UvA-DARE (Digital Academic Repository)

Energy Technology Roll-Out for Climate Change Mitigation: A Multi-Model Study for Latin America

van der Zwaan, B.; Kober, T.; Calderon, S. ; Clarke, L.; Daenzer, K. ; Kitous, A.; Labriet, M. ; Lucena, A.F.P.; Octaviano, C.; Di Sbroiavacca, N.

Link to publication

Energy technology roll-out for climate change mitigation: A multi-model study for Latin America

CrossMark

Bob van der Zwaan [a,b,c,*], Tom Kober [a], Silvia Calderon [d], Leon Clarke [e], Katie Daenzer [f], Alban Kitous [g], Maryse Labriet [h], André F.P. Lucena [i], Claudia Octaviano [j], Nicolas Di Sbroiavacca [k]

[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] National Planning Department, Sub-Directorate of Sustainable Development, Bogota, Colombia
[e] Pacific Northwest National Laboratories, Joint Global Change Research Institute, College Park MD, USA
[f] Pennsylvania State University, College of Agricultural Sciences, University Park PA, USA
[g] European Commission, Joint Research Centre, Sevilla, Spain
[h] Eneris Environment Energy Consultants, Madrid, Spain
[i] Federal University of Rio de Janeiro, Energy Planning Program, Rio de Janeiro, Brazil
[j] Massachusetts Institute of Technology, Joint Program on the Science and Policy of Global Change, Cambridge MA, USA
[k] Fundacion Bariloche, Energy Program, Bariloche, Argentina

ARTICLE INFO

ABSTRACT

In this paper we investigate opportunities for energy technology deployment under climate change mitigation efforts in Latin America. Through several carbon tax and CO_2 abatement scenarios until 2050 we analyze what resources and technologies, notably for electricity generation, could be cost-optimal in the energy sector to significantly reduce CO_2 emissions in the region. By way of sensitivity test we perform a cross-model comparison study and inspect whether robust conclusions can be drawn across results from different models as well as different types of models (general versus partial equilibrium). Given the abundance of biomass resources in Latin America, they play a large role in energy supply in all scenarios we inspect. This is especially true for stringent climate policy scenarios, for instance because the use of biomass in power plants in combination with CCS can yield negative CO_2 emissions. We find that hydropower, which today contributes about 800 TWh to overall power production in Latin America, could be significantly expanded to meet the climate policies we investigate, typically by about 50%, but potentially by as much as 75%. According to all models, electricity generation increases exponentially with a two- to three-fold expansion between 2010 and 2050. We find that in our climate policy scenarios renewable energy overall expands typically at double-digit growth rates annually, but there is substantial spread in model results for specific options such as wind and solar power: the climate policies that we simulate raise wind power in 2050 on average to half the production level that hydropower provides today, while they raise solar power to either a substantially higher or a much lower level than hydropower supplies at present, depending on which model is used. Also for CCS we observe large diversity in model outcomes, which reflects the uncertainties with regard to its future implementation potential as a result of the challenges this CO_2 abatement technology experiences. The extent to which different mitigation options can be used in practice varies greatly between countries within Latin America, depending on factors such as resource potentials, economic performance, environmental impacts, and availability of technical expertise. We provide concise assessments of possible deployment opportunities for some low-carbon energy options, for the region at large and with occasional country-level detail in specific cases.

1. Introduction

The CLIMACAP-LAMP project investigated, among others, the energy technologies needed in Latin America for the region to contribute to global climate change control. The main tools of the research teams contributing to this project – energy–economy, integrated assessment and/ or energy system models that serve studying the energy-economic

* Corresponding author at: Energy Research Centre of the Netherlands, Policy Studies, Amsterdam, The Netherlands.
E-mail address: vanderzwaan@ecn.nl (B. van der Zwaan).

implications of climate change mitigation efforts – allow in principle for determining the extent, direction and cost of the technological change necessary to significantly abate emissions of greenhouse gases (GHGs). We inspect in this article how much technological change is required, in the short- to mid-term (i.e. until 2050), if countries in Latin America adopt, for example, carbon taxes or abatement targets to stimulate GHG emission reductions. We examine which energy options should be reduced, as well as how fast, and which others need to be expanded, and at what scale, in a similar way as has recently been done on the global scale in e.g. Wilson et al. (2012), Riahi et al. (2013) and van der Zwaan et al. (2013b). We do not assess what the direct implementation costs would be of the technological transformation associated with climate change mitigation action in Latin America, as was done in some previous studies (see e.g. McCollum et al., 2013). For an inspection of the investment requirements associated with climate-mitigating technological change in Latin America we refer to another publication in this special issue (Kober et al., 2015).

With our analysis we connect to a growing body of literature on energy system transition pathways, in particular those that involve renewable forms of energy (see e.g. GEA, 2012; IPCC, 2011). Given our focus on Latin America, our work also pertains to the UN's Sustainable Energy for All initiative (UN, 2012), even while we here do not explicitly nor extensively assess energy transformation in relation to economic development. Technology transformation pathways have recently been studied in a number of publications, both at the global level (such as in Krey et al., 2014; Weyant and Kriegler, 2014) and regional level (Calvin et al., 2012; Clarke et al., 2012, for Asia; Clarke et al., 2014a, 2014b; Fawcett et al., 2014, for the USA; Knopf et al., 2013, for Europe). In this paper we attempt to put our work on energy technology transitions in Latin America into a broader perspective, by comparing it to the existing literature on the subject matter and by reflecting on questions like how the decarbonization scenarios presented here differ from (or are similar to) those reported in the literature. We investigate whether possible technology transformation pathways for Latin America have commonalities or dissimilarities with those in other regions. Likewise, we are interested in knowing whether our results are similar or not to those obtained for the energy system transition required at a world-scale, in the context of which we inspect the global average perspective provided by the Intergovernmental Panel on Climate Change (see Clarke et al., 2014a, 2014b; IPCC, 2014). Other publications in this special issue also present narratives on how the CLIMACAP-LAMP findings relate to the literature on transition pathways and climate policy, such as notably Clarke et al. (2016). In this paper we also inspect the reasons for differences in technology roll-out that we observe across models, some of which relate to structural differences between models, others to different parameter assumptions (see e.g. Kriegler et al., 2014a, 2014b, who present results of extensive analysis in an effort to do the same through novel work on the basis of diagnostic indicators).

None of the energy technological transformation questions we raise can be answered with certainty, but integrated assessment models (as used for essentially all of the previously mentioned studies) can take away some of the uncertainties, in addition to help understanding some of the key drivers of technology developments in view of the strong linkages within the energy systems: the benefit of using a set of different models, as we do in this study, is that the diversity in their outcomes may be indicative for the nature of the technological change that needs to be initiated in the energy system. In this article we focus mostly on the energy sector and CO_2 as contributor to climate change, since sectors like agriculture and emissions of other GHGs (e.g. from AFOLU[1]: agriculture, forestry and land-use) are investigated in other contributions to this special issue (see e.g. Calvin et al., 2016). We particularly zoom in on electricity generation, as in developing countries (and especially in Latin America), this sector is likely to grow fast over the decades to come, with a two- to three-fold expansion between

today and 2050 (see for example IEA-ETP, 2012, 2014). A number of recent studies have shown that the decarbonization of non-electric energy supply, such as in the transport sector and industry, poses crucial challenges for low atmospheric CO_2 concentration stabilization, since either fewer technology options exist or low-carbon technologies abound but are more expensive than for electricity generation (see e.g., Krey et al., 2014; Kriegler et al., 2014a, 2014b; Luderer et al., 2012; Rösler et al., 2014; van der Zwaan et al., 2013a). A detailed inspection of these other sectors, however, is beyond the scope of the present paper. In Section 2 of this paper we briefly introduce the methodology used for our work, list the models on which our research results are based, and concisely describe the scenarios that we investigated. Section 3 reports our main findings in several subsections dedicated, respectively, to (1) CO_2 emissions, (2) primary energy supply (including fossil and renewable resources), (3) electricity production (overall tendencies and fossil fuelled power plants versus alternative options such as nuclear energy or renewables like hydro, solar and wind power), (4) the potential expansion of CO_2 capture and storage (CCS), (5) energy efficiency, and (6) short-term technology deployment implications, as applied to Latin America. In Section 4 we discuss our results, draw some conclusions and formulate several recommendations for stakeholders in the public and private sectors.

2. Models and scenario design

The features of the integrated assessment models used in this technology diffusion comparison analysis vary widely: some are of a general equilibrium type, while others are partial equilibrium models; they include different simulation and/or optimization routines; they vary in terms of technological detail, diversity and inclusiveness in the energy system, as well as technical and (macro-)economic parameter assumptions; they are distinct with regards to the way in which they represent technological change, endogenously or exogenously; they differ with regard to assumptions on land-use emissions and greenhouse gas species; they are diverse vis-à-vis assumed natural resource availabilities and prices, such as of fossil fuels (but also e.g. CO_2 storage options); et cetera (see also van der Zwaan et al., 2013b). For detailed model descriptions we refer to publications by their respective modeling teams: EPPA (Paltsev et al., 2005); GCAM (Calvin et al., 2011); Phoenix (Sue Wing et al., 2011); POLES (Criqui et al., in press; Kitous et al., 2010); TIAM-ECN (Rösler et al., 2014; van der Zwaan et al., 2013a) and TIAM-WORLD (Loulou, 2008; Loulou and Labriet, 2008).

A multi-model comparison study of technology diffusion for Latin America under climate change measures can involve investigating many possible aspects of technological change. Our focus is first on the options available for the primary energy mix, in order to comprehend the dynamics behind the main energy resources required if the region adopts climate change mitigation policies. We particularly investigate electricity production. The reason for choosing this sector is that it represents a rapidly growing GHG emitting sector, which may in some respects be more easily adaptable to (partial or complete) decarbonization than some other sectors, while it can contribute to GHG emission reductions in these other sectors by their electrification (IEA-ETP, 2012; IPCC, 2014). Also, other sectors and emissions associated with AFOLU, that are particularly relevant for Latin America, are studied in other contributions to this special issue from the CLIMACAP-LAMP research project (see Calvin et al., 2016). We inspect the behavior under carbon taxes and emission reduction targets of a broad range of different energy technologies, including high-carbon coal, oil and natural gas-based electricity, as well as low-carbon nuclear, hydro, solar and wind-based power (while leaving biomass-based options for Calvin et al., 2016). We thus try to answer how and how fast the transition may materialize from fossil to non-fossil energy options. We also assess the potential widespread use of CCS, because this technology could prolong the use of fossil fuels in an emissions-constrained world and is hoped to play an important role in reaching ambitious climate change control, either as bridging technology or not.

---

[1] Previously referred to as LULUCF: land-use, land-use change and forestry.

We perform our analysis around five main scenarios, listed and shortly specified below.[2] For articles with more detailed descriptions of these scenarios, we refer to van der Zwaan et al. (2016) who present an overview of this special issue, as well as van Ruijven et al. (2015) and Clarke et al. (2016) who provide extensive narratives for the Core baseline respectively a diverse set of policy scenarios. In the CLIMACAP-LAMP project we also investigated an alternative to the (business-as-usual) Core baseline scenario, the Policy baseline, which is similar to the former but with the important difference that it also includes climate and energy policies enacted or proposed since the UNFCCC Conference of the Parties held in December 2009 (hence comprising the so-called "Copenhagen pledges"). Accounting for these energy and climate policies may for some models have a significant impact on indicators such as CO_2 emissions and the level of primary energy consumption until 2050, while for other models it has only a moderate effect. For a detailed analysis of the Policy baseline we refer to Clarke et al. (2016). The Low CO_2 price scenario differs from the High CO_2 price scenario in that the former generates much lower diffusion of low-carbon energy technologies than the latter, while being approximately similar in terms of e.g. the type of energy technologies deployed; we find that a comparison between the two yields little additional insight for the ways in which climate change mitigation can be implemented, so that we only show results for the former in one instance and restrict ourselves to inspecting the High CO_2 price scenario in all other cases. The Low CO_2 price scenario yields a CO_2 emission pathway that is only somewhat (typically around 10%) below the one we find for the Core baseline scenario (while the technology mix and diffusion trends remain largely unaltered), which constitutes another reason for leaving a more detailed inspection of the Low CO_2 price scenario to several of the country-specific papers in this special issue (that includes studies on Argentina (Di Sbroiavacca et al., 2016), Brazil (Lucena et al., 2016), Colombia (Calderon et al., 2016) and Mexico (Veysey et al., 2016)).

