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Emissions reduction scenarios in the Argentinean Energy Sector☆

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ABSTRACT

In this paper the LEAP, TIAM-ECN, and GCAM models were applied to evaluate the impact of a variety of climate change control policies (including carbon pricing and emission constraints relative to a base year) on primary energy consumption, final energy consumption, electricity sector development, and CO_2 emission savings of the energy sector in Argentina over the 2010–2050 period. The LEAP model results indicate that if Argentina fully implements the most feasible mitigation measures currently under consideration by official bodies and key academic institutions on energy supply and demand, such as the ProBiomass program, a cumulative incremental economic cost of 22.8 billion US$(2005) to 2050 is expected, resulting in a 16% reduction in GHG emissions compared to a business-as-usual scenario. These measures also bring economic co-benefits, such as a reduction of energy imports improving the balance of trade. A Low CO_2 price scenario in LEAP results in the replacement of coal by nuclear and wind energy in electricity expansion. A High CO_2 price leverages additional investments in hydropower. By way of cross-model comparison with the TIAM-ECN and GCAM global integrated assessment models, significant variation in projected emissions reductions in the carbon price scenarios was observed, which illustrates the inherent uncertainties associated with such long-term projections. These models predict approximately 37% and 94% reductions under the High CO_2 price scenario, respectively. By comparison, the LEAP model, using an approach based on the assessment of a limited set of mitigation options, predicts an 11.3% reduction. The main reasons for this difference include varying assumptions about technology cost and availability, CO_2 storage capacity, and the ability to import bioenergy. An emission cap scenario (2050 emissions 20% lower than 2010 emissions) is feasible by including such measures as CCS and Bio CCS, but at a significant cost. In terms of technology pathways, the models agree that fossil fuels, in particular natural gas, will remain an important part of the electricity mix in the core baseline scenario. According to the models there is agreement that the introduction of a carbon price will lead to a decline in absolute and relative shares of aggregate fossil fuel generation. However, predictions vary as to the extent to which coal, nuclear and renewable energy play a role.

1. Introduction

The CLIMACAP-LAMP project[1] aims to facilitate evidence-based policy making by providing a robust quantitative analysis of the effectiveness and costs of potential climate control measures in Latin American countries and the region as a whole. According to Argentina's Second National Communication, greenhouse gas (GHG) energy sector emissions increased from 48% of total GHG emissions in 1990 to 55% in 2000 (SAyDS, 2007). Energy sector emissions are expected to continue to grow rapidly in the coming years. In the lead-up to the 21st Conference of the Parties (COP 21) of the United Nations Framework Convention on Climate Change (UNFCCC) in Paris, 2015, Argentina will prepare and submit an Intended Nationally Determined Contribution (INDC), describing Argentina's contribution to global efforts to combat climate change. In this context, the CLIMACAP-LAMP project seeks to provide descriptions of the energy-economic implications of a series of climate control measures for the Argentinian energy sector to inform this, and other relevant on-going processes. For a detailed overview of the CLIMACAP-LAMP project, we refer to van der Zwaan et al. (2016–in this issue).

The approach taken in this study is based primarily on the application of a bottom-up simulation model (Long-Range Energy Alternatives

☆ This paper examines the implications of climate policy on energy sector emissions in Argentina, using an energy-economic model (LEAP) as well as two global integrated assessment models (TIAM-ECN and GCAM).

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[1] The Integrated Climate Modelling and Capacity Building Project in Latin America (CLIMACAP) is a European Commission funded effort focused on analyzing the effects of mitigation strategies in key Latin American Countries. 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. (2016–in this issue). The database of the project can be found at: https://tntcat.iiasa.ac.at/CLIMACAP-LAMPDB/.

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Planning System Model [LEAP]), compared to two global integrated assessment models, the TIMES Integrated Assessment Model – Energy research Centre of the Netherlands [TIAM-ECN], and the Global Change Assessment Model [GCAM]). For a brief characterization of the models we refer to van der Zwaan et al. (2016–in this issue), and detailed model descriptions can be derived from publications by their respective modelling teams: LEAP (SEI, 2014); TIAM-ECN (Keppo and van der Zwaan, 2012; Kober et al. 2014, Rösler et al., 2014, van der Zwaan et al., 2013a,b) and GCAM (Calvin et al., 2011).

