scenario.

Regarding the timing of investments, differences amongst the scenarios can be observed. In 2020, energy sector investments in the 450 concentration scenarios slightly decline compared to the Core baseline scenario as a result of the more efficient use of energy and hence a lower energy supply. The stringent $CO_2$ cap (50% abatement (FF&I) scenario) imposes on average the strongest investment growth in the periods 2020, 2030 and 2040 with 4 to 6% higher investments compared to the Core baseline, as a result of higher emission reductions in the corresponding periods than in other scenarios. In the long-run (2050) a 2 °C climate policy scenario (450 concentration) requires the highest level of investment in absolute terms on average across the three models. For TIAM-ECN and TIAM-WORLD this scenario is characterised by a high, but relatively late, emissions reduction in Latin America, resulting in higher investments in later periods than in the 50% abatement (FF&I) scenario where investments in mitigation measures start earlier. The 2 °C climate stabilisation target implies for Latin America investment needs in the energy supply sector of 260 billion US$ in 2050 (average across models), corresponding to a 6% increase compared to the Core baseline scenario.

[4] In the result section of this article, investment figures stated for the year 2010 refer to average investments for the period 2000–2013 based on IEA (2014a).

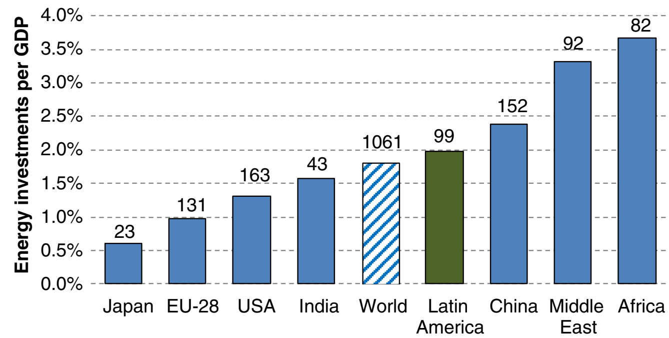


**Fig. 1.** Annual average energy supply investments (2000–2013) as share of average GDP(PPP) globally and for selected world regions, figures in the chart represent absolute investment values in billion US$ (IEA, 2014a; World Bank, 2013).
N.B.: According to IEA's definition Africa includes northern African countries and Sub-Saharan countries. Middle East includes Bahrain, the Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates and Yemen. It includes the neutral zone between Saudi Arabia and Iraq. For Latin America we accumulated IEA's reported figures for non-OECD America and estimated figures for Mexico and Chile which both are accounted under OECD-America.

In absolute terms, there is a significant increase in investment in all of the scenarios. However, inspecting the investment requirements as a share of GDP, it can be seen that the proportional investment remains below 2010 levels (2%) until 2050 under all scenarios, as a result of expected GDP growth in Latin America over the coming decades. Even under the most ambitious climate policy scenario, long-term proportional investment in energy supply is 1.7% at most and, thus, lower than that in 2010 for Latin America. Nonetheless, this is still above current EU-28 (1%) and USA (1.3%) proportional investment rates (see Fig. 1 above).

Historically, investments for oil and gas production represent the highest share among all energy supply investments. These investments depend on the region's domestic energy demand and the competitiveness of domestic resources on global fuel markets, and hence global energy demand. The development of synthetic fuels from coal or biomass may also contribute to the larger use of domestic resources. For exports of crude oil in the absence of climate policy measures, models show export quantities remaining stable at roughly the 2010 level until 2050 (TIAM-WORLD and POLES), or an increase by a factor of 3 between 2010 and 2050 in the case of TIAM-ECN. Global efforts to achieve the 2 °C climate target would result in a substantial reduction in worldwide demand for petroleum products, and consequently a shift of global oil trade patterns. TIAM-ECN shows a decrease of crude oil exports from Latin America to the rest of the world under the 450 concentration scenario compared to the Core baseline scenario of up to 25 EJ in 2050, meaning that Latin America remains self-sufficient regarding its crude oil supply but without any significant exports in 2050. For investments in the oil production sector of Latin America these different developments translate on the one hand into increasing investments over the coming decades to around 130 billion US$ by 2050 under the Core baseline scenario and on the other hand declining investments to 28 billion US$ by 2050 under the 450 concentration scenario (compared with 58 billion US$ average between 2000 and 2013 (IEA, 2014a).

Looking at the distribution more closely, and in particular at the electricity sector as a sub-sector of total energy supply, it can be seen in Fig. 5 that on average around 20% (range between 12 and 32% across the models) of total energy supply investments in the Core baseline scenario in 2050 are directed towards electricity generation, which is slightly above the historic share of 14% (calculated based on IEA, 2014a). It should be noted that the shares refer to investments in electricity production equipment only, and that shares referring to the total electricity supply sector (including investments in generation and transmission and distribution) are comparably higher. For instance TIAM-ECN reports a 30% share of electricity supply investments of