Core baseline:	Business-as-usual scenario including climate and energy policies enacted prior to 2010.
Low CO_2 price:	A carbon tax is levied of 10 \$/tCO_2e in 2020, growing at a rate of 4%/yr to reach 32\$/tCO_2e in 2050.
High CO_2 price:	A carbon tax is levied of 50 \$/tCO_2e in 2020, growing at a rate of 4%/yr to reach 162\$/tCO_2e in 2050.
20% abatement (FF&I):	Fossil fuel and industrial CO_2 emissions are reduced by 5% in 2020, linearly increasing to 20% in 2050, w.r.t. 2010.
50% abatement (FF&I):	Fossil fuel and industrial CO_2 emissions are reduced by 12.5% in 2020, linearly increasing to 50% in 2050, w.r.t. 2010.

The characteristics of the models we use determine to significant extent the nature of their outcome. In Table 1 we therefore summarize the main features, representations and assumptions of the six models employed in our cross-model comparison study, in an attempt to clarify some of our findings. We refer to the model references for more specific assumptions on technology costs, substitution elasticities and other such variables. In the remainder of our paper we refer to the characteristics listed in Table 1 in order to try to advance our understanding and state-of-the-art knowledge of how variations in model outcomes can be explained on the basis of structural differences between models and/or diverse parameter assumptions (as also done, for example, in Kriegler et al., 2014a, 2014b). Table 1 is sub-divided in three major parts: basic model features, representation of key regional resources, and expansion and share constraints for key technologies and representation of technological change. The main clusters of energy technologies are listed, particularly as related to power production. These include especially both biomass and non-biomass based renewables, since they are likely to play a key role in the climate change mitigation policies that we investigate. For solar energy, for instance, it is indicated whether a model distinguishes between PV and CSP, while for wind energy possible distinction is mentioned between turbines built onshore and offshore (see Table 1,

under the rows "Solar (power supply)" and "Wind (power supply)"). Particularly important for a paper like this one is whether biomass energy in combination with CCS (referred to as BECCS or BioCCS) is represented, and whether models assume the availability for BioCCS for both electric and non-electric energy supply or, alternatively, only for power plants (see Table 1, which provides biomass-related details under the rows "Bioenergy", "CO_2 storage supplies" and "CCS"). For a description of all other biomass-related model assumptions we refer to Calvin et al. (2016) in this special issue.

3. Results

3.1. CO_2 emissions

In the upper left plot of Fig. 1 we see that all models agree, with a high level of consistency, that in a business-as-usual scenario CO_2 emissions are likely to substantially increase over the next 3–4 decades in Latin America, possibly by about a factor of two between today and 2050. We also observe that the climate mitigation programs designed under the 20% and 50% (FF&I) abatement scenarios reduce emissions in 2050 by about 60% respectively 75% with respect to that year's CO_2 emission levels in the Core baseline, as demonstrated by the lower two plots in Fig. 1. Note that for the years 2000 and 2010 historical data are shown, but for some models 2010 is actually a modeled year rather than a historical exogenous input parameter. Differences in base year are discussed in van Ruijven et al. (2015). This, along with differences in data sources, explains the spread between the linear downward sloping lines until the middle of the century (lower plots). As the 20% and 50% abatement panels of Fig. 1 clearly demonstrate, the base year spread of CO_2 emissions is around 300 MtCO_2, i.e. some 20% of base year emissions, for various definitional and data source reasons. This is a non-trivial amount that should be born in mind for interpreting other findings in this paper (see van Ruijven et al., 2015, and the national contributions to this Special Issue). While the models are in agreement that the implementation of a high CO_2 price substantially reduces the CO_2 emissions path in comparison to that modeled in the Core baseline, from the upper right plot of Fig. 1 it is clear that these models react quite differently under the same carbon taxation introduced in the High CO_2 price scenario.

For two models (EPPA and Phoenix) emissions continue to increase until 2050 in spite of this taxation, whereas for two other models (POLES and TIAM-ECN) a downward trend kicks in around 2030–2040. For GCAM emissions dive deeply from the beginning, which results particularly from the large presumed potential for the implementation of CCS technology in combination with both fossil fuels and biomass. For the specific case of Brazil these large emission reductions are mostly achieved through BioCCS, that is, biomass used as feedstock in power plants that are equipped with CCS (see Lucena et al., 2016). Fig. 14 in the Appendix shows the CO_2 price development for our two emission abatement scenarios. With this Figure the carbon prices (or CO_2 emission certificate prices) for these scenarios can be directly compared to those in our two carbon tax scenarios, while Fig. 1 allows for comparing the emission reductions achieved in all of them. As can be seen, the CO_2 prices in the 20% abatement (FF&I) scenario are significantly higher than those in the High CO_2 price scenario for at least several of the models (see also Clarke et al., 2016, in this special issue for more information on this comparison). For this and following figures the blue shading represents a subjective measure of realism formulated collectively by the authors, that is, scenarios that we judge either unlikely or not matching the majority of other models we exclude from the shading.

3.2. Primary energy and savings (supply side)

The difference between adopting a low or high carbon tax scheme over the forthcoming decades is likely to be significant in terms of primary energy consumption, according to essentially all models, as can be seen in

the two upper plots of Fig. 2.[3] In these upper two plots the Low and High CO_2 price scenarios are compared with the Core baseline: only small differences are observed in terms of energy consumption between the Core baseline scenario and the Low CO_2 price scenario, while quite substantial differences emerge when comparing the Core baseline scenario with the High CO_2 price scenario. Even with the carbon taxation as elevated as in the high CO_2 price scenario we see that all models agree that primary energy consumption is higher in 2050 than it is today, sometimes even substantially higher. The spread in results, however, is rather large: while some models find an increase from 30 EJ primary energy consumption today to close to 40 EJ in 2050, other models yield an increase to close to 80 EJ over this time span. The difference between modeling outcomes in terms of primary energy consumption can be explained, among others, by varying assumptions with regards to demographics, economic growth and the implementation of energy efficiency and savings measurements.

As can be seen from Fig. 2, with high carbon taxation a divergence becomes apparent between two clusters of models, technology-rich partial equilibrium energy systems models (GCAM, POLES, TIAM-ECN and TIAM-WORLD) and general equilibrium economy-environment models (EPPA and Phoenix). The latter two react much more strongly to the introduction of CO_2 pricing as a result of price elasticities included in these models as well as tax-induced (endogenous) reductions of overall production hence GDP (that lower energy demand), while the former yield a more conservative reaction given their explicit and detailed account of many energy technologies and their (often elevated) costs (as alternatively expressed through marginal abatement cost curves, or MACCs; see e.g. McKinsey, 2009). Also, unlike the latter, the former do not include endogenous GDP effects, since they are not general equilibrium models (see Table 1). If one replaces the high carbon taxation with either of the two CO_2 emission reduction schemes as designed under the two abatement scenarios (see the lower two plots of Fig. 2), then we see a similar shift in primary energy consumption in comparison to the Core baseline scenario as in the high CO_2 price case. For the two general equilibrium models, however, the reduction in energy consumption becomes even more significant: for EPPA and Phoenix we see energy consumption falling to 25–30 EJ and 35–40 EJ, respectively, in 2050. It is interesting to see that the changes projected in the 50% abatement scenario are not very different from those in the 20% abatement scenario, which means that additional mitigation in the former in comparison to the latter is realized in secondary and final sectors (e.g. through CCS deployment, as we see in Fig. 4). Fig. 3, which reports for the High CO_2 price scenario and the 20% and 50% abatement (FF&I) scenarios the primary energy savings realized over time (with regard to the business-as-usual scenario) under three different types of climate change mitigation regimes, also visualizes the clustering between the two main types of models. For the general equilibrium oriented models energy savings amounting to 40–60% in 2050 are common, while for the energy systems models 10–20% turns out to be a ceiling for most of this half-century. Diversity exists also within the category of technology-rich energy system models: in the abatement scenarios GCAM and TIAM-World yield energy savings of no more than 10%, while POLES and TIAM-ECN generate primary energy consumption reductions of as much as 20%, as a result of differences between these models in energy (saving) technology cost assumptions.

Fig. 4 reports for all models in the Core baseline and three climate policy scenarios the total level of primary energy consumption in Latin America in 2050, as well as its breakdown by type of energy resource. As one can see, all models agree that in the business-as-usual case fossil fuels continue to dominate energy supply until the middle of the century.

Under a low carbon tax regime (as in the Low CO_2 price scenario), the primary energy consumption pattern observed in the upper left plot of Fig. 4 is not much altered, that is, the energy mix does not change by a significant extent, in particular with regard to the demand for fossil fuels. When high carbon taxes are imposed (like in the High CO_2 price scenario), however, their use is curtailed in relative terms and, especially, in absolute terms (see the numbers indicated above the histograms). In most cases, we observe that the use of fossil fuels is also complemented with CCS technology, especially for natural gas and coal. The main difference between the two abatement scenarios is the extent to which CCS is deployed, while the relative shares of the main energy resources remain little affected. The reason that EPPA and Phoenix have a greater share of fossils fuels without CCS in the energy mix is that these CGE models have much lower overall primary energy supply than in the other 4 models (as we observed in Fig. 2). The use of oil is not necessarily reduced in relative terms, and it is little complemented with CCS, because of its continued importance in particularly the transport sector (where CCS is not directly implementable). Several models, especially GCAM, yield substantial roles for the combination of CCS and biomass, which can yield negative GHG emissions and thereby compensate for emissions in other sectors where GHG abatement is more difficult and costly. The combination of CCS with biomass is particularly pertinent for Latin America, given the abundance of biomass resources in the region (which is visualized in all four plots of Fig. 4). All models suggest that especially (but not only) in all of the three climate policy scenarios hydropower plays a substantial role in total energy supply (between close to 10% up to 20%), which is justified on the basis of the large hydro potentials available in especially the Southern American continent.

3.3. Electricity production

Fig. 5 (upper left plot) shows that differences exist between models with regards to the extent to which power production expands over the next few decades. All of them agree, though, that economic development is likely to be strongly associated with an increased electrification of the energy system. Power production is likely to expand two- to three-fold in the Core baseline between 2010 and 2050 according to these models. The upper right plot of Fig. 5 demonstrates that with high CO_2 taxation all models except one (GCAM) find that electricity generation will be lower than in the Core baseline scenario. The explanation for this reduction is that energy (and consequently electricity) savings is considered a cost-efficient means to achieve emissions abatement under a climate-policy induced CO_2 price. For GCAM, inversely, the expansion of electrification is larger than under the business-as-usual scenario, since it is assumed that the power sector and savings are more suitable than other sectors to least-costly achieve CO_2 emission reductions through technological change in response to stringent climate policy with relatively high carbon taxation. The fact that GCAM shows an expansion of electricity generation under the High CO_2 price scenario is probably also related to the electrification of previously un-electrified sectors such as transportation (which may overcompensate the savings in other sectors).

For the two abatement scenarios (lower two plots in Fig. 5), we see that the upper level of growth in the power sector remains almost unchanged with respect to the Core baseline, while the lower level of the model solutions space reduces by about 1 PWh in 2050. Deepening the CO_2 emissions cut (that is, moving from the 20% to the 50% abatement scenario) leads to several, but not all, models increasing their levels of electricity generation by the middle of the century (GCAM, TIAM-ECN and Phoenix). This again points towards diverging views with regards to the potential of achieving emission reductions through an electrification of energy supply. Our results regarding electricity production and demand are consistent with those obtained at the global level by other studies, which concluded that an accelerated shift towards the use of electricity as final energy carrier is generally a robust feature of climate change mitigation scenarios (Krey et al., 2014;

---

[3] Total primary energy was calculated on a 1:1 basis for energy vs. electricity, as explained in the text accompanying our database (https://tntcat.iiasa.ac.at/CLIMACAP-LAMPDB/). For an inspection of energy accounting method caveats, including ambiguities in the treatment of e.g. renewables versus nuclear energy in this respect, see Macknick (2011).

Table 1
Main features of the models in our comparative study.