The LEAP model was configured considering a limited set of mitigation measures,[2] which could be seen as a lower estimate of emission reductions that could be achieved in the Argentine energy sector. By contrast, as TIAM-ECN and GCAM are optimization and market-equilibrium models, respectively, that consider a larger set of potential mitigation measures, they generate emissions reductions estimations that could be considered as an upper estimate of what could be achieved under a given set of market conditions.

As with any modelling analysis, there are an array of assumptions, methodological approaches, and uncertainties that have an important impact on the results. The results therefore need to be interpreted with these limitations in mind, and thus throughout the paper we highlight methodological approaches and assumptions where appropriate. The departure point of the analysis is a deep-dive into the results of the LEAP model, which constitutes the main focus of this paper. The methodology used for the application of the LEAP model, and the main results obtained, are described in detail. We then compare the LEAP results with the two global integrated assessment models (TIAM-ECN, GCAM). Finally, a series of policy relevant conclusions are articulated.

2. Methodology of LEAP simulation

LEAP is a software tool for energy policy analysis and climate change mitigation assessment. It can be used to create models of different energy systems, and supports a wide range of different modeling methodologies: on the demand side these range from bottom-up, end-use accounting techniques to top-down macroeconomic modeling. On the supply side, LEAP provides a range of accounting and simulation methodologies for modeling electricity sector generation and capacity expansion planning (SEI, 2014).

Calibration of the LEAP model involved incorporation of historical and base year data and anticipated evolutions of the different variables. The base year was determined by the availability of official energy data; namely the year 2010. As national energy balances are not disaggregated by energy service (end use), energy sector consumption was disaggregated into residential, transport, agriculture, industry, commercial, and electricity supply sectors at the level of the end user. In the transport sector, which is the main energy consumer (responsible for 26% of final energy demand in 2010) and also the main producer of GHG emissions (29% of energy sector GHG emissions in the same year), a more detailed analysis was undertaken involving a disaggregation by modes and means of transport.

A policy review was conducted to understand the potential mitigation options that could be considered for inclusion in the LEAP model. The measures considered are those that are being studied by official bodies and academic institutions and whose implementation has already been analyzed at least partially, and for which there is some quantitative data regarding penetration and costs. Among the institutions that are working on the assessment of mitigation options are the Energy Secretariat, the Environment and Sustainable Development Secretariat, the Vida Silvestre Foundation and the Bariloche Foundation. The availability of information was a significant restriction when it came to selecting the mitigation measures to be considered in the model. In addition, the uncertainty associated with the costs and the technology implementation pathways is also significant for most mitigation measures, especially in the long term. The gaps in the information were covered by assumptions formulated by the authors.

A common scenario protocol was defined in the CLIMACAP-LAMP project, in order to facilitate comparison of results with other models. The scenario analysis focused on five main scenarios, summarized below. For more detailed descriptions of these scenarios we refer to van Ruijven et al. (2016–in this issue) and Clarke et al. (2016–in this issue), for the baseline and policy scenarios respectively.

Core baseline: Business-as-usual scenario including climate and energy policies enacted prior to 2010.
Policy baseline: Business-as-usual scenario including "Copenhagen pledges" enacted since 2010.
Low CO2 price: A carbon tax is levied of 10 $/tCO_2e$ in 2020, growing at 4%/yr to reach 32$/tCO_2e$ in 2050.
High CO2 price: A carbon tax is levied of 50 $/tCO_2e$ in 2020, growing at 4%/yr to reach 162 $/tCO_2e$ in 2050.
20% abatement (GHG): GHG emissions, excluding LUC CO_2, are reduced by 5% in 2020, linearly increasing to 20% in 2050, with respect to 2010.

The *Core baseline* scenario takes into account the energy policies implemented shortly before the year 2010. In LEAP, policies that were incorporated include the phasing-out of incandescent light-bulbs

Table 1
Policy baseline measures.