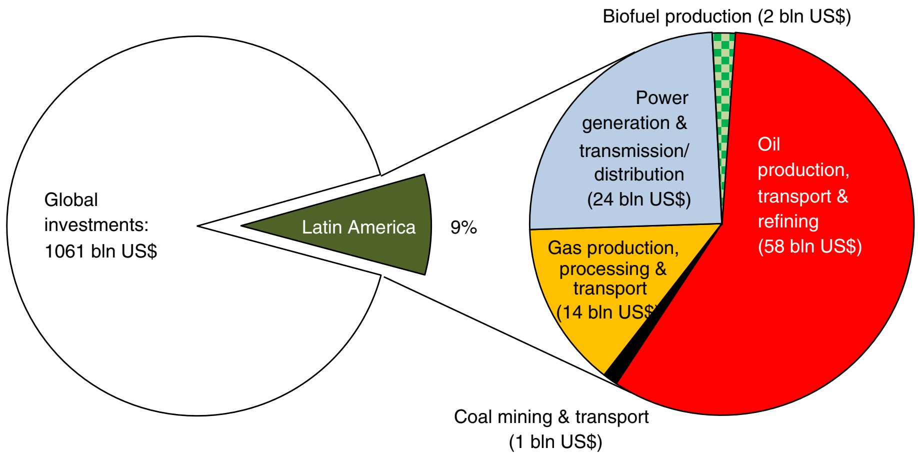


**Fig. 2.** Average annual investments for energy supply technology in the period 2000–2013 (IEA, 2014a).

total energy supply in the Core baseline scenario in 2050. The models largely agree that climate policy increases the proportional share of electricity sector investments in the long-term (2050). This is driven by decarbonisation of energy demand sectors through an increasing use of electric appliances (substituting fossil fuels), and reduced investments in technology for production and processing of fossil fuels. In the 450 concentration scenario, 34–47% of total energy supply investments are dedicated to electricity generation in 2050. These results clearly indicate that climate policy shifts traditional investment patterns from upstream oil and gas production towards downstream investments in low-carbon technologies.

### *3.2. Electricity generation investments*

Given the importance of the electricity sector under climate change control policy, we analyse these investments in detail. Fig. 6 displays the development of investments for electricity generation technologies across the four models used in this analysis. On average across all models, electricity sector cumulative investments between 2010 and 2050 are 1.4 trillion US$ in the Core baseline scenario. For this scenario all models expect an increase of absolute investments in electricity supply technology, with agreement of three models on annual investments of about 20–40 billion US$ in 2050, which is growth by a factor of 1.5 to

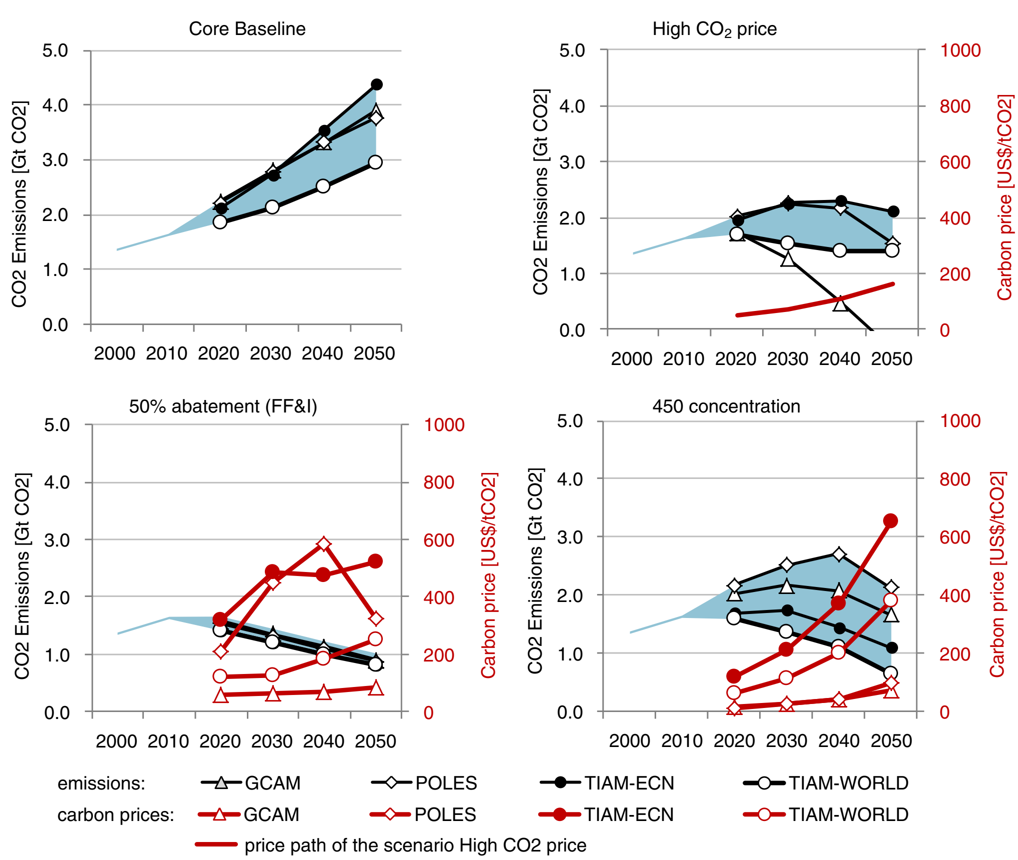


**Fig. 3.** $CO_2$ emissions from fossil fuel combustion and industry and carbon prices in Latin America in the Core baseline scenario and the three climate policy scenarios. N B: In the Core baseline scenario we assume neither the existence of carbon taxes nor GHG emission reduction obligations. Hence we omitted carbon prices in the plot for that scenario.