Model type/feature	EPPA	GCAM	Phoenix	POLES	TIAM-ECN	TIAM-WORLD
Basic model features						
Economic coverage and feedback	General Equilibrium	Partial Equilibrium	General Equilibrium	Partial Equilibrium	Partial Equilibrium	Partial Equilibrium
Model type	Optimization	Market Equilibrium	Optimization	Simulation	Optimization	Optimization
Foresight	Myopic	Myopic	Myopic	Myopic	Intertemporal optimization	Intertemporal optimization
Calibration to base-year shares	Calibrated production function	Calibrated discrete-choice model	Calibrated production function	Calibrated discrete-choice model	Base year calibrated technology mix	Base year calibrated technology mix
Representation of key regional resources						
Solar power supply	Regional supply curves	Regional supply curves	Fixed factor in CGE[a]	Regional production limits	Regional supply curves	Regional supply curves
Wind power supply	Regional supply curve	Regional supply curves	Fixed factor in CGE[a]	Regional supply curves	Regional supply curves	Regional supply curves
Bioenergy	Endogenous land competition	Endogenous land competition	Endogenous land competition	Regional supply curves	Regional supply curves	Regional supply curves
CO_2 storage supplies	Fixed factor in CGE[a]	No limits (with exception of Japan and Korea)	Fixed factor in CGE[a]	Regional supply curves	Regional production limits	Regional production limits
Expansion and share constraints for key technologies and representation of technological change						
Coal-fired power	No constraints on expansion; Capital vintaging; Exogenous and price-driven technological change	No constraints on expansion; Exogenous technological change	No constraints on expansion; Exogenous technological change	No constraints on expansion; No technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change
Natural gas fired power	No constraints on expansion; Capital vintaging; Exogenous and price-driven technological change	No constraints on expansion; Exogenous technological change	No constraints on expansion; Exogenous technological change	No constraints on expansion; No technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change
CCS	Only in electricity generation; Capital vintaging; Exogenous and price-driven technological change	Includes BioCCS[b]; No constraints on expansion; Exogenous technological change	Only in electricity generation; No constraints on expansion; Exogenous technological change	Includes BioCCS[b]; No constraints on expansion; No technological change	Includes BioCCS[b]; Growth Constraint; Exogenous technological change	Includes BioCCS[b]; Growth Constraint; Exogenous technological change
Hydroelectric power	Fixed path; Exogenous technological change	Fixed path; No consideration of technological change	No constraints on expansion; Exogenous technological change	Fixed path; No technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change
Nuclear	Capital vintaging; Exogenous and price-driven technological change	No constraints on expansion; Exogenous technological change	No constraints on expansion; Exogenous technological change	No constraints on expansion; No technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change
Solar	Only PV available; Capacity expansion costs; Capital vintaging; Intermittency costs; Exogenous and price-driven technological change	Capacity backup model; Exogenous technological change	No constraints on expansion; Exogenous technological change	Distinction between PV and CSP No constraints on expansion; No technological change	Distinction between PV and CSP Growth Constraint; Exogenous technological change	Distinction between PV and CSP Growth Constraint; Exogenous technological change
Wind	Only onshore options available; Capacity expansion costs; Capital vintaging; Intermittency costs; Exogenous and price-driven technological change	Onshore and offshore wind lumped together; Capacity backup model; Exogenous technological change	No constraints on expansion; Exogenous technological change	Distinction between onshore and offshore wind; No constraints on expansion; No technological change	Distinction between onshore and offshore wind; Growth Constraint; Exogenous technological change	Distinction between onshore and offshore wind; Growth Constraint; Exogenous technological change

^a Computable General Equilibrium.
^b Models that have CCS in bioenergy (referred to as BioCCS) include CCS in electricity generation and fuel production.
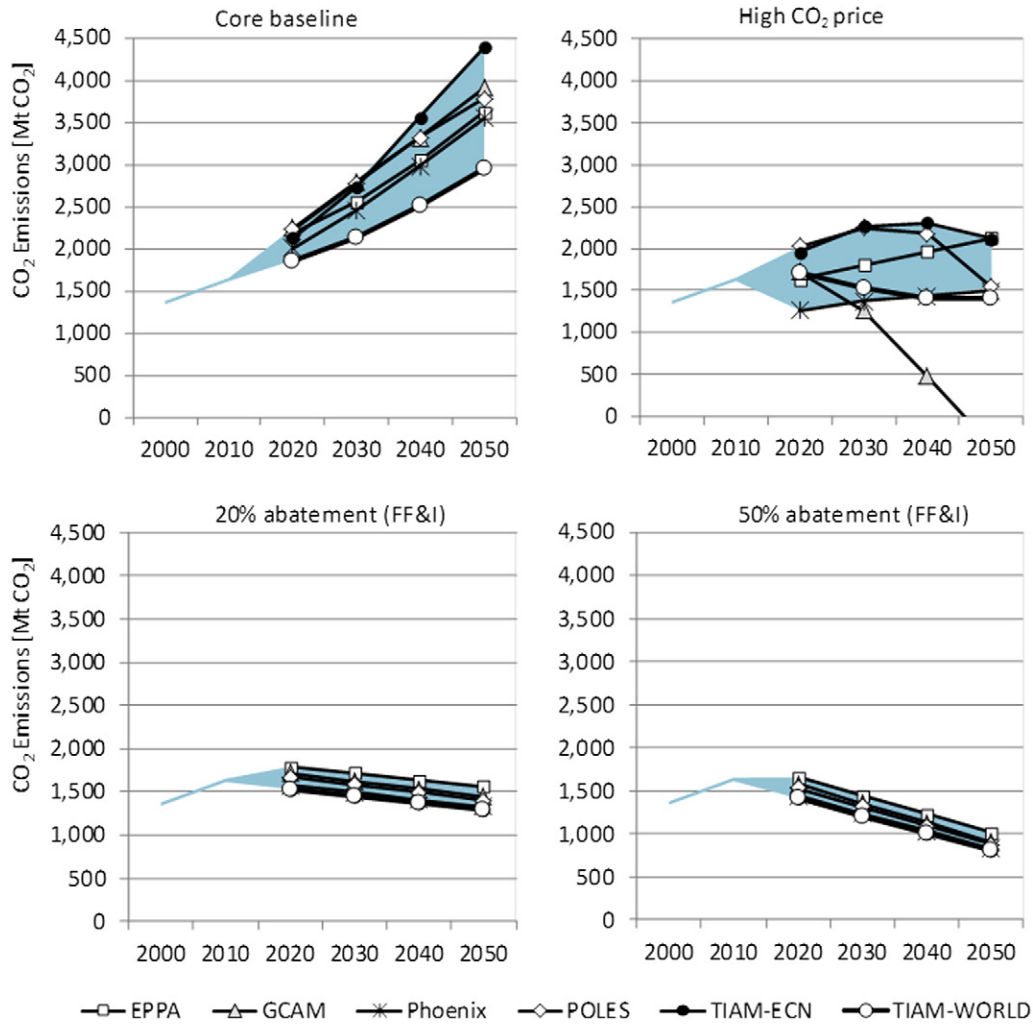
Fig. 1. CO_2 emissions from fossil fuel use and industry in Latin America.

Weyant and Kriegler, 2014). The reason that EPPA and Phoenix do not increase their electricity generation as much as the other models is again that these CGE models have substantially lower overall energy demand, induced by sizeable losses in GDP, which is matched by relatively high CO_2 prices (see Fig. 14).

For power production, innovative (e.g. renewable) technology deployment under a climate change control regime is particularly pertinent, not only since it is among the largest and most rapidly growing CO_2 emitting sectors in Latin America, but also because it represents a part of the energy system in which emission reductions can be realized at costs often lower than incurred in several other sectors such as road transportation or aviation (see also Clarke et al., 2014a, 2014b; IEA-ETP, 2012). Fig. 6 describes the nature of possible technological changes in the power sector according to our set of models: it shows that not only substantial differences exist between models in terms of the absolute level of electricity generation in Latin America in 2050, for either the Core baseline or the three different climate change control scenarios, but also in terms of its breakdown by type of resource and technology. For example, CCS may play a small to negligible role in some models (e.g. TIAM-WORLD in the High CO_2 price scenario), while its implementation may account for a third to about half of all electricity generation in others (GCAM in the High CO_2 price scenario and the two abatement scenarios). Large differences also exist with regards to the extent to which options like solar and wind energy may be used (30–40% for POLES and TIAM-WORLD, and at most 10% for EPPA and Phoenix). The results across models concerning hydropower are pretty much consistent in that a large share is foreseen for this

option in all cases (25–50% in all scenarios for all models). Obviously, the three climate policy scenarios involve much less fossil-fuel based electricity production (without CCS) than in the Core baseline, while CCS deployment allows for a model like GCAM a substantial continuation of the use of, in particular, natural gas for power production.

A closer inspection of individual technologies demonstrates more clearly the electricity generation similarities and differences reported by our set of models under varying types of climate policy regimes. For example, Fig. 7 shows that hydropower today already contributes with close to 800 TWh to annual electricity generation in Latin America, and that in a business-as-usual scenario its role is likely to increase over the decades to come, on average by 25% before 2050, according to our models. Almost all models (except GCAM) agree that, if any sort of climate policy is introduced, the amount of electricity produced through various hydropower options further expands, typically by around 50% but perhaps by as much as 75% in 2050, as can be seen from a comparison of the High CO_2 price and the two abatement scenarios with the Core baseline scenario. This outcome matches the current trend for some countries. In the case of Argentina, for example, national energy authorities are currently conducting a study to update the figures for the country's hydroelectric potential, which could perhaps be as high as around 40 GW (Di Sbroiavacca et al., 2016). The hydroelectric power plant capacity installed in Argentina at present is around 11 GW, that is, less than 30% of the total presumed national potential. In Colombia today around 9 GW of hydropower capacity is operational, on a total national theoretical potential of about 90 GW, which constitutes an upper limit for the techno-economical potential (Calderon
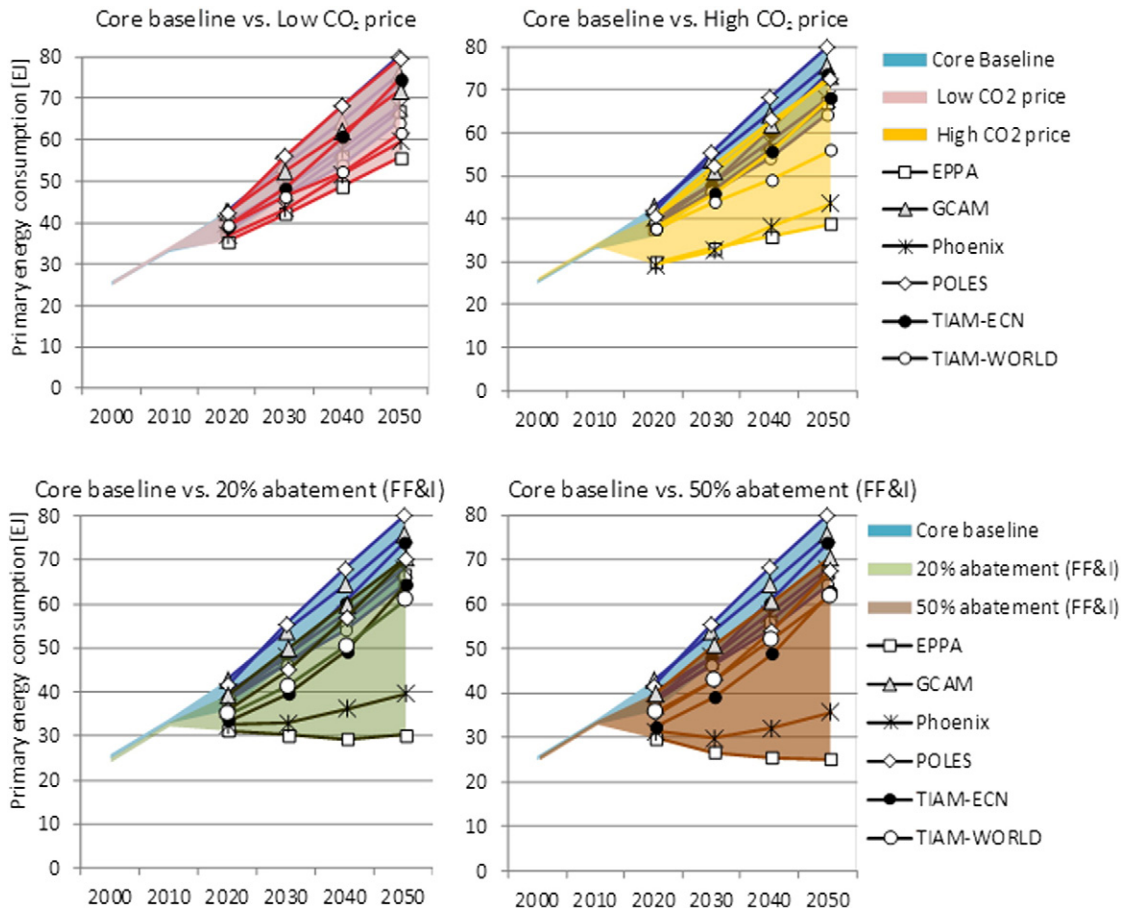
Fig. 2. Primary energy consumption in Latin America.

et al., 2016). In Brazil, hydropower currently takes up a large share of electricity generation (an average of around 80% over the last ten years (see EPE, 2014)). However, the remaining unexplored sites are located in the Amazon region and thus face large local environmental constraints, which may hamper hydropower expansion in the country (see e.g. Lucena et al., 2016). Among this large overall potential in Latin America, particular opportunities exist for small- to medium-scale hydropower plants (that today already account for over 10% of all operational hydropower capacity). Hydropower is, like geothermal energy, among the power production options for which a large theoretical availability exists in many countries in Latin America, but the economic potential

of the latter hasn't been exploited yet the way it has been for the former.