Policy baseline demand side measures:
- Increase in solar water heaters in the household sector (area of installed solar thermal collectors by 2050: 360,000 m^2, corresponding to 4.4GJ of final energy production).
- Improved thermal efficiency in the residential buildings (percentage of buildings with improvements by 2050: 10%[a]).
- Eco-driving in freight transport and public transport (100% of drivers in these areas trained by 2050).
- Introduction of gasoline hybrid cars (share of 0% in 2010 and 5% of the car fleet by 2050).
- Higher level of biofuel penetration (average blend B7[b] in 2010, and B20 in 2050 in transport and agriculture. Average E1.2 and E45 in transport).
- Freight from truck to train transport (rail corresponds to 5% of freight transport in 2010, and 25% by 2050). In 2010, 71% of train transport consumed diesel and the remaining 29% electricity.

Policy baseline supply side measures[c]:
- Implementation of the ProBiomass Program (larger use of biomass in electricity generation, increase in installed capacity of 1784 MW by 2050). Biomass represents 1.6% of installed capacity in 2010 and 2.4% by 2050.[d]
- Promotion of hydroelectric generation (incorporation of 4647 MW during the period under consideration). Hydro represents 31% of installed capacity in 2010 and 2050.
- Promotion of wind generation (incorporation of 1560 MW during the period under consideration). Wind represents 0.1% of installed capacity in 2010 and 4% by 2050.
- Promotion of nuclear generation (incorporation of 5615 MW during the period under consideration). Nuclear represents 3.5% of installed capacity in 2010 and 11% by 2050.
- Promotion of natural gas combined-cycle (CC) generation (incorporation of 5530 MW during the period under consideration, maintaining its traditional role in covering the base load). CC represents 30% of installed capacity in 2010 and 34.5% by 2050.

[a]This percentage was selected based on the authors' expertise.
[b]This refers to the percentage of biofuel in the total volume of fuel consumed.
[c]All the capacity additions quoted in each diversification or promotion scenario are expressed in relative terms to Core baseline capacity incorporations of the related technology.
[d]Total installed capacity in 2050 is 116 GW.

[2] The application of the models, in particular the LEAP model, required a detailed representation of the structure of energy supply and demand, as well as the identification of specific mitigation measures. To this end, a series of measures, plans, and actions were analyzed, that the Secretariat of Energy and the Secretariat of Environment and Sustainable Development of Argentina are currently studying at the national level, with different degrees of detail.

Table 2
Net present value methodology results for identification of measures to be included in carbon price scenarios.

Costs – Billion 2005 U.S. Dollar. discounted at 5.0% to year 2010.	Demand side measures						Supply side measures				
	Biofuels	Ecodriving freight and public transport	Freight from truck to train	Thermal efficiency in residential buildings	Hybrid cars	Solar Water Heaters	Hydroelectric plants	Wind Power	Combined cycle	Probiomasa	Nuclear
Demand											
Residential	0	0	0	8.8	0	0.2	0	0	0	0	0
Transport	0	0.05	1.9	0	2.3	0	0	0	0	0	0
Transformation											
Electricity selfproduction	0	0	0	0	0	0	0	0	0	2.91	0
Electricity utilities	0	0	0.56	−0.05	0	0	3.52	1.39	−2.34	−2.2	4.68
Biodiesel plants	0.52	−0.04	−0.04	0	0.01	0	0	0	0	0	0
Ethanol destillery	0.09	−0.01	0	0	−0.01	0	0	0	0	0	0
Resources											
Production	92.43	−9.53	−6.86	−1.35	0.27	0	1.03	−0.12	3.79	−2.9	0.76
Imports	−34.8	−23.04	−11.78	−3.24	3.58	0	−0.54	−3.67	22.6	−8.59	−7.42
Exports	−10.12	−1.83	0.12	0.22	−5.78	−0.18	0.76	−0.09	−0.18	−1.51	1.56
Environmental externalities (low CO_2 price)	−1.14	−0.95	−0.38	−0.26	−0.06	−0.02	−1.89	−0.34	−1.13	−0.48	−1.99
Net Present value (low CO_2 price)	46.98	−35.35	−16.48	4.12	0.31	0.0	2.88	−2.83	22.74	−12.77	−2.41
Environmental externalities (high CO_2 price)	−5.71	−4.74	−1.88	−1.3	−0.28	−0.1	−9.46	−1.7	−5.63	−2.39	−9.96
Net present value (high CO_2 price)	42.41	−39.14	−17.98	3.08	0.09	−0.1	−4.69	−4.19	18.24	−14.68	−10.38

in the household sector, refrigerator efficiency labeling regulations, phasing-out of incandescent light-bulbs for street lighting, and efficiency labeling in air conditioning devices (Baragatti, 2012; Furfaro, 2013). This scenario should be considered an academic exercise as there is no official baseline for Argentina's energy sector.