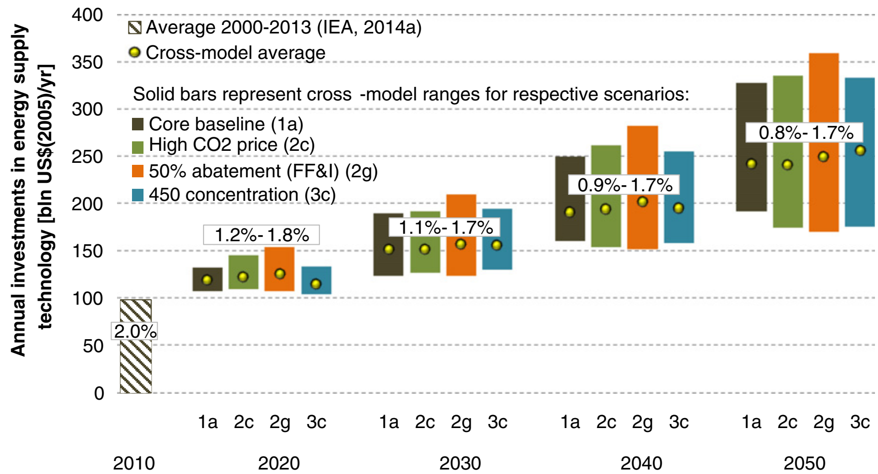


**Fig. 4.** Energy supply investments in Latin America based on results from POLES, TIAM-ECN and TIAM-WORLD in the Core baseline scenario (1a) and the three climate policy scenarios (2c, 2 g, 3c). Percentages in boxes represent the proportion of investments of GDP, which refers for the period 2020 and onwards to the entire range across models and scenarios. N.B.: GCAM did not report total energy sector investments and are not included in this figure.

3 compared to 2010. All models agree that in the scenarios with climate change mitigation measures cumulative investments for electricity supply between 2010 and 2050 are higher than in the Core baseline scenario, ranging from additional 630 billion US$ (average across all models) in the High $CO_2$ price scenario to 710 billion US$ in the 50% abatement (FF&I) scenario and 840 billion US$ in the 450 concentration scenario.

Increases in investments in the electricity supply sector are driven by two key factors. Firstly, the growth in absolute and proportional terms of total electricity consumption and production, in particular when there is a shift in the end-use sectors from fossil fuels to electricity. All models agree that electricity generation increases in future. On average across all four models, electricity generation in the Core baseline scenario triples between 2010 and 2050. For the 50% abatement (FF&I) scenario and the 450 concentration scenario three of the four models report an electricity generation in 2050 of 3 to 16% above the production level of the Core baseline scenario. Secondly, investments in electricity supply increase due to changes in the electricity generation mix towards technologies with comparably high specific investment costs, such as low- or zero-carbon emission power plants, i.e. technologies based on nuclear or renewable energy and technologies with $CO_2$ capture and storage (CCS).

Looking specifically at the behavior of the different models provides important insights into investment patterns.

POLES exhibits relatively lower increases in investment levels for electricity supply across all scenarios compared with the other models, with a maximum increase of cumulative investments of 20% in the 50% abatement (FF&I) scenario compared to the Core baseline scenario. This is due to the lower variation in total electricity production between scenarios and a rather consistent deployment structure in the sector across scenarios, with a significant increase of the total electricity generation over the forthcoming decades in the Core baseline scenario and a substantial deployment of low-carbon technologies (see Fig. 7 in Section 3.3). Among the four models, POLES shows the highest electricity generation in the Core baseline scenario peaking at about 5100 TWh in 2050. Unlike the other models, POLES is a simulation model that considers endogenous technological learning for several technologies which has an important impact on investments in wind, solar and hydro technology in the Core baseline scenario and in the climate policy

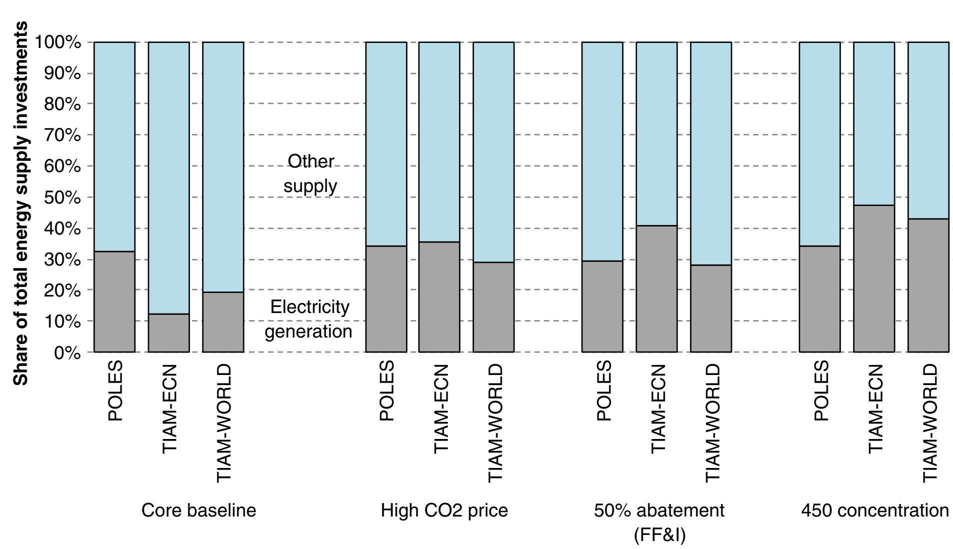


**Fig. 5.** Breakdown of energy investments in Latin America in 2050 in the Core baseline scenario and the three climate policy scenarios.