Fig. 8 depicts simulated installed wind power levels until 2050 for the four scenarios. In the Core baseline scenario wind power in several models grows from close to zero in 2010 to hundreds of TWh in 2050, while in other models wind energy potentials remain less exploited until then. Most of these projections match current developments: according to GWEC (the Global Wind Energy Council) by the end of 2013 about 4.8 GW of wind power was installed in Latin America, most of which in Brazil (3.5 GW) with 4.7 GW in addition in the planning phase: this is admittedly much less than in other regions such as
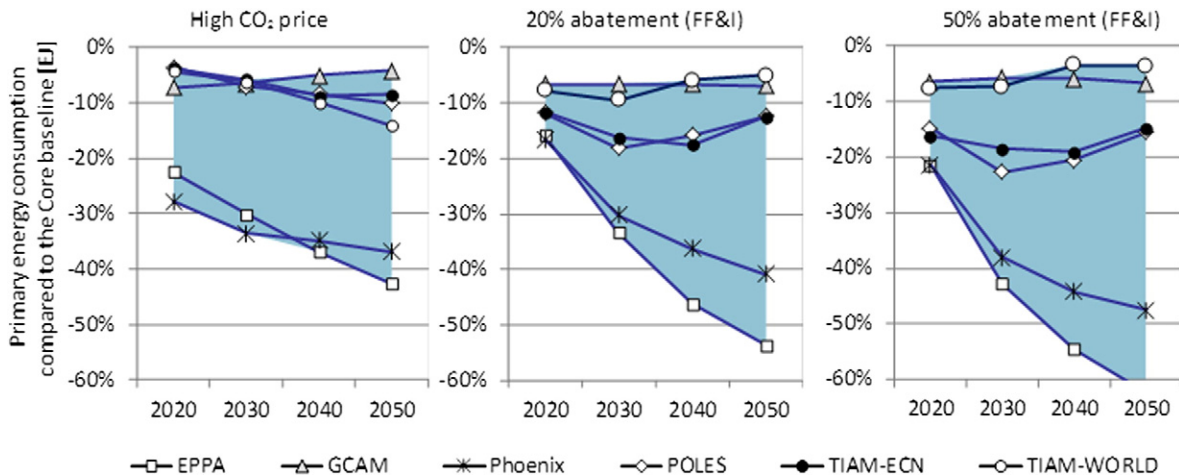

Fig. 3. Primary energy savings (supply side) in Latin America with respect to the Core baseline.
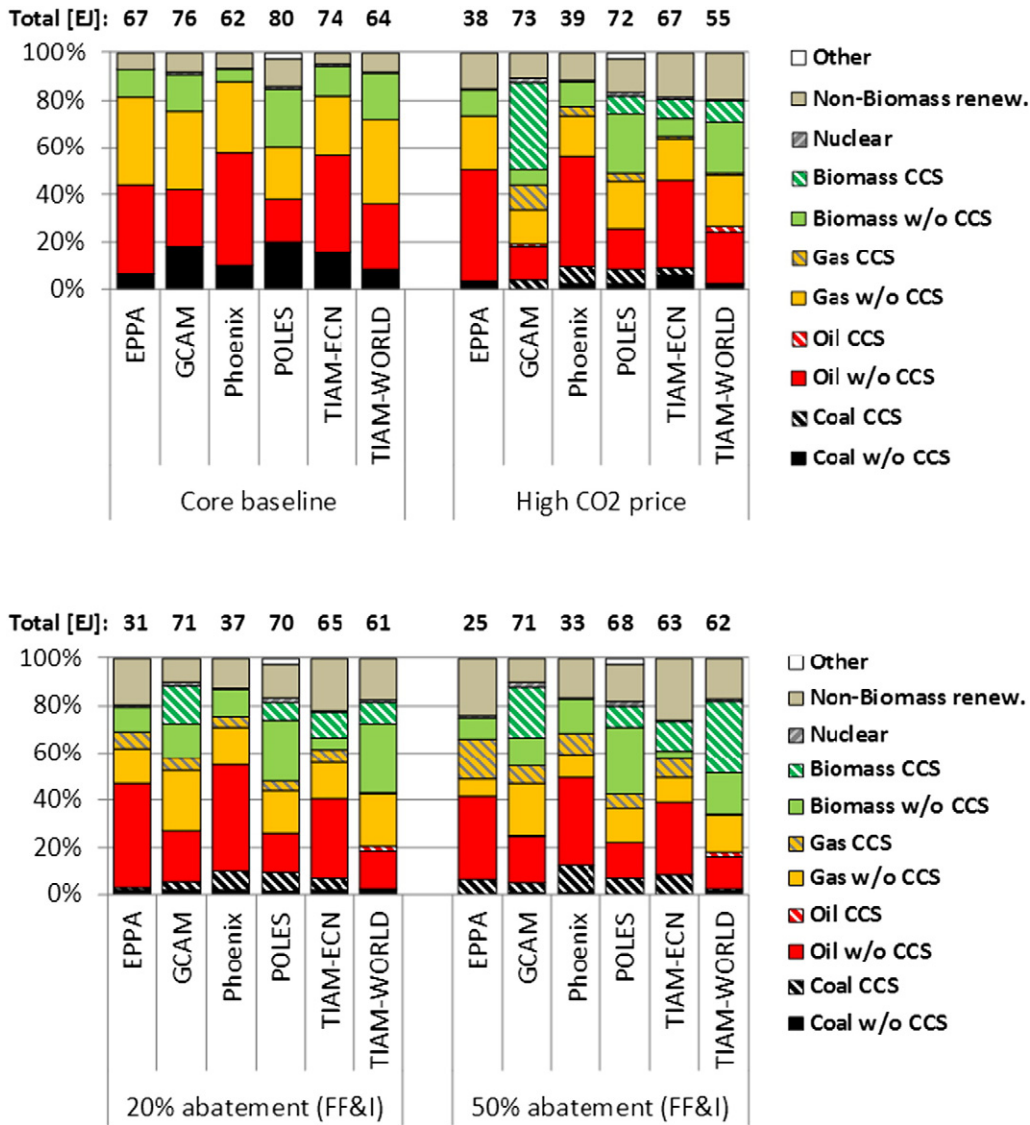
Fig. 4. Breakdown of primary energy consumption in Latin America by resource in 2050.

Asia, North America, or Europe, but still results in wind electricity generation of already close to 10 TWh (GWEC, 2014). All models concur that wind power will grow substantially if climate policies are implemented, reaching a level of at least a couple hundred TWh in 2050 under any of the three climate policies we inspect. For some models, and especially in the high carbon tax scenario, wind electricity generation even reaches a level in 2050 close to the current level of hydropower generation. The high levels of wind energy in essentially all models – especially when large relative shares are realized in individual countries – undoubtedly require addressing issues such as intermittency, supply-demand balancing and/or energy storage, and could also have important land-use implications (see e.g. IPCC, 2011). Practically, these are issues that haven't been extensively addressed in current energy systems yet on the scale ultimately required in many countries, except for some regions in the world or European nations like Denmark, even while several studies have theoretically explored scenarios with high shares of renewables through models with a high degree of bottom-up detail (see e.g. Ludig et al., 2011; Mai et al., 2012; Sullivan et al., 2014). It is uncertain today how aspects of integration will ultimately be tackled in the financial, social and institutional environment of the future. Developments regarding future technology costs and performance are also uncertain, and add to the incertitude related to the costs of renewables integration. All such uncertainties, and the extent to which the most

recent technology cost change developments have been taken into account, imply relatively large differences across models in assumptions regarding these variables, which in turn result in the large ranges depicted in the plots for wind energy of Fig. 8 (see also Luderer et al., 2014, for a detailed study for matters like these).

In Fig. 9 we see an even larger divergence between models of results for solar power generation in Latin America under the various scenarios. There is virtually no agreement as to whether solar energy makes a chance to be broadly developed without climate policy, as pointed out in the upper left plot of Fig. 9 (see for similar results IPCC, 2011, 2014). In two models (EPPA and Phoenix) solar energy potentials remain largely unexploited, even under stringent climate policy, the main reason for which is that energy demand is substantially reduced as a result of high GDP losses (and in response to high carbon taxation), much more so than in the other (partial equilibrium) models. The underlying reason is that EPPA and Phoenix are pessimistic on the options for low carbon electricity supply, including solar based technologies. In other words, relatively less favorable solar energy cost and potential assumptions in EPPA and Phoenix, in comparison to those in other models, form the explanation for why this resource remains little exploited. At present it is, of course, unknown which projection of solar power deployment will ultimately prevail. Today, however, in several regions of the world and under different policy settings (usually less stringent than those implemented in our
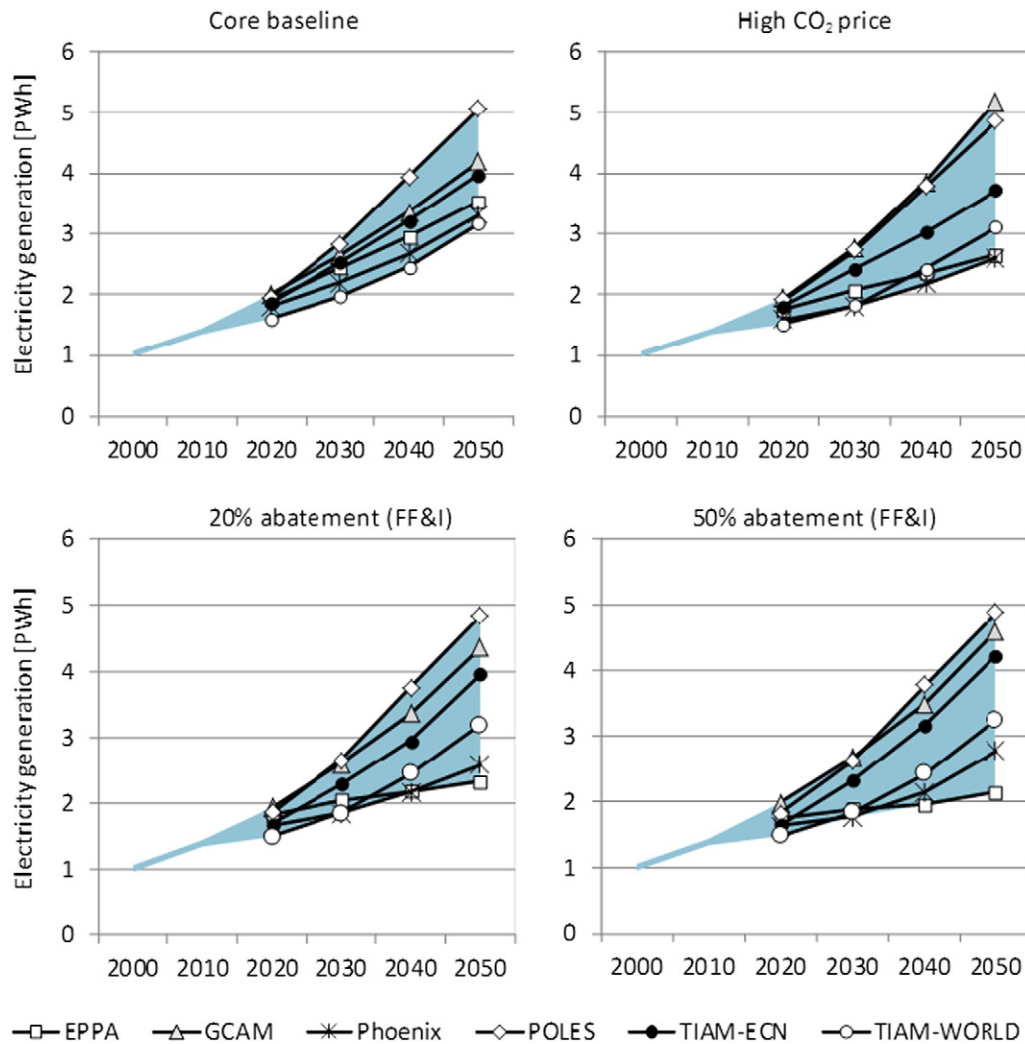
Fig. 5. Electricity generation in Latin America.

scenarios, but in regions such as Asia, Europe and North America involving sizeable subsidies, feed-in-tariffs or renewable portfolio standards that stimulated learning-by-doing and economies-of-scale), solar energy use is exponentially increasing, partly as result of the impressive cost reductions materialized over the past years for especially PV technology. On a global level, PV- and CSP-derived electricity generation combined passed already the 100 TWh level in 2012 (IEA-ETP, 2014). Inspired by this, the level of solar power production grows significantly in some of our models, from around zero today to hundreds of TWh in 2050 for all three climate policy cases (and even more for POLES; see e.g. Griffin et al., 2014). Of course, it remains to be seen whether hundreds of GW of solar energy capacity can realistically be deployed in Latin America by 2050, as challenges associated with such an extensive technology roll-out – related to e.g. costs and intermittency, as well as land use needs and environmental impacts – remain in several cases substantial at present. Our results are largely compatible with the MACC-based finding that at CO_2 prices below approximately 100 \$/tCO2, renewable options like solar PV and CSP (and wind energy, as well as most CCS options for that matter) become competitive with fossil-based power production options (McKinsey, 2009).