In the *Policy baseline* scenario, eleven mitigation measures (demand and supply sides) were selected based on the criteria outlined above. The measures have the highest implementation feasibility (based on the technological soundness for Argentina), and on which there is some prior research or preliminary estimate that assisted determination of the associated costs and emission-reductions potential (Baragatti, 2012; CABA, 2009; FVS, 2013; Furfaro, 2013; Gil et al., 2011; IDEHAB, 2006; Paisan, 2006; FAU, 2006). Although a policy 'baseline' scenario, it in fact represents a scenario with a relatively high level of ambition. Assumptions concerning the phasing in of mitigation measures were made based on authors' expertise. The measures defined for this scenario are listed in Table 1 below.

The *CO_2 price scenarios* were constructed by including the fixed price path per ton of CO_2e (carbon tax) as defined by the CLIMACAP-LAMP scenario protocol (described above) as a real cost for each of the measures. Only those measures (from the 11 considered in the Policy baseline scenario) that have a net present value less than or equal to zero, with respect to the Core baseline scenario, were then included as they bring a net benefit to society (see Table 2 below). The implications of this approach is that in the Low CO_2 price scenario only 3 mitigation measures for the final demand sector and 3 measures for the electricity generation sector are considered (highlighted in green in Table 2). In the High CO_2 price scenario, the same measures are included as in the Low CO_2 price scenario, with the addition of hydropower expansion which is incentivized by the higher CO_2 price.

The *20% abatement (GHG)* scenario sets an objective of 20% reduction of GHG emissions in the energy sector by 2050, with respect to 2010. The pathway to reaching the reductions target is not prescribed in the scenario definition. In order to reach this target, the scenario includes a higher penetration level for the measures considered in the Policy baseline scenario, and additional measures (penetration of electricity for cooking, water heating and heating in residential and commercial sectors; decreasing useful energy intensity while keeping constant the efficiency for steam and direct heat uses in industry). On the supply side, this scenario also incorporates the implementation of carbon capture and storage technology (CCS). This scenario is a highly theoretical exercise as there is a lack of information for assessing the implementation feasibility of many of these mitigation measures.

A summary of the different demand and supply measures considered in each of the scenarios is presented in Table 3 below.

3. LEAP model results

3.1. Primary energy

In all five scenarios (Core baseline, Policy baseline, Low CO_2 price, High CO_2 price and 20% abatement) a significant growth in primary energy demand is recorded by the year 2050. In the Core baseline, it grows from 3.5 EJ in the base year to 9.9 EJ by 2050. This can be accounted for mainly by the assumed growth in demand sectors considered in the socio-economic scenario, among them the increase in industrial added value.[3] The relative difference in primary energy demand across Core baseline, Policy baseline, Low CO_2 price and High CO_2 price by 2050 scenarios is not very significant, as shown in Fig. 1: 5.8% across the Core baseline and Policy baseline scenarios, 1.4% across the Low CO_2 price scenario and 0.4% across High CO_2 price scenario by 2050.

[3] In the framework of the present study a socio-economic scenario was developed which states an inter-annual rate for GDP of 3.1% and for the industrial sector 3.3% per year, during the period 2010–2050.

Table 3
Summary of demand and supply side measures included in each of the scenarios.

	Demand side measures										Supply side measures						
	Pre-2010 measures	Eco-driving	Biofuels	Thermal efficiency	Truck to train	Hybrid cars	Electric cars	Solar water heaters	Increased electricity penetration	Industry measures	Pre 2010 measures	ProBiomass	Hyrdo power	Wind	Nuclear	Combined cycle	CCS
Core baseline	✓										✓						
Policy baseline	✓	✓	✓	✓	✓	✓		✓			✓	✓	✓	✓	✓	✓	
Low CO_2 price	✓	✓			✓			✓			✓	✓		✓	✓		
High CO_2 price	✓	✓			✓			✓			✓	✓	✓	✓	✓		
20% abatement (GHG)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