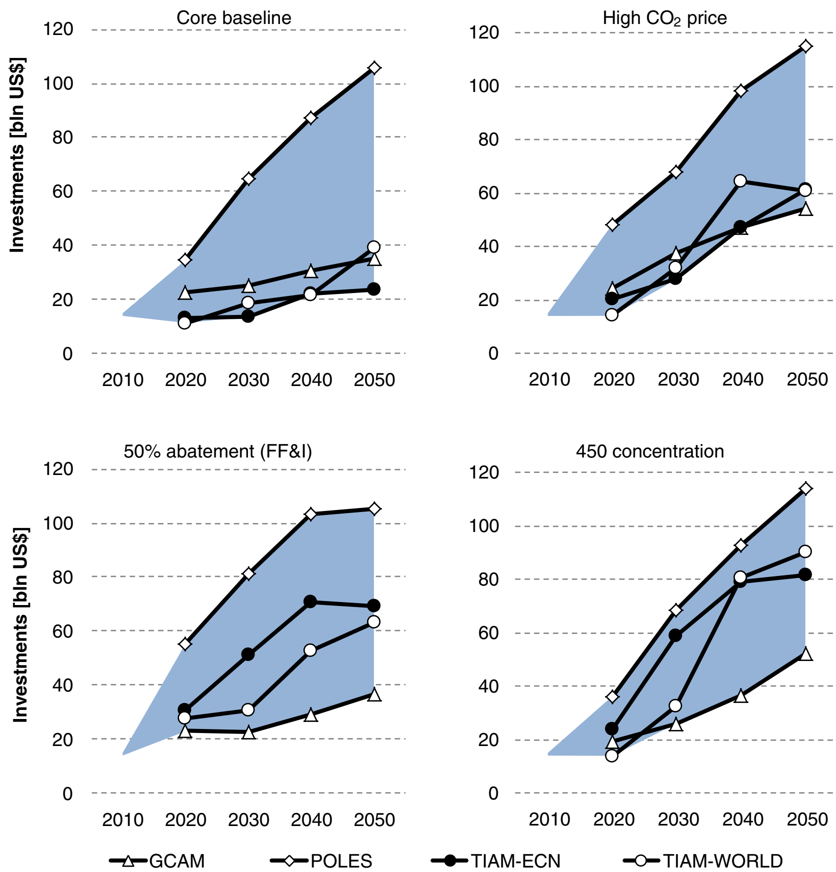


**Fig. 6.** Investments in electricity generation technology in Latin America in the Core baseline scenario and the three climate policy scenarios. N. B.: The data point for 2010, which is starting point for the area that covers the model's results bandwidth, refers to the average annual investments between 2000 and 2013 based on IEA (2014a).

scenarios. As a consequence, total electricity sector investments in the climate policy scenarios converge to the investment level of the Core baseline scenario. Already in the medium-term, POLES model results indicate a significant electricity demand growth in Latin America, which leads to an increase of electricity generation in the Core baseline scenario from 1400 TWh in 2010, to 2000 TWh in 2020, and 2800 TWh in 2030. This drives installation of new generation capacities which grow disproportionally high at a rate of 60% from 2010 to 2020 and 50% from 2020 to 2030, which is the result of investments in technologies using intermittent renewable energy with low annual full load hours compared to the average of power plants operated in 2010, and investments in flexible generation capacity based on natural gas, which is necessary for the stable electricity system operation. These capacity additions would require a significant and immediate ramp-up of Latin America's electricity generation investments with a doubling of the average annual investments of the period 2000 to 2013 by the year 2020.

In TIAM-ECN investments in electricity generation increase significantly under climate change control scenarios, mainly driven by a shift of the fuel mix from fossil fuels to renewable energy, without significant variation in the amount of electricity produced across scenarios. In the Core baseline scenario, electricity generation in Latin America shows a continuous increase from 1400 TWh in 2010 (IEA, 2014b) to 4000 TWh in 2050 with an increasing share of fossil fuel based technologies without CCS growing from 41% in 2010 (IEA, 2014b) to 63% in 2050. As a consequence of the shift of investment patterns towards power plants using coal and natural gas, which typically have low specific investment costs and/or higher annual availabilities compared to renewable technologies, total investments in electricity generation equipment under the Core baseline conditions increase only slightly over time, despite the strong growth of electricity generation. Compared to the Core baseline scenario, the total electricity generation in the three climate policy scenarios is rather stable with changes less than 7% in the long-run (2040/2050). Technologies based on fossil fuels without CCS, however, lose significant market shares if climate policy is introduced, and reach not more than 9% share of the total electricity generation in 2050 in the High $CO_2$ price scenario and diminish almost entirely from the electricity mix by mid of the century in the 50% abatement (FF&I) scenario and the 450 concentration scenario. Under stringent climate policy conditions, the electricity sector in Latin America undergoes a transition towards renewable energy with technologies that are often characterised by high investment costs and low annual availabilities due to the intermittent nature of many of the renewable energy resources, such as wind and solar. This development is responsible for a substantial increase of the total power plant investments in TIAM-ECN up to about 60 billion US$ in 2050 in the High CO2 price scenario, 70 billion US$ in 2050 in the 50% abatement (FF&I) scenario and around 80 billion US$ in 2050 in the 450 concentration scenario.