The differences between our models with regards to the penetration of renewable forms of energy underscore the need to advance modeling techniques that more accurately capture their potential deployment patterns (see e.g. Luderer et al., 2014). While probably critical to decarbonising the power sector, wind and solar energy resources are intermittent and therefore impose challenges for their integration into

the power grid. Large-scale penetration of renewable energy requires a fundamental transformation of the current operation of power systems as well as the deployment of technologies that allow for more operational flexibility such as storage options, improvements in transmission and distribution networks, and demand-response management tools. Especially general equilibrium modeling approaches (but to some extent partial equilibrium models as well) are currently unable to capture the fine time dynamics that determine the economics of renewable energy, and therefore need to adopt stylistic assumptions to account for the costs of intermittency that may limit its penetration (see e.g. Luderer et al., 2014; Sullivan et al., 2013, for studies on this topic at the global level, and Ludig et al., 2011; Mai et al., 2012; Sullivan et al., 2014, for regional studies thereon). Also partial equilibrium energy systems models, even while they tend to be more technology-rich, have yet to incorporate some of the features (such as resource stochasticity and supply reliability) that refined power systems or dispatch models account for. There are also possible economy-wide responses to the large-scale deployment of renewables that both types of models still have to grasp (including a wide spectrum of changes or opportunities, such as employment creation, sectorial shifts, increased decentralization, and alignment of industrial and manufacturing activity to variable power supply). Understanding the potential changes and economic opportunities brought about by renewables, both to the energy system and global and regional economies at large, is an open area of research.

The prospects for nuclear power suffer from drawbacks related to e.g. reactor accidents, radioactive waste, and proliferation of
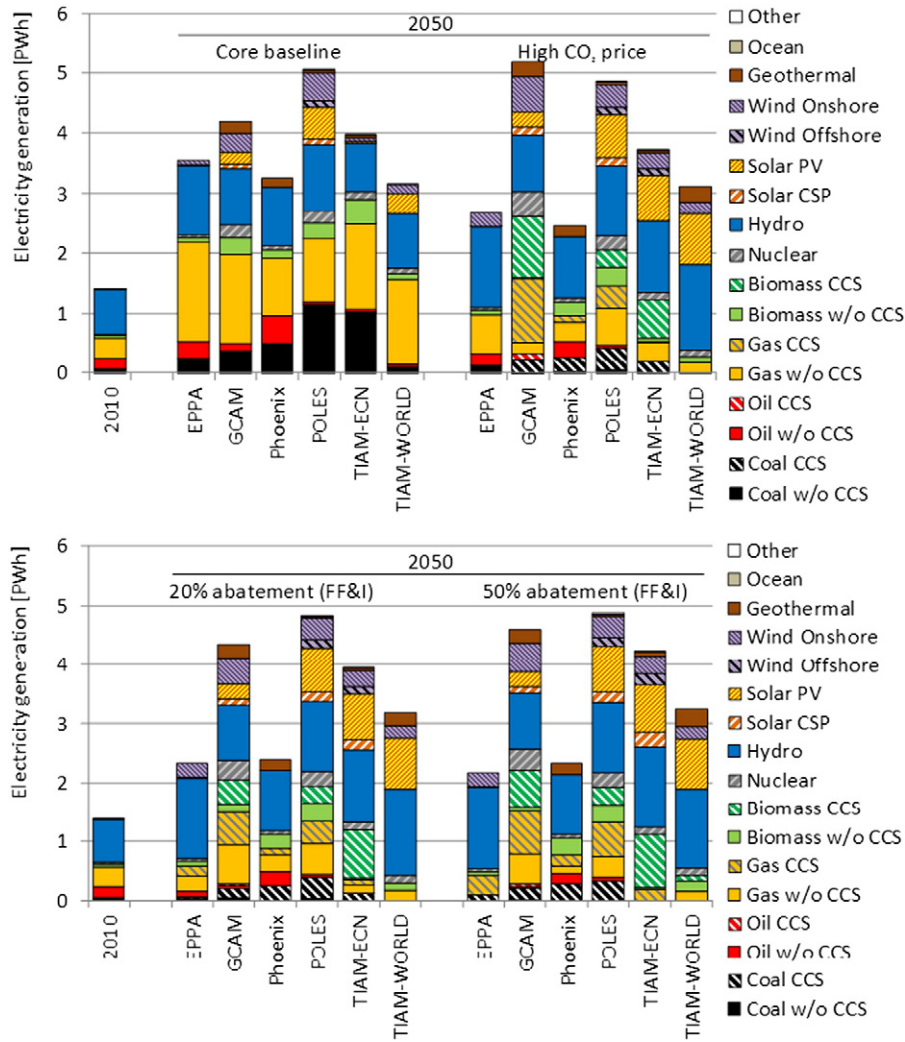
Fig. 6. Breakdown of electricity generation in Latin America by resource and technology in 2050.

nuclear technology and materials to military or terrorist purposes, as well as high investment costs, large capacity scales, and long construction (lead) times. It has among one of its major benefits though that it is a low-carbon power production option (van der Zwaan, 2013). Nuclear power has been investigated in several recent integrated assessment model exercises, which yielded varying findings regarding the prospects for this technology (Bauer et al., 2012; Kim et al., 2014; Tavoni and van der Zwaan, 2011). In the present multi-model comparison exercise for Latin America, we find that nuclear energy may benefit from climate policy. This incremental benefit appears marginal, however, with regards to the increase in nuclear power generation that all models already project in the Core baseline scenario, as can be seen in the upper left plot of Fig. 10. The extent of its possible expansion varies strongly across models: GCAM and POLES yield much larger nuclear energy expansion rates than the other models.

There is at present limited nuclear expertise and/or industrial activity in the majority of countries in Latin America, and many of them do not possess adequate nuclear safeguarding & control institutions. In spite of these shortcomings, some governments in the region without prior experience in nuclear energy have recently expressed interest in exploring the feasibility of domestic nuclear power production, while several other governments have explicitly renounced to adopt nuclear energy to date or question the local deployability of nuclear power plants based on arguments such as risks for earthquakes. National nuclear energy development intrinsically involves

long lead times (typically 10 years for the construction of a nuclear power plant, but sometimes decades), in comparison to those associated with other energy technologies. Hence it is probably unrealistic to assume that nuclear power will be domestically produced over the medium term in countries in the region other than Argentina, Brazil and Mexico.

In the case of Argentina (with nuclear energy accounting for 6% of installed electricity capacity, the highest share in Latin America), its government is currently investigating a possible re-launch of nuclear energy: a new reactor has just become operational and the construction of three additional nuclear reactors are under consideration. In Brazil (with two reactors in operation and one under construction) and Mexico (with two reactors in operation), likewise, no further reactor construction is planned for the near term. The figures for these three countries are in agreement with the blue-shaded results depicted in Fig. 10. The political and public acceptance inertia to which nuclear power plant planning and construction is currently subjected in these three countries, like has been the case in other countries in the past, makes it unlikely that more than a two- to three-fold expansion of nuclear power can materialize over the next decades in Latin America. Models like EPPA and Phoenix appear to best match this reality, while TIAM-ECN and TIAM-World present more optimistic views – POLES and GCAM yield outcomes that go beyond those of the other models, as a result of low nuclear power cost assumptions and (absence of) nuclear power diffusion deployment constraints.
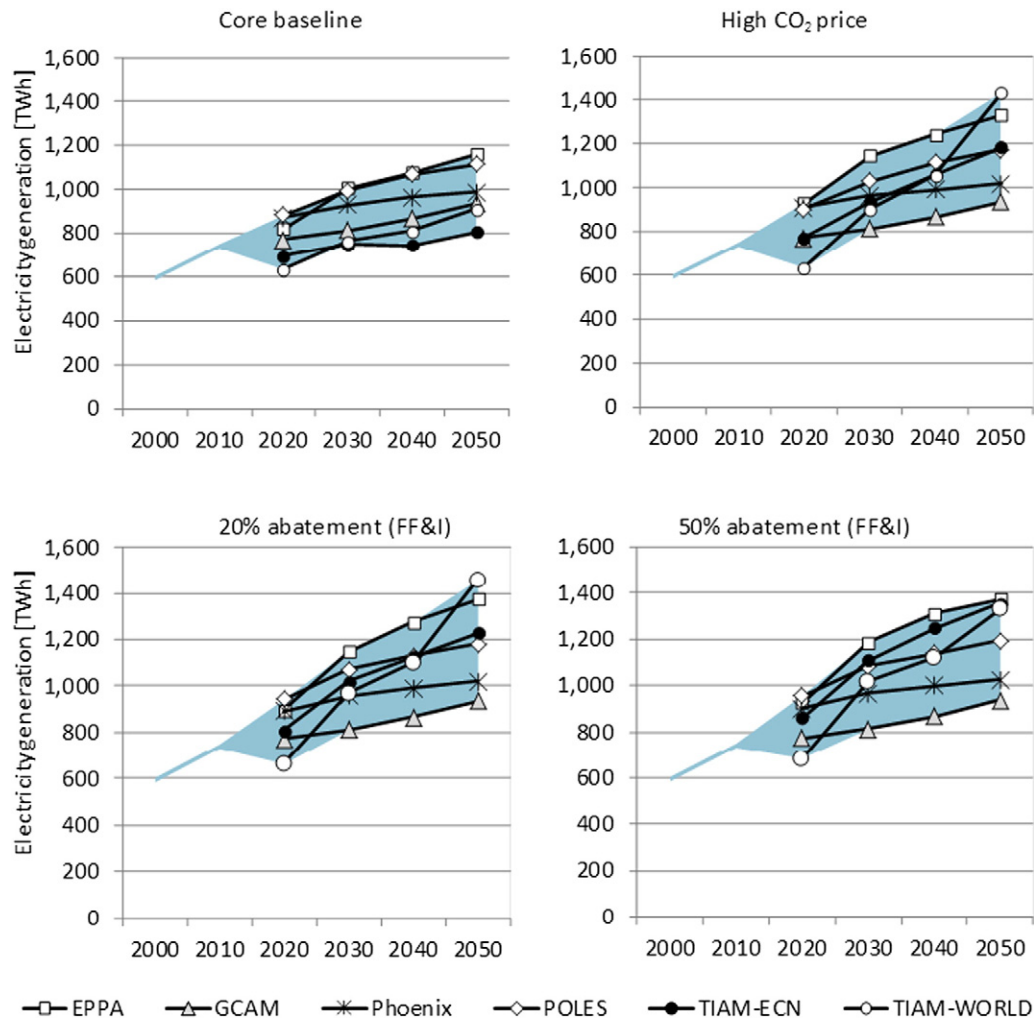
Fig. 7. Hydropower generation in Latin America.

3.4. CCS technology

It is broadly recognized that CCS technology is an important candidate among GHG mitigation options available in principle to control global climate change (IEA-ETP, 2012; IPCC, 2005). CCS has therefore extensively been subjected to analysis through integrated assessment models, which almost invariably agree on the primordial importance of this technology (Azar et al., 2006; Edenhofer et al., 2010; Gerlagh and van der Zwaan, 2012; Koelbl et al., 2014; Mikunda et al., 2014). Our model runs corroborate with this view, and suggest that CCS may (need to) become an important option to reach CO_2 emission reductions, as demonstrated in Fig. 11. This Figure shows that during the first half of the 21st century CCS deployment is likely to grow exponentially in each of the three depicted climate policy scenarios (in the Low CO_2 price scenario, CCS is implemented as well, but to a much smaller extent). Substantial variety exists, however, between models in terms of how much CCS could actually be deployed, but the overall tendency is clear: in 2050, under a high carbon tax regime, CCS may involve hundreds Mt of captured CO_2 per year, while under a stringent CO_2 emissions abatement regime its deployment may capture (not avoid) an amount that exceeds a thousand $MtCO_2/yr$. To date, the high ambitions to demonstrate CCS technology on power plant scale, let alone to deploy it on a broader industrial level, have largely been left unmet. Among the reasons are the high costs associated with CCS implementation and the infrastructural requirements to transport CO_2 in large quantities from capture location to storage sites. Public opposition to storage risks adds to the obstacles that CCS technology has experienced so far. It needs to be studied further whether and how Latin America might be different from the rest of the world regarding the possible role of CCS; especially the situation regarding the CO_2 storage potential in the region is important in this context.