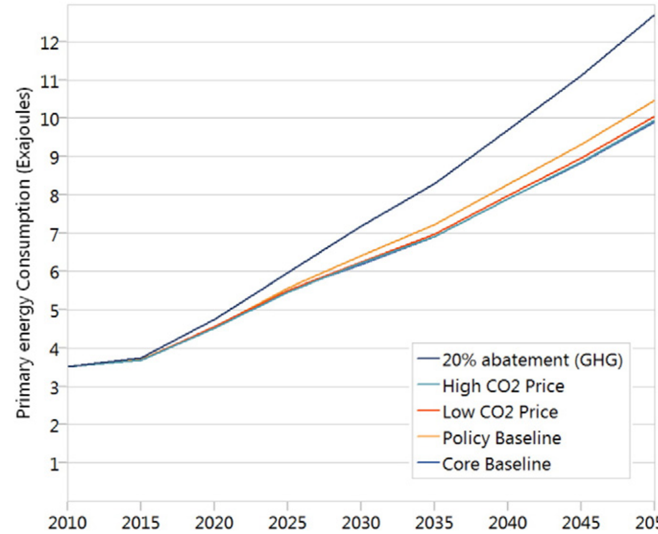

Fig. 1. Primary energy consumption in Argentina for the five CLIMACAP-LAMP scenarios.

The 20% abatement scenario has a higher primary energy demand than the rest of the scenarios, mainly due to the significant penetration of biofuels and an electricity generation matrix strongly based on biomass energy resources with lower conversion efficiency, as well as decreased electricity generation efficiency due to CCS technologies. The increase in primary energy demand from the Core baseline to the 20% abatement (GHG) scenario by 2050 is 28.3%.

Regarding the structure by fuels, Fig. 2 shows that the main difference between the Core baseline and Policy baseline scenarios is a lower share of coal in the Policy baseline scenario, and an increase in nuclear and renewable energies (mainly biomass). In the Low CO_2 price and High CO_2 price scenarios, the restriction based on the price of CO_2 produces differences mainly relative to the Core baseline, regarding the share of nuclear (which increases in both scenarios) and coal (which decreases in both scenarios). The 20% abatement (GHG) scenario presents the most significant variation in the primary sources structure compared to any of the other four scenarios. Biomass increases significantly and, to a lesser extent, wind and solar energy, while that of natural gas and oil is reduced. Coal maintains a similar share to that obtained in the Core baseline scenario (since it is a cheap fuel and the 20% abatement scenario includes carbon capture technology). By the year 2050, the 20% abatement (GHG) scenario reaches a 22.2% and 3.1% share for biomass and wind energy respectively, tripling their share with respect to the Policy baseline scenario.

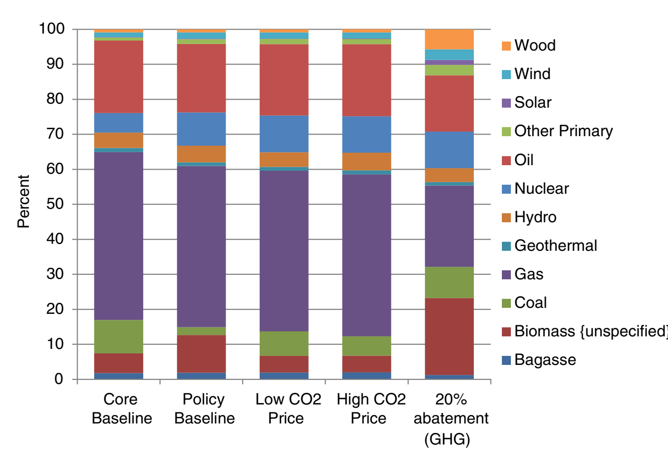

Fig. 2. Breakdown of primary energy consumption in Argentina by resource in 2050 for the five CLIMACAP-LAMP scenarios.