In TIAM-WORLD, the absolute value and allocation of investments in the power sector follow a similar trajectory in all climate scenarios until 2030: an increase of 65–73% over the Core baseline scenario is observed in 2030, and investments which were allocated to natural gas in the baseline are rather allocated to technology using renewable energy in all climate scenarios (renewable, including hydro, reach 73% of total investments in 2030 compared to 57% in the Core baseline scenario). The share of investments in renewable energy technology increases substantially in all climate scenarios after 2030 (more than 80% of total investments in 2050) but the amount and nature of investment decisions differ after 2030. Firstly, much higher investments are needed to meet the 2 °C climate stabilisation target (450 concentration scenario) than in other climate policy scenarios after 2030 (increase of more

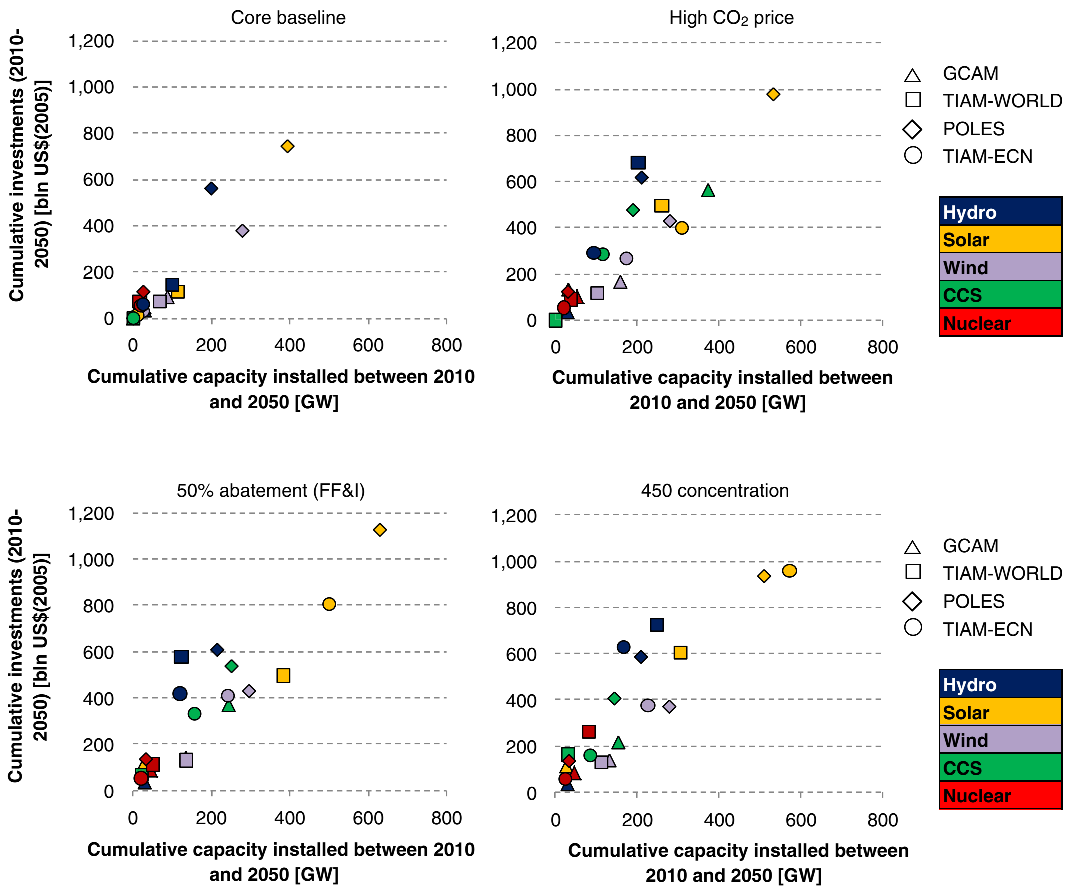


**Fig. 7.** Cumulative cost versus capacity until 2050 for five low-carbon power supply in Latin America in the Core baseline scenario and the three climate policy scenarios.

than 80% over the Core baseline scenario compared to 45–50% in the scenarios with climate policy). Indeed, the electrification of the energy system of Latin America is higher in the 50% abatement (FF&I) scenario after 2030, reflecting the measures for high emission reductions implemented in 2050 in this scenario. Second, more low-carbon power plants are installed in this scenario, including renewable energy technologies but also biomass power plants equipped with CCS, and nuclear power plants, which are investment intensive technologies. Apart from the power sector, CCS technology applied to bio-refineries occurs as soon as 2030 in both the High $CO_2$ price scenario and the emission bounded scenario (50% abatement (FF&I)).