3.5. Final energy consumption (demand side)

In addition to energy savings on the supply side, energy savings on the demand side can contribute to achieving CO_2 emission reductions. One way to express the extent to which in our models energy reduction contributes to meeting the goals set in the three climate policies scenarios is to inspect the effect these policies have on final energy consumption, in comparison to the energy consumption level in the Core baseline scenario, as is shown in Fig. 12 for four time steps until 2050. Clearly, as the cross-model average lines show in this Figure, there is a tendency that the more stringent the climate target gets (by moving from the High CO_2 price scenario to the 20% and 50% abatement scenarios), the larger the role is played by final energy savings technology on the demand side. This tendency augments as time proceeds. Again, like with primary energy savings, we see a clear clustering between two main categories of models. General equilibrium models (EPPA and Phoenix) project significantly more final energy consumption reductions than partial equilibrium models (GCA, POLES and TIAM-ECN), essentially for the same reasons as mentioned earlier. The former two models treat final energy as input to a macro-economic production function. Hence energy demand reduction can be achieved by substitution with other production factors, such as capital and labor, or by reducing economic output. Since capital and labor are limited in supply, the large
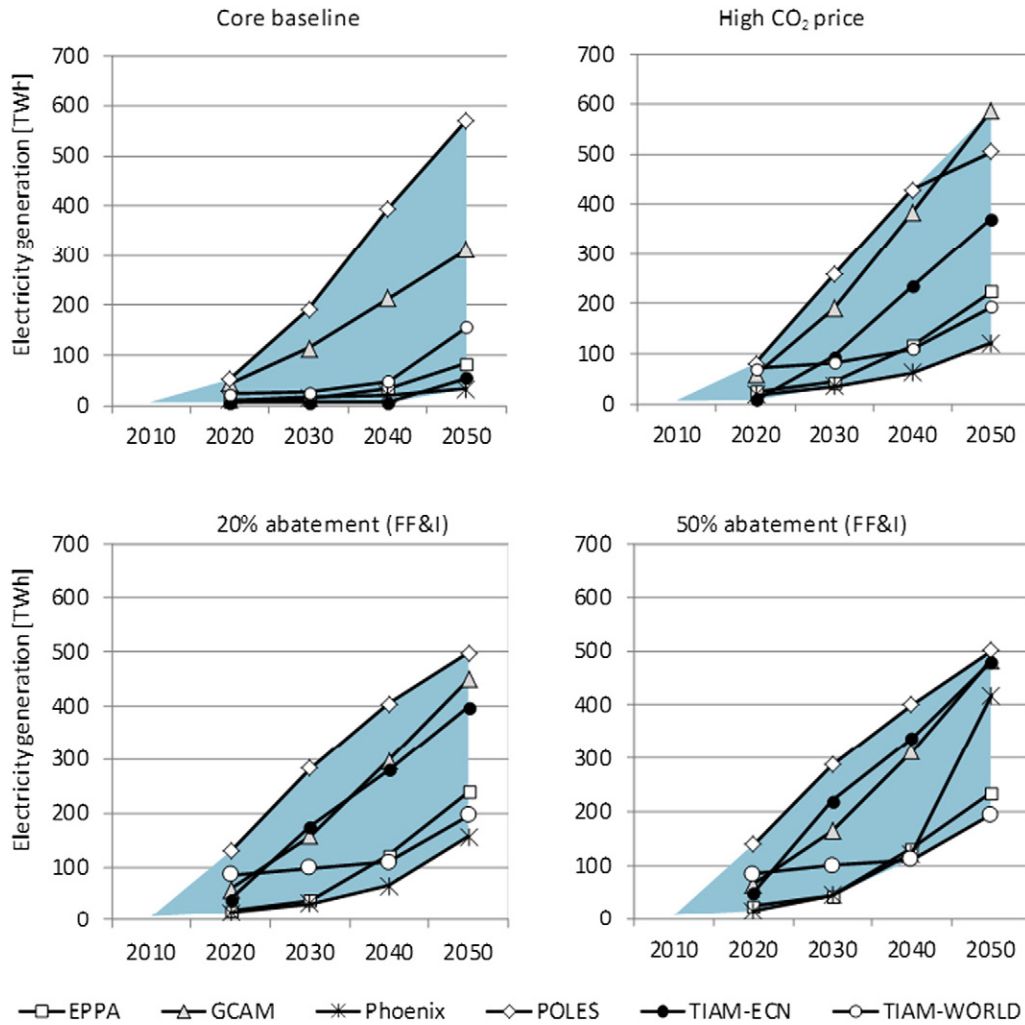
Fig. 8. Expansion of wind power production in Latin America.

reductions in final energy consumption are largely enabled by sizeable losses in GDP.

3.6. Technology deployment implications

Fig. 13 shows, for Latin America, annual capacity additions for the short to medium term future (2010–2030 respectively 2030–2050), for various potential low-carbon energy technologies, induced by the emission reduction requirement of the 50% abatement (FF&I) scenario. Also indicated is, as benchmark for the purpose of comparison, the technology deployment rate of several (conventional and renewable) energy technologies in Europe, the US and Latin America during the 1980s and in the recent past (2002–2012). As one can see, the annual new capacity deployment intensity (expressed in GW/yr) that is projected for solar energy in Latin America between 2010 and 2030 falls only somewhat short of that recently observed in Europe for the same technology, and amounts to only little below the level observed for coal-based power plants in Europe during the 1980s. It would on average be much higher during the period 2030–2050 under this stringent emissions abatement scenario. For wind energy also a large expansion is projected for Latin America, but with deployment levels substantially below those for solar energy (but this finding is strongly model-dependent). Other low-carbon options such as hydropower and biomass-based options (and to a lesser extent potentially also nuclear energy and fossil-based CCS power production), as demonstrated by

the results reported in Fig. 13, also may receive (in some cases substantial) impetus under this climate change mitigation scenario.

There is thus a significant expansion opportunity for the manufacturing and installation industry for the above-mentioned renewable energy options, in Latin America as well as elsewhere in the world. This will require significant public policy support in addition to the economy-wide carbon tax or emissions caps that are examined in our scenarios, including for example appropriate legal and regulatory frameworks and enabling physical infrastructures in which these low-carbon options can be implemented. It will also challenge the ability of the private sector to expand at the necessary rates. In addition to industrial challenges, such technology diffusion implies infrastructural, financial, socio-political and institutional requirements not yet experienced for several technologies at this scale in Latin America (GEA, 2012; IEA-ETP, 2012; IPCC, 2011). Wilson et al. (2012) investigate whether climate policy scenarios for future capacity growth of new energy technologies are consistent with historical evidence and find that future required low-carbon technological growth in the power sector appears to be conservative relative to what has been evidenced historically. Differently from them, and probably because they use a different analysis framework (expressing their findings in terms of speed-based technology diffusion variables), van der Zwaan et al. (2013a) find that needed average annual capacity additions for a couple of low-carbon energy technologies (solar and wind power) are the opposite of conservative in historic terms, that is, they are several times higher than the maximum average annual capacity additions rate observed in the past
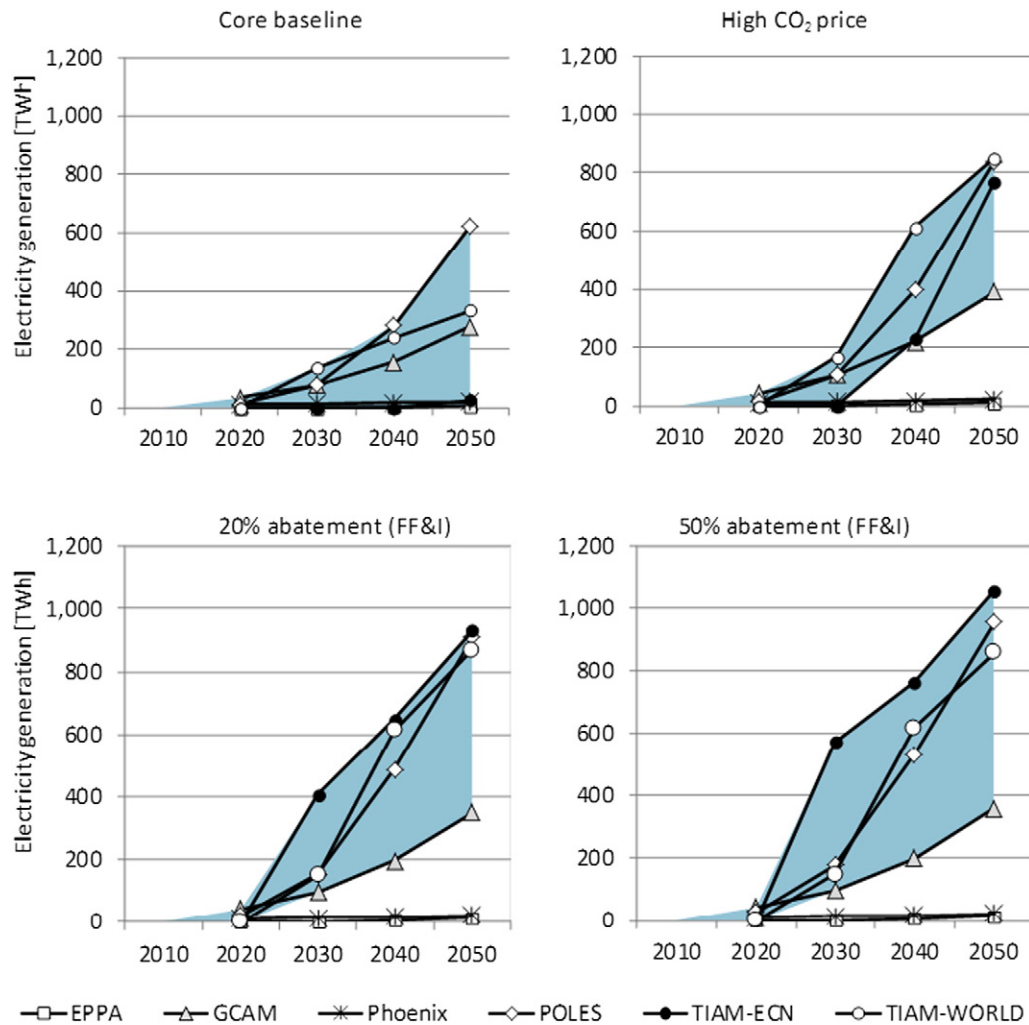
Fig. 9. Solar power generation in Latin America.

(for e.g. coal-based power plants) if one desires to seriously control climate change. Here we support the findings by van der Zwaan et al. (2013a): if global GHG emissions are going to be reduced substantially, Latin America may need to prepare itself for capacity additions of some renewable energy options in a few decades from now that are not only much larger than what has historically been observed (for any energy technology) in the region itself, but also substantially higher than (or at least as much as) what has materialized in the past in Europe and the US in terms of annual conventional or renewable energy capacity additions. The body of literature on technology expansion rates is likely to grow further over the years to come (for another recent article, with similar conclusions, see e.g. Eom et al., 2014).

The multi-model comparison literature has recently spent substantial effort investigating the incremental energy system costs required for implementing low-carbon development strategies (see e.g. Kober et al., 2014; McCollum et al., 2013; Tavoni et al., 2013; van der Zwaan et al., 2013a). We here refer to Kober et al. (2015), as published in the present special issue, for an in-depth analysis of the investment dimension of low-carbon technology deployment in Latin America.

4. Discussion, conclusions and policy & strategy implications

As we show in this study, the different experts behind our models foresee substantially varying scales for the global contraction of high-carbon energy resources, respectively the diffusion of low-carbon energy technologies. This is an expression of the multitude of pathways available to reduce GHG emissions, in our case on the Latin American continent. Other studies at the global level confirm this diversity in possible climate mitigation pathways (see notably Clarke et al., 2014a, 2014b; IPCC, 2014). From a technology perspective, our model results diverge in each of the scenarios we developed. This uncertainty in the energy system transformation process yields important implications for the public sector: except when local circumstances so dictate, for instance because of a lack of certain energy resources at the national level or because of policies driven by local priorities, policy makers may not necessarily want to pick winners today, since we do not (yet) know in all countries what the optimal or most cost-effective GHG emissions abatement technology is (see e.g. the studies in this special issue on the specific cases of Argentina, Brazil, Colombia and Mexico, by Di Sbroiavacca et al., 2016; Lucena et al., 2016; Calderon et al., 2016; respectively Veysey et al., 2016). Important though is to implement stringent policies that can stimulate the market to decide which emission reduction and technology deployment path to optimally take given locally pertaining circumstances.