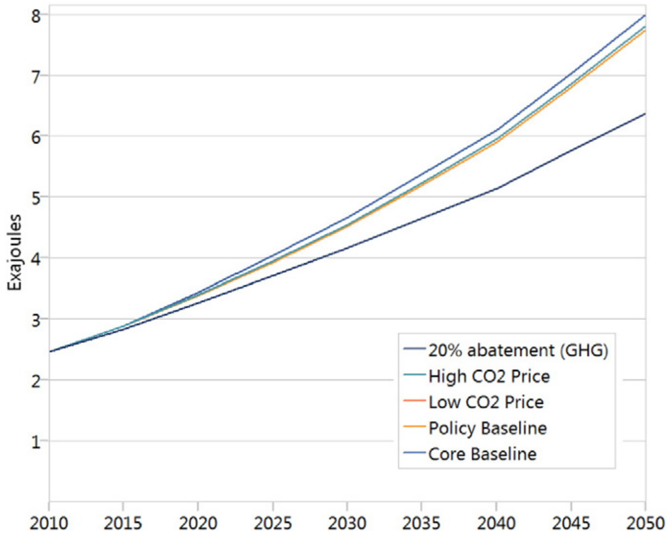

Fig. 3. Final energy demand by scenario.

In the Core baseline, Policy baseline, Low CO_2 price and High CO_2 price scenarios, the most significant share in primary energy demand is that of natural gas, followed by oil, with 48.0% and 20.7% of the total primary energy by 2050 in the Core baseline scenario, respectively. In the 20% abatement scenario, the most significant share corresponds to biomass (bagasse, wood and other biomasses), closely followed by natural gas and oil. Fossil fuels reach a minimum share of 48.4% in the 20% abatement scenario, and a maximum of 78.2% in the Core baseline scenario. The share of renewable fuels reaches its minimum amount in the Core baseline scenario, with 16.2%, and it reaches around 16.3% in Low CO_2 price, 17.2% in High CO_2 price scenario, 22.7% in the Policy baseline scenario, and 41.3% in the 20% abatement scenario.

3.2. Final energy demand

Final energy demand grows from 2.5 EJ in the base year to 8 EJ in the Core baseline scenario by 2050 (Fig. 3). The Policy baseline scenario reduces final energy demand by 3% by the year 2050 relative to the Core baseline scenario. Increasing the penetration of these mitigation measures and including new measures in the 20% abatement scenario reduces the final energy demand by 20.2% by the year 2050 relative to the Core baseline scenario. The Low CO_2 price and High CO_2 price scenarios are comparable from the perspective of final energy demand, and record intermediate values of energy demand reduction relative to the Core baseline scenario.

The contribution to final energy demand reduction of each of the measures under consideration in the Policy baseline scenario, relative to the Core baseline scenario, is shown in Fig. 4. The most significant reduction results from introducing eco-driving measures in public and freight transport (52% of the total reduction by the year 2050), followed by change of freight transport mode from truck to train (22%), thermal efficiency in residential buildings (20%), and hybrid gasoline cars (6%). Both biofuels and solar water heating measures do not result in significant reductions in final energy demand compared to the core baseline scenario since they are mainly fuel switching measures.

Regarding the contribution of each demand sector to the reduction of final energy demand by 2050 relative to the Core baseline scenario, in the Policy baseline scenario 79% of energy savings result from measures in the transport sector, and 21% have to do with measures in the household sector (heating). When considering the CO_2 price scenarios (Low CO_2 price and High CO_2 price), 100% of energy savings are the result of measures in the transport sector. Finally, in the 20% abatement scenario, mitigation measures in the transport sector explain 51% of the reduction in final energy demand, industry 27%, and residential 20%.

The variation in final energy demand fuel share across the different scenarios relative to the Core baseline scenario is illustrated in Fig. 6. The reduction in final energy demand in the Policy baseline scenario is mainly related to diesel oil, motor gasoline, and distributed gas (with measures related to the use of biofuels, thermal efficiency and eco-driving). In the Policy baseline scenario there is a significant increase in biodiesel and ethanol demand (through the use of biofuels). In the Low CO_2 price and High CO_2 price scenarios, the reduction is much smaller than in the case of the Policy baseline scenario, and this is a consequence of the reduction in use of diesel oil and, to a lesser extent, biodiesel, distributed natural gas and motor gasoline (with measures having to do with eco-driving, freight from truck to train and solar water heaters). In the 20% abatement scenario the reduction in final energy demand is much larger than for the other scenarios; this is due mainly to a lower demand of distributed natural gas and diesel oil, and to a lesser extent to gasoline. Conversely, in the 20% abatement scenario the penetration of biodiesel, electricity, biomass