Like POLES, GCAM has lower increases in investment levels for electricity supply across all scenarios compared with the other models. In the Core baseline scenario, investments grow modestly, but investments in 2050 are about 50% larger in the two stringent mitigation scenarios (High $CO_2$ price and 450 concentration) as they are in the Core baseline scenario, despite similar levels of electricity generation. This increase in investment is due to a heavy reliance on biomass and gas with $CO_2$ capture and storage, which have higher capital costs compared to other technologies. GCAM assumes fixed learning over time and across scenarios, with larger decreases in capital cost for low carbon technologies (e.g., the cost of biomass with CCS declines by approximately 1% per year between 2010 and 2050; the cost of PV declines by 2.5% per year).

### 3.3. Low-carbon electricity technology investments

Having investigated the required investments in the electricity supply sub-sector, we now analyse specific low-carbon electricity technologies. Several recent publications have spent sizeable effort on, and/or were especially dedicated to, analysing the various cost dimensions of the energy system transformation required for low-carbon development scenarios, such as described in Luderer et al. (2009) and those developed in the LIMITS project (see e.g. McCollum et al., 2013; Tavoni et al., 2013; Kober et al., 2014). In this section we highlight one relevant techno-economic aspect, as was done in van der Zwaan et al. (2013b). Fig. 6 presents four cross-model comparison scatter-plots depicting cumulative total energy technology investment costs versus cumulative new commissioned capacity until 2050 for five low-carbon power supply options (CCS, nuclear, hydro, solar and wind energy) under the four scenarios.

Fig. 7 shows that apart from technology diversity across models, there is also some variability in terms of the assumptions on the technology's investment costs between the models. This is evidenced by different ratios of total investment costs per installed capacity of the selected technology groups across models. The models do, however, provide some robust conclusions that are evident from inspection of these scatter plots. As the level of ambition on climate policy increases, the level of investment in low-carbon technology increases. Nuclear power is expected to experience only modest growth in terms of capacity, and hence investments which stay below 200 billion US$ cumulatively for the period 2010 to 2050 across most of the scenarios and models. For wind power technology, a maximum additional new capacity of 280 GW between 2010 and 2050 can be observed, which is lower than for solar electricity technology. This new wind turbine capacity corresponds to a 430 billion US$ investment opportunity in that period (global installed capacity in 2013 was 318 GW (GWEC, 2014)). Three out of four model agree that cumulative investments in solar energy technology between 2010 and 2050 exceed those of wind turbine technology. Our results show, that solar energy has a higher deployment potential than wind energy with up to 630 GW new installed capacity between 2010 and 2050, translating into greater investment requirements of up to 1.1 trillion US$. Hydropower will continue to receive significant investment flows which cumulate for the period 2010 to 2050 to up to 720 billion US$, corresponding to about 250 GW additionally installed capacity. Compared to other electricity technology based on renewable energy, hydro power plants are expected to require higher specific investment cost per installed unit of new capacity, which leads to comparably larger investment volumes. However, this does not necessarily represent a competitive disadvantage of hydro compared to other renewable energy technologies, i.e. wind and solar, because average annual availabilities of hydro power plants in Latin America are usually higher[5], with positive effects on the costs of generating electricity. For CCS technology, applied to all kinds of combustible fuels, cumulative investments until 2050 amount to a maximum of 560 billion US$ in the existence of climate policies. The extent to which CCS power plants and technologies using renewable energy are deployed and the investment required varies considerably between models. For a comprehensive discussion of the different technology pathways, we refer to the article of van der Zwaan et al. (2016a), that explores in detail technology diffusion of low-carbon technology in Latin America.

## 4. Discussion

In this paper we examined the investment needs for Latin America in the energy supply sector up to 2050 under a business-as-usual and climate control scenarios. We find that, compared to 2010, more than a doubling of average annual investments in absolute terms is required by 2050 to cover the investment needs of the energy supply sector in Latin America in the absence of climate policy. When climate policies are introduced up to 5% additional cumulative investment is necessary until 2050, which corresponds to roughly 330 billion US$ cumulative for the period 2010 to 2050, and which combines increased investments in clean energy technology with disinvestments in carbon-intensive fuel technology. These results are broadly in line with an earlier analysis performed by McCollum et al. (2013), who calculated a cross-model range of average annual energy supply investments[6] between 2010 and 2050 of 117–233 billion US$ in the reference policy scenario and 132–275 billion US$ in the scenario with a 2 °C climate target. Despite increasing absolute energy supply investments in future, investment costs as a share of GDP decline over time in all scenarios. The electricity supply sector as a sub-sector of total energy supply is expected to increase its share of total energy supply investments. Under the Core baseline scenario, cumulative investments of 1.4 trillion US$ are needed until 2050 for the region's electricity generation technologies. The electricity sector becomes increasingly important when climate policies are introduced: under a carbon tax of 50 \$/t$CO_2$e in 2020 increasing with a rate of 4%/yr, an additional cumulative 630 billion US$ (+45%) investment is required until 2050. Wind, solar, and CCS will play an important role under climate policy scenarios, and nuclear power does not in Latin America in the scenarios and models included in this study. The transition required for the energy supply sector in Latin America to reach a 2 °C climate stabilisation target implies substantial additional investments in the electricity sector (840 billion US$ cumulative between 2010 and 2050), accompanied by reduced investment activities in other energy supply sectors, such as fossil fuel production and refining.