Despite the large cross-model differences that we observe, also some robust conclusions can be drawn, for example with regards to the importance of the power sector for implementing low-carbon energy technologies. Studies at the global level (such as in Krey et al., 2014; Weyant and Kriegler, 2014) and regional level (Calvin et al., 2012; Clarke et al., 2012, for Asia; Clarke et al., 2014a, 2014b; Fawcett et al., 2014, for the USA; Knopf et al., 2013, for Europe) come to the same conclusion in this respect. For large-scale low-CO_2 electricity generation, renewables like solar and wind energy dominate the present view of many analysts on future global energy systems. Particularly in Latin America, other options could also
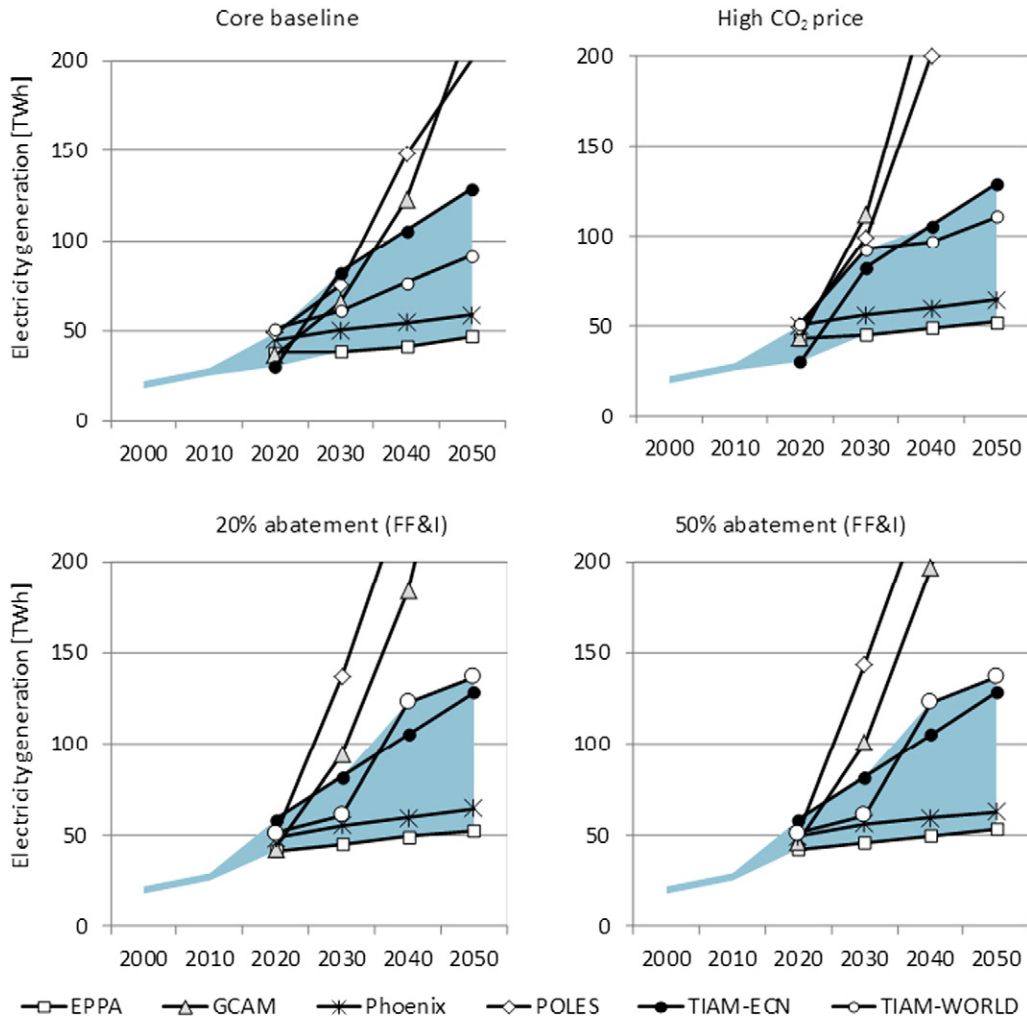
Fig. 10. Nuclear power generation in Latin America.

play a significant role, among which biomass (either or not in combination with CCS, see Calvin et al., 2016), hydropower and/or geothermal energy (see e.g. Arias Gaviria et al., 2015). Nuclear power diffusion is likely to be limited, even while certain prospects for its deployment cannot be ruled out in a few countries in Latin America. In this article we particularly study carbon taxes and abatement targets as two main economy-wide policy interventions to stimulate low-carbon energy development. Dedicated additional policy instruments can support these policies and the emergence of markets for renewables, such as subsidies, RDD&D (Research, Development, Demonstration and Deployment) programs, feed-

in tariffs and loan guarantees (but the simultaneous implementation of such policy tools, such as subsidies and carbon taxes, yields the risk of creating economic inefficiencies). The public sector thus has a dominant role to play in the transition towards a low-carbon energy system that contributes to mitigating climate change.

Our study bears also important strategic lessons for the private sector, since the annual capacity deployment intensity (in GW/yr) needed for e.g. wind energy after 2030 needs to be similar to that recently observed for wind power in the US. For solar energy it may have to be higher than that observed between 2002 and 2012 in Europe and the
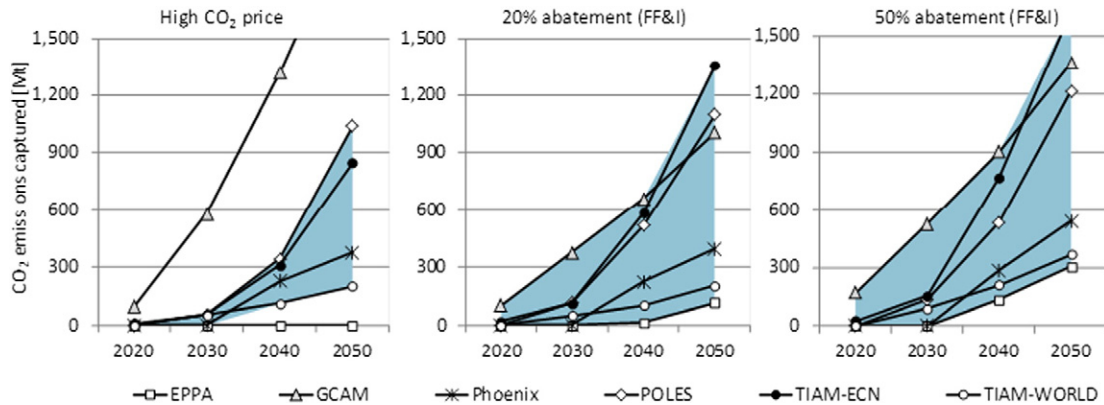

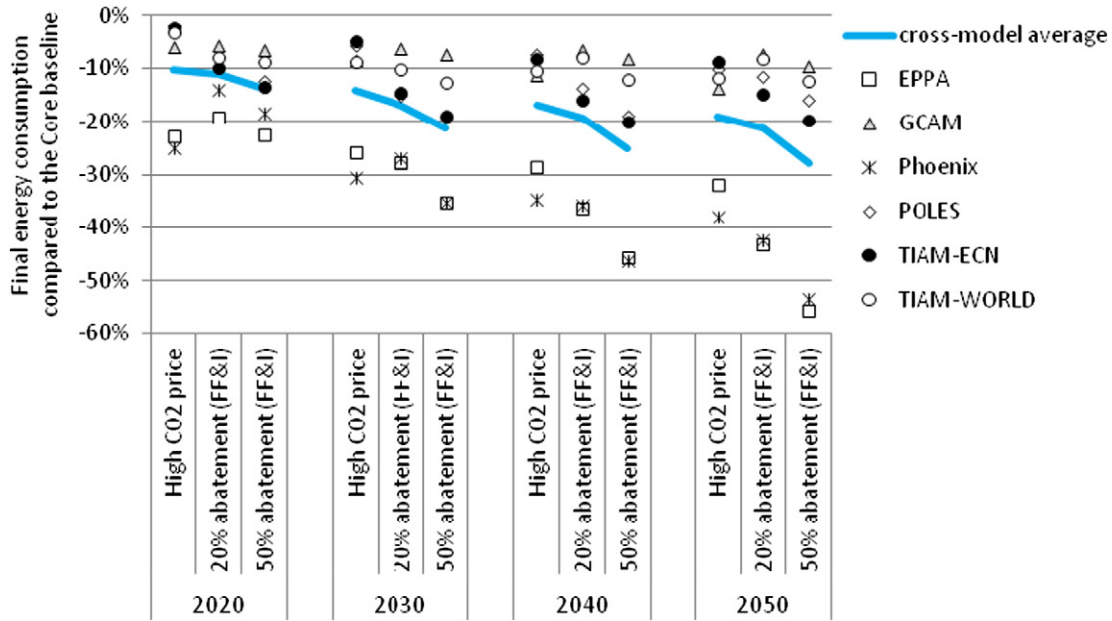**Fig. 11.** The use of CCS in Latin America.

Fig. 12. Final energy savings (demand side) in Latin America with respect to the Core baseline.

US combined. Although these observations constitute a significant opportunity for Latin American industry, as well as multinationals that have Latin American countries among their clientele, this up-scaling needs to be prepared for, and public policy needs to create a conducive enabling environment. According to most modeling teams CCS constitutes a significant way to reduce CO_2 emissions, so also this technology proffers opportunities for industry, while necessitating preparations for both the private and public sector. For all these technologies strong policy signals from government about support for low carbon-emitting energy sources (whether through economy-wide emission targets, carbon intensity targets, or carbon taxes) and subsequent financial returns drive investment decisions in the private sector. The transition process will be intrinsically uncertain. Not only does uncertainty abound with regards to the technology type and diffusion extent of low-carbon energy alternatives that need to be deployed until 2050, but also concerning

the respective cumulative costs involved (for which we refer to Kober et al., 2015).

The results from RDD&D may also steer the decision process regarding where and how to commercially invest, hence industry could undertake such RDD&D, potentially assisted herein through public research endeavors. Both the public and private sectors could stimulate and/or undertake technology-specific RDD&D, in order to prepare for the changes the energy sector needs over the next few decades. For Latin America such RDD&D could for example focus on BECCS options, given the abundance of biomass options in the region, or solar energy alternatives, given their prominence in our modeling results. As complementary measures, or perhaps as viable alternatives, perhaps development assistance or technology transfer agreements could bring about benefits without necessarily conducting the R&D part of RDD&D efforts in Latin America.
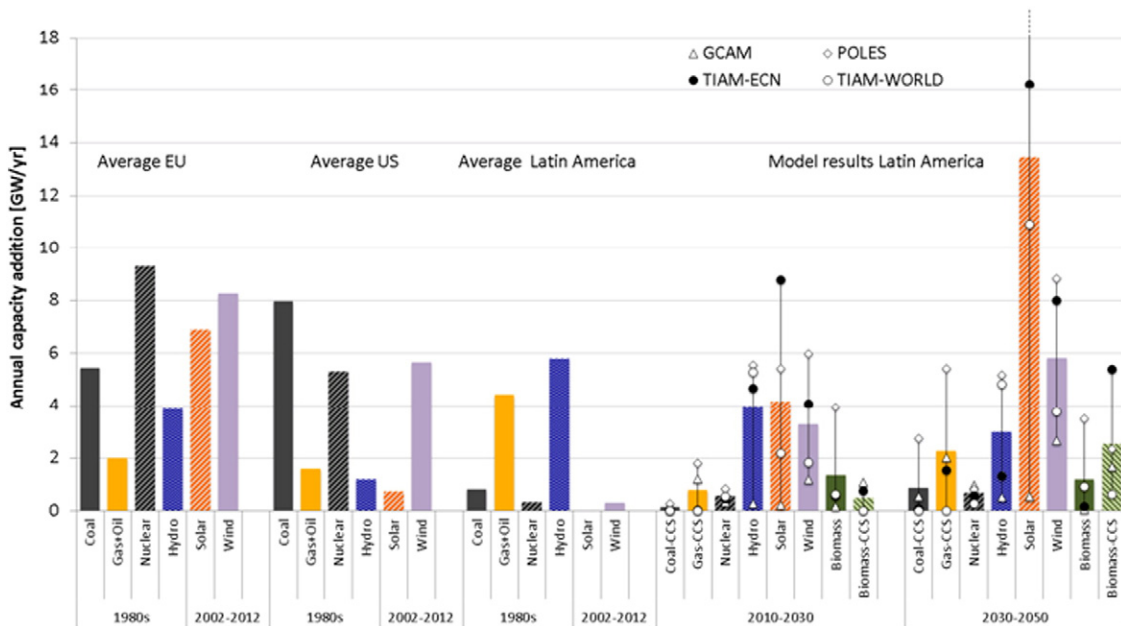