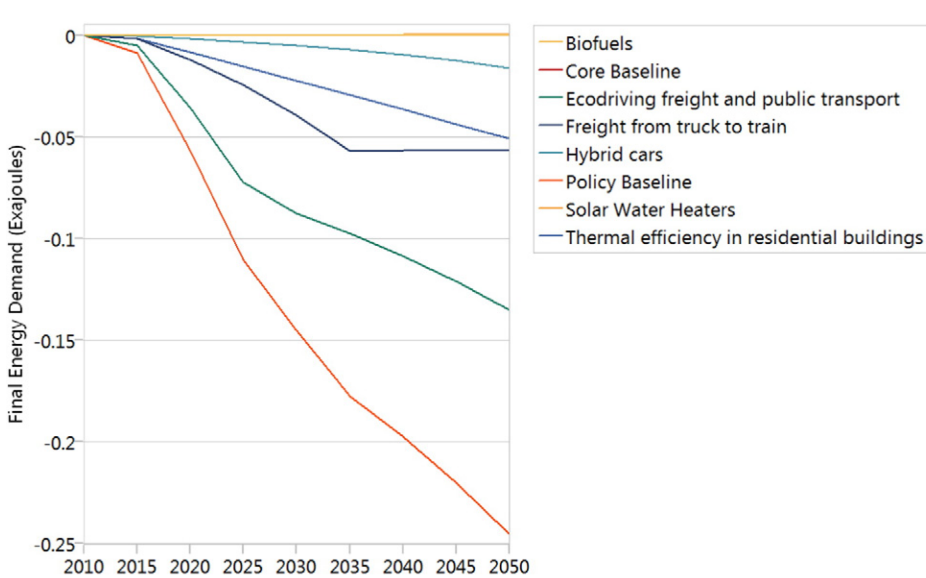

Fig. 4. Final energy demand by mitigation measure in Policy baseline scenario relative to the Core baseline scenario.

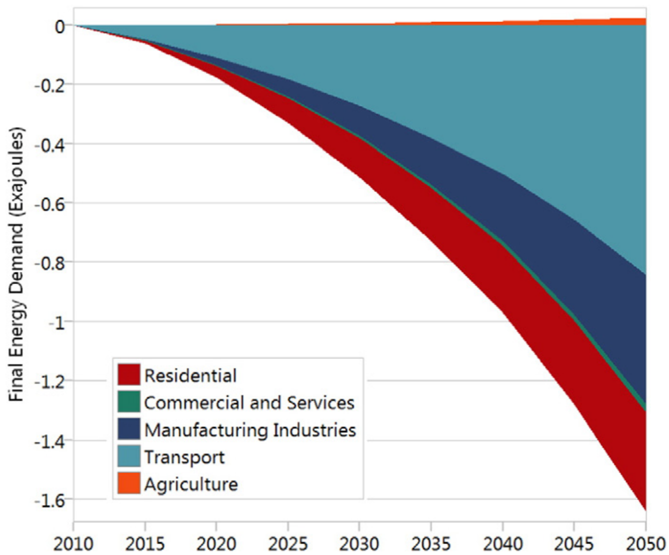

Fig. 5. Final energy demand by sector in 20% abatement scenario relative to Core baseline scenario.

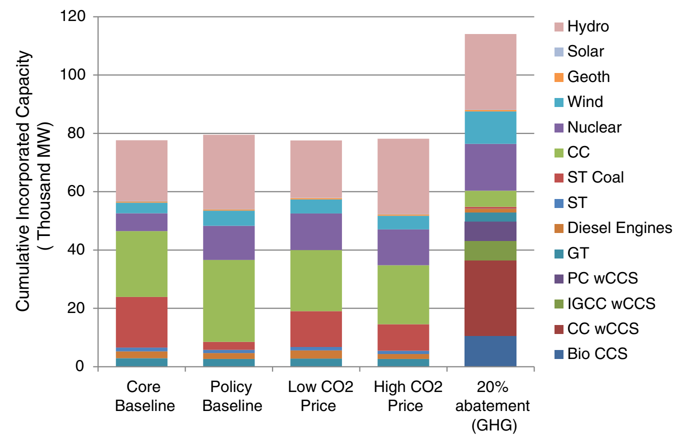

Fig. 7. Cumulative Incorporated Capacity by scenario between years 2010 and 2050 (CC: natural gas – diesel dual firing combined cycle, ST Coal: coal fired supercritical fluidized bed, ST: residual fuel oil fired steam turbine, PC: pulverized coal supercritical w/CCS, IGCC: coal gasified combined cycle w/CCS, CC: natural gas fired combined cycle w/CCS, Bio: wood fired supercritical steam turbine w/CCS).