These findings have clear implications for policy makers. Moving forward, increased absolute investment in energy supply, even in the absence of climate control policies, is needed to underpin economic and energy demand growth in the region. Mobilising necessary additional investment capital, in particular for low-carbon technologies, will be a challenge, and suitable frameworks and enabling environments for a scale-up in public and private investment will be critical to reach required investment levels (IPCC 2014).

As this paper has focused on financial investments, the economic and social implications of a transition to a low-carbon energy supply sector have not been analysed in depth. According to Akbar et al. (2014) and Clarke et al. (2014), there are significant potential co-benefits of climate policy including improved health of the population, increased jobs, higher crop yields, reduced infrastructure losses from acid rain, improved visibility, and time savings, to name a few. Policy makers will also need to take into account the 'losers' of climate policy, namely the fossil fuel industry and investors who may face a devaluation of assets related to fossil fuel reserves (Bauer et al. 2015). These wider social and economic impacts are not captured in the investment analysis of this study, and in order to have a more complete picture, additional analysis is required, for example based on a social cost–benefit analysis (see Akbar et al. 2014 for a description as to how to approach this analysis).

Despite the above limitation, this analysis does provide a sense of scale for the amount of additional capital that is required to fund a low-carbon transition in Latin America, which has some relevance for current global discussions on a climate agreement in 2015. If we divide the 850 billion US$ additional cumulative investment that is required in the electricity sector over a 40 year time period to meet the 2 °C climate change control target, our analysis suggests that an additional 21 billion US$ per year of electricity supply investments is required in Latin America under ambitious climate policy, which, when compared to 100 billion US$$_{2020}$ targeted to be mobilised globally under the Copenhagen accord by 2020 (UNFCCC, 2014), is substantial.

A major limitation of this analysis is the absence of estimations on the investment needs for the corresponding energy demand sector. Demand side investments in energy efficient technology are not captured, and thus in models that project extensive improvements of energy efficiency measures, the costs on the supply side may be less than one which has fewer deployment of energy efficiency measures. Further analysis on the investment costs of the demand side is needed in order to have a more complete picture of the overall energy system investment needs in Latin America up to 2050.

## Acknowledgements

The research that allowed the publication of this paper has been produced with the financial assistance of the European Union in the context of the CLIMACAP project (EuropeAid/131944/C/SER/Multi) and of the U.S. Agency for International Development and the U.S. Environmental Protection Agency in the context of the LAMP project (under Interagency Agreements DW89923040 and DW89923951US). The contents of this publication are the sole responsibility of the authors and can in no way be taken to reflect the views of the European Union or the U.S. government. The authors would like to thank the feedback and efforts from all CLIMACAP and LAMP project partners for enabling the research results reported in this article.

## References

Akbar, Sameer, Kleiman, Gary, Menon, Surabi, Segafredo, Laura, 2014. Climate-smart development: adding up the benefits of actions that help build prosperity, end poverty and combat climate change. Main report. Vol. 1, Washington, DC: World Bank Group. http://documents.worldbank.org/curated/en/2014/06/19703432/climate-smart-development-adding-up-benefits-actions-help-build-prosperity-end-poverty-combat-climate-change-vol-1-2-main-report.

Bauer, N., Mouratiadou, I., Luderer, G., Baumstark, L., Brecha, R.J., Edenhofer, O., Kriegler, E., 2015. Global fossil energy markets and climate change mitigation—an analysis with REMIND. Clim. Chang. http://dx.doi.org/10.1007/s10584-013-0901-6 in press.

Bloomberg New Energy Finance (BNEF), 2013, Climate Scope 2013—new frontiers for low-carbon energy investment in Latin America and the Caribbean, www.climatefinanceoptions.org, Accessed 09/01/2014.

Calvin, K.V., et al., 2011. GCAM Wiki documentation. https://wiki.umd.edu/gcam/.

[5] For example, POLES and TIAM-ECN results on installed capacities and electricity generation quantities for the period 2020 to 2050 show annual availabilities of 50–55% over all hydro power plants and 18–32% for onshore wind and solar technologies.

[6] In the figures provided by McCollum et al. (2013) investments in energy efficiency improvements are included.

Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P. R. Shukla, M. Tavoni, B. C. C. van der Zwaan, and D.P. van Vuuren, 2014, "Assessing transformation pathways". In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clarke, L., McFarland, J., Octaviano, C., van Ruijven, B., Beach, R., Daenzer, K., Hernandez, S., Lucena, A., Kitous, A., Labriet, M., Loboguerrero Rodriguez, A.M., van der Zwaan, B., 2016. Long-term mitigation potential and current policy trajectories in Latin American countries. Energy Econ. 56, 513–525.

Criqui, P., Mima, S., Menanteau, P., Kitous, A., 2014. Mitigation strategies and energy technology learning: an assessment with the POLES model. Technol. Forecast. Soc. Chang. http://dx.doi.org/10.1016/j.techfore.2014.05.005 ((in press). ISSN: 00401625).