Fig. 13. Average annual capacity additions (history EU, US and LA; short-medium future LA) for various fossil-based and low-carbon energy technologies in the 50% abatement (FF&I) scenario.
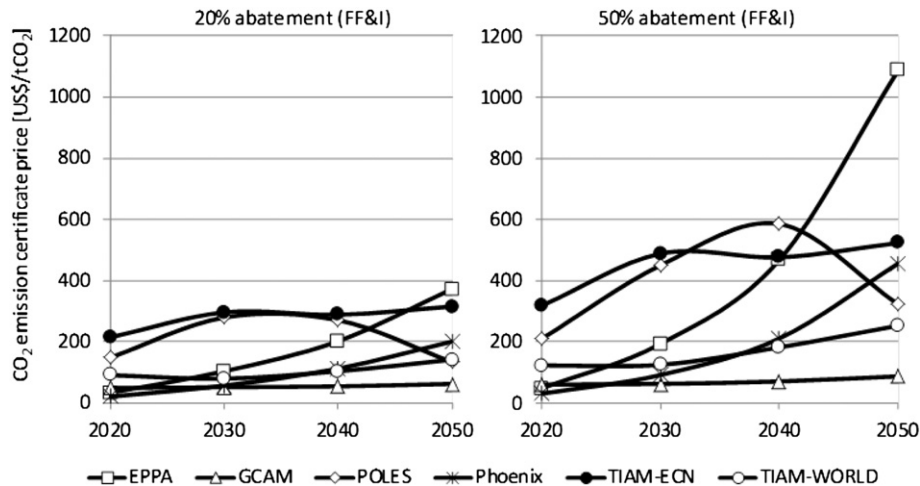
Modeling exercises like those presented in this paper should be pursued to allow for energy systems analysis that instructs both these sectors on how to steer their planning and decision-making processes. This is particularly true for several rapidly growing economies in Latin America, since some of these countries have just embarked on an important mission to gradually decarbonize their national energy infrastructures. Particularly interesting in this respect are economies, such as those of Brazil and Colombia, that so far have managed to remain relatively low-carbon despite substantial economic growth (largely as a result of the large-scale use of hydropower), but whose challenge henceforth is to avoid the risk of going fossil, stay low-carbon or even further reduce their carbon intensity under continued socio-economic progress (see Lucena et al., 2016 respectively Calderon et al., 2016). Subjects abound that are yet to be explored by integrated assessment models like ours. A question closely related to the theme of this article is what the realistically feasible and/or technologically permissible rates of change are in countries in Latin America that the required energy system transformation demands (see e.g. Riahi et al., 2013; van der Zwaan et al., 2013a; Wilson et al., 2012, which deal with this topic in a generic context). Related to this, an important field of continuing research related to the large-scale deployment of renewable energy in view of its intermittent nature and the economic benefits it could bring to the region, as elsewhere.

Acknowledgments

Appendix A. Figure 14. CO_2 prices for two emission abatement scenarios.

References

Arias Gaviria, J., van der Zwaan, B., Kober, T., Arango Aramburo, S., 2015. Prospects for Small Hydropower in Colombia: an inspection of Learning-by-doing and Economies-of-scale. Working Paper Submitted For Review.

Azar, C., Lindgren, K., Larson, E., Möllersten, K., 2006. Carbon capture and storage from fossil fuels and biomass - costs and potential role in stabilizing the atmosphere. Clim. Chang. 74, 47–79.

Bauer, N., Brecha, R.J., Luderer, G., 2012. Economics of nuclear power and climate change mitigation policies. PNAS 109, 16805–16810.

Calderon, S., et al., 2016. Achieving CO_2 reductions in Colombia: effects of carbon taxes and abatement targets. Energy Econ. 56, 575–586 (this special issue).

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

Calvin, K., Clarke, L., Krey, V., Blanford, G., Jiang, K., Kainuma, M., Kriegler, E., Luderer, G., Shukla, P.R., 2012. The role of Asia in mitigating climate change: results from the Asia modeling exercise. Energy Econ. 34 (Supplement 3), S251–S260.

Calvin, K.V., et al., 2016. Agriculture, forestry, and other land-use emissions in Latin America. Energy Econ. 56, 615–624 (this special issue).

Clarke, L., Krey, V., Weyant, J., Chaturvedi, V., 2012. Regional energy system variation in global models: results from the Asian Modeling Exercise scenarios. Energy Econ. 34 (Supplement 3), S293–S305.

Clarke, L.E., Fawcett, A.A., Weyant, J.P., McFarland, J., Chaturvedi, V., Zhou, Y., 2014a. Technology and US emissions reductions goals: results of the EMF 24 modeling exercise. Energy J. 35.

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

Clarke, L., et al., 2016. Long-term abatement potential and current policy trajectories in Latin American countries. Energy Econ. 56, 513–525 (this special issue).

Criqui, P., et al., 2014. Mitigation strategies and energy technology learning: an assessment with the POLES model. Technol. Forecast. Soc. Chang. (in press).

Di Sbroiavacca, N., et al., 2016. Emissions reduction scenarios in the Argentinean Energy Sector. Energy Econ. 56, 552–563 (this special issue).

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magne, B., Scrieciu, S., Turton, H., van Vuuren, D.P., 2010. The economics of low stabilization: model comparison of mitigation strategies and costs. Energy J. 31, 11–48.

Eom, J., Edmonds, J., Krey, V., Johnson, N., Longden, T., Luderer, G., Riahi, K., van Vuuren, D.P., 2014. The impact of near-term climate policy choices on technology and emission transition pathways. Technol. Forecast. Soc. Chang. 90, 73–88.

EPE, 2014. National Energy Balance 2014. Empresa de Pesquisa Energética, Brazil (Available at: https://ben.epe.gov.br/).

Fawcett, A.A., Clarke, L.C., Rausch, S., Weyant, J.P., 2014. Overview of EMF 24 policy scenarios. Energy J. 35.

GEA, 2012, Global Energy Assessment, IIASA (Laxenburg, Austria), Cambridge University Press, Cambridge, UK.

Gerlagh, R., van der Zwaan, B.C.C., 2012. Evaluating uncertain CO_2 abatement over the very long term. Environ. Model. Assess. 17 (1/2), 137–148.

Griffin, B., et al., 2014. White knights: will wind and solar come to the rescue of a looming capacity gap from nuclear phase-out or slow CCS start-up? Clim. Chang. 123 (3–4), 623–635.

GWEC (Global Wind Energy Council), 2014. Global Wind Energy Outlook 2014 available at: http://www.gwec.net/.

IEA-ETP, 2012. International Energy Agency (IEA), OECD, Energy Technology Perspectives (ETP), Paris, France.

IEA-ETP, 2014. International Energy Agency (IEA), OECD, Energy Technology Perspectives (ETP), Paris, France.

IPCC, 2005. Special report on carbon dioxide capture and storage. Working Group III, Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2011. Special report on renewable energy sources and climate change mitigation. Working Group III, Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2014. Climate change mitigation. Fifth Assessment Report (AR5), Working Group III, Intergovernmental Panel on Climate Change. Cambridge University Press.

Kim, S.H., Wada, K., Kurosawa, A., Roberts, M., 2014. Nuclear energy response in the EMF27 study. Clim. Chang. 123, 443–460.

Kitous, A., et al., 2010. Transformation patterns of the worldwide energy system — scenarios for the century with the POLES model. Energy J. 31, 49–82.

Knopf, B., Chen, Y.-H.H., De Cian, E., Förster, H., Kanudia, A., Karkatsouli, I., Keppo, I., Koljonen, T., Schumacher, K., van Vuuren, D.P., 2013. Beyond 202 — strategies and costs for transforming the European energy system. Clim. Change Econ. 04, 1340001.

Kober, T., van der Zwaan, B.C.C., Rösler, H., 2014. Emission certificate trade and costs under regional burden-sharing regimes for a 2 °C climate change control target. Clim. Change Econ. 5 (1), 1–32 (1440001).

Kober, T., Falzon, J., van der Zwaan, B., Calvin, K., Kanudia, A., Kitous, A., Labriet, M., 2015. A Multi-Model Study of Energy Supply Investments in Latin America under Climate Control Policy (this special issue).

Koelbl, B.S., van den Broek, M.A., Faaij, A.P.C., van Vuuren, D.P., 2014. Uncertainty in carbon capture and storage (CCS) deployment projections: a cross-model comparison exercise. Clim. Chang. 123, 461–476.

Krey, V., Luderer, G., Clarke, L., Kriegler, E., 2014. Getting from here to there — energy technology transformation pathways in the EMF27 scenarios. Clim. Chang. 1–14.

Kriegler, E., Petermann, N., Krey, V., Schwanitz, V.J., Luderer, G., Ashina, S., Bosetti, V., Eom, J., Kitous, A., Méjean, A., Paroussos, L., Sano, F., Turton, H., Wilson, C., van Vuuren, D.P., 2014a. Diagnostic indicators for integrated assessment models of climate policy. Technol. Forecast. Soc. Chang. http://dx.doi.org/10.1016/j.techfore.2013.09.020.

Kriegler, E., Weyant, J.P., Blanford, G.J., Krey, V., Clarke, L., Edmonds, J., Fawcett, A., Luderer, G., Riahi, K., Richels, R., Rose, S.K., Tavoni, M., van Vuuren, D.P., 2014b. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. Clim. Chang. 123, 353–367.

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.

Lucena, A.F.P., et al., 2016. Climate policy scenarios in brazil: a multi-model comparison for energy. Energy Econ. 56, 564–574 (this special issue).

Luderer, G., Bosetti, V., Jakob, M., Leimbach, M., Steckel, J.C., Waisman, H., Edenhofer, O., 2012. The economics of decarbonizing the energy system—results and insights from the RECIPE model intercomparison. Clim. Chang. 114, 9–37.

Luderer, G., Krey, V., Calvin, K., Merrick, J., Mima, S., Pietzcker, R., Vliet, J.V., Wada, K., 2014. The role of renewable energy in climate stabilization: results from the EMF27 scenarios. Clim. Chang. 123, 427–441.

Ludig, S., Haller, M., Schmid, E., Bauer, N., 2011. Fluctuating renewables in a long-term climate change mitigation strategy. Energy 36, 6674–6685.

Macknick, J., 2011. Energy and CO$_2$ emission data uncertainties. Carbon Manag. 2, 189–205.

Mai, T., Sandor, D., Wiser, R., Schneider, T., 2012. Renewable Electricity Futures Study: Executive Summary. National Renewable Energy Laboratory (NREL), Golden, CO, USA.

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

McKinsey, 2009. Pathways to a low-carbon economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve. McKinsey & Company.

Mikunda, T., Kober, T., de Coninck, H., Bazilian, M., Rösler, H., van der Zwaan, B.C.C., 2014. Designing policy for deployment of CCS in industry. Clim. Pol. 1–12.

Paltsev, S., Reilly, J., Jacoby, H., Eckhaus, R., McFarland, J., Saforim, M., Asadoorian, M., Babiker, M., 2005. The MIT emission prediction and policy analysis (EPPA) model: version 4. Report: No. 125. MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA.

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., McCollum, D.L., Mima, S., Turton, H., van Vuuren, D.P., Wada, K., Bosetti, V., Capros, P., Criqui, P., Kainuma, M., 2013. Locked into Copenhagen Pledges — implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technol. Forecast. Soc. Chang.

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.

Sue Wing, I., Daenzer, K., Fisher-Vanden, K., Calvin, K., 2011. Phoenix Model Documentation downloadable from www.globalchange.umd.edu.

Sullivan, P., Krey, V., Riahi, K., 2013. Impacts of considering electric sector variability and reliability in the MESSAGE model. Energy Strategy Rev. 1, 157–163.

Sullivan, P., Uriarte, C., Short, W., 2014. Greenhouse gas mitigation options in the US electric sector: a ReEDS analysis. Energy J. 35.

Tavoni, M., van der Zwaan, B.C.C., 2011. Nuclear versus coal plus CCS: a comparison of two competitive base-load climate control options. Environ. Model. Assess. 16 (5), 431–440.

Tavoni, M., Kriegler, E., Aboumahboub, T., Calvin, K., De Maere, G., Wise, M., Klein, D., 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. Clim. Change Econ. 4 (4), 1–25 (1340006).

UN, 2012. Sustainable Energy for All: A Framework for Action. United Nations, The Secretary-General's High-level Group on Sustainable Energy for All, New York.

van der Zwaan, B.C.C., 2013. The role of nuclear power in mitigating emissions from electricity generation. Energy Strategy Rev. 1, 296–301.

van der Zwaan, B.C.C., Keppo, I.J., Johnsson, F., 2013a. How to decarbonize the transport sector? Energy Policy 61, 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". Clim. Change Econ. 4 (4), 1–24 (1340013).

van der Zwaan, B.C.C., Calvin, K., Clarke, L., (Guest Editors), 2016. 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 Ruijven, B., et al., 2015. A cross-model investigation of energy and emission baseline scenarios for Latin America. Energy Econ. (this special issue).

Veysey, J., et al., 2016. Pathways to Mexico's climate change mitigation targets: a multi-model analysis. Energy Econ. 56, 587–599 (this special issue).

Weyant, J., Kriegler, E., 2014. Preface and introduction to EMF 27. Clim. Chang. 123, 345–352.

Wilson, C., Grübler, A., Bauer, N., Krey, V., Riahi, K., 2012. Future capacity growth of energy technologies: are scenarios consistent with historical evidence? Clim. Chang. 118 (2), 381–395.