GEA, 2012: Global Energy Assessment—Toward a Sustainable Future, Cambridge University Press, Cambridge UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

GWEC, 2014. Wind energy global status. Taken from website http://www.gwec.net/global-figures/wind-energy-global-status/ (Accessed 31/7/2014).

IEA, 2014a. International Energy Agency (IEA), OECD, *World Energy Investment Outlook*, Paris, France.

IEA, 2014b. International Energy Agency (IEA), *IEA Statistical Database of OECD and Non-OECD Countries*, Paris, France.

IPCC, 2014, "Climate change 2014: mitigation of climate change". Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Keppo, I., van der Zwaan, B.C.C., 2012. The impact of uncertainty in climate targets and $CO_2$ storage availability on long-term emissions abatement. Environ. Model. Assess. 17 (1/2), 177–191.

Kitous, A., Criqui, P., Bellevrat, E., Chateau, B., 2010. Transformation patterns of the worldwide energy system—scenarios for the century with the POLES model. Energy J. 31 (Special Issue, 2010), 49–82.

Kober, T., van der Zwaan, B.C.C., Rösler, H., 2014. Regional burden sharing regimes for reaching a global long-term 2 °C climate change control target. Climate Change Econ. 5 (1), 1–32 (2014, 1440001).

Loulou, R., 2008. ETSAP-TIAM: the TIMES integrated assessment model, Part II: mathematical formulation. Comput. Manag. Sci. 5 (1–2), 41–66.

Loulou, R., Labriet, M., 2008. ETSAP-TIAM: the TIMES integrated assessment model, Part I: model structure. Comput. Manag. Sci. 5 (1–2), 7–40.

Luderer, G., Bosetti, V., Steckel, J., Waisman, H., Bauer, N., Decian, E., Leimbach, M., Sassi, O., Tavoni, M., 2009. The economics of decarbonization—results from the RECIPE model intercomparison. RECIPE Background Paper. http://www.pik-potsdam.de/recipe (Accessed 15th January 2015).

Markandya, A., Gonzalez-Eguino, M., Criqui, P., Mima, S., 2014. Low climate stabilisation under diverse growth and convergence scenarios. Energ Policy 64, 288–301.

McCollum, D., Nagai, Y., Riahi, K., Marangoni, G., Calvin, K., Pietzcker, R., van Vliet, J., van der Zwaan, B., 2013. Energy investments under climate policy: a comparison of global models. Climate Change Econ. 4 (4), 1–37 (2013, 1340010).

PLATTS, 2012. World Electric Power Plants Database. McGraw-Hill Companies, Inc., Washington DC, USA.

Rösler, H., van der Zwaan, B.C.C., Keppo, I.J., Bruggink, J.J.C., 2014. Electricity versus hydrogen for passenger cars under stringent climate change control. Sustainable Energy Technol. Assess. 5, 106–118.

Tavoni, M., Kriegler, E., Aboumahboub, T., Calvin, K., De Maere, G., Jewell, J., Kober, T., Lucas, P., Luderer, G., McCollum, D., Marangoni, G., Riahi, K., van Vuuren, D., 2013. The distribution of the major economies' effort in the Durban platform scenarios. Climate Change Econ. 4 (4), 1–25 (2013, 1340000).

UNFCCC, 2014. Financial, technology and capacity-building support. Taken from website http://cancun.unfccc.int/financial-technology-and-capacity-building-support/new-long-term-funding-arrangements/ (Accessed 31st July 2014).

van der Zwaan, B.C.C., Keppo, I.J., Johnsson, F., 2013a. How to decarbonize the transport sector? Energ Policy 61 (2013), 562–573.

van der Zwaan, B.C.C., Rösler, H., Kober, T., Aboumahboub, T., Calvin, K.V., Gernaat, D.E.H.J., Marangoni, G., McCollum, D.L., 2013b. A cross-model comparison of global long-term technology diffusion under a 2 °C climate change control target. Climate Change Economics 4 (4), 1–24 (2013, 1340013).

van der Zwaan, B.C.C., Calvin, K., Clarke, L., (Guest Editors), 2016a. "Climate mitigation in Latin America: implications for energy and land use", Introduction to the Special Issue on the findings of the CLIMACAP-LAMP project. Energy Econ. 56, 495–498.

van der Zwaan, B.C.C., Kober, T., Calderon, S., Calvin, K., Daenzer, K., Kitous, A., Labriet, M., de Lucena, A.F.P., Octaviano, C., di Sbroiavacca, N., 2016b. Energy technology roll-out for climate change mitigation: a multi-model study for Latin America. Energy Econ. 56, 526–542.

van Ruijven, B.J., Daenzer, K., Fisher-Vanden, K., Kober, T., Paltsev, S., Beach, R.H., Calderon, S.L., Calvin, K., Martinez, S.H., Kitous, A., Lucena, A.F.P., 2016. The starting points: base-year assumptions and baseline projections for Latin America. Energy Econ. 56, 499–512.

World Bank, 2013, "World development indicators", The World Bank database, www.worldbank.org 2013, (Accessed 31st July).