and solar energy (solar water heaters) is strongly increased. (See Fig. 5.)

3.3. Electricity production

The resulting power generation mix across the scenarios differs somewhat, in particular in the 20% abatement scenario. As can be seen in Fig. 7, in the Core baseline scenario capacity expansion is based on a balance between natural gas-diesel oil dual fired combined cycle plants (CC, with 29% share of cumulative installed capacity), hydro plants (27%) and supercritical fluidized bed coal fired plant (ST, Coal 22%). Nuclear power plants (8%), wind (5%), gas turbines (4%) and diesel generators (3%) account for smaller percentages. On the other hand, the Policy baseline scenario diversifies capacity expansion by boosting hydro, nuclear and combined cycle plants, reducing thus the dependence on coal that is strongly present in the Core baseline scenario. The largest capacity expansion corresponds to combine cycles (with 35% share of total incorporated capacity up to 2050), followed by hydro plants (32%), nuclear plants (15%) and onshore wind farms (6%), leaving the share of the rest of the technologies practically unchanged in the expansion portfolio.

The 20% abatement (GHG) scenario leads to electric capacity additions that are all low-emitting or non-emitting technologies (CCS, nuclear and renewables), covering up to 94% of the total additions and accounting for a reduction in the emissions of 115% compared to the Core baseline scenario, making the electricity sector a sink for CO_2 emissions. The simulated 20% abatement scenario includes CC w/CCS and coal fired PC w/CCS in the short and midterm (starting with incorporations of new plants in 2018 most intensively based on the CC type). From 2030 new capacity includes both Bio CCS (firing wood) and IGCC coal fired plants in addition to CC w/CCS in a proportion of about 25%, 20% and 55% of the additions, respectively. CCS technologies were not included in the other scenarios, as they are extremely unlikely to be rolled out in the midterm in Argentina – they were included in this scenario, however, as there was no other means to reach the target without this technology. The use of CCS technologies diminishes the overall efficiency of electricity generation leading to an increase in fuel use for electricity generation. In addition, the capacity factor of the combined cycles is constantly decreasing along the years from an average of 60% in the year 2010, reaching 35–40% in 2050, but those plants were mostly the old ones which had an important role in the first years of the scenario where the electricity generation was based mostly on natural gas.

In the scenarios that consider the implementation of a carbon tax (Low CO_2 price and High CO_2 price scenarios), natural gas combined cycles (CC) are not included as base load plants to the same extent as implemented in the Policy baseline scenario, where this technology displaces almost all coal fired plants in base load generation. The rapidly growing natural gas price trend for Argentina and the low discount

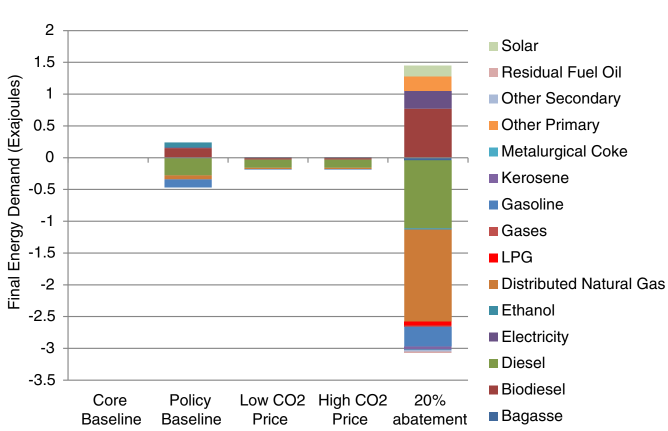

Fig. 6. Final energy demand by fuel relative to Core baseline scenario in 2050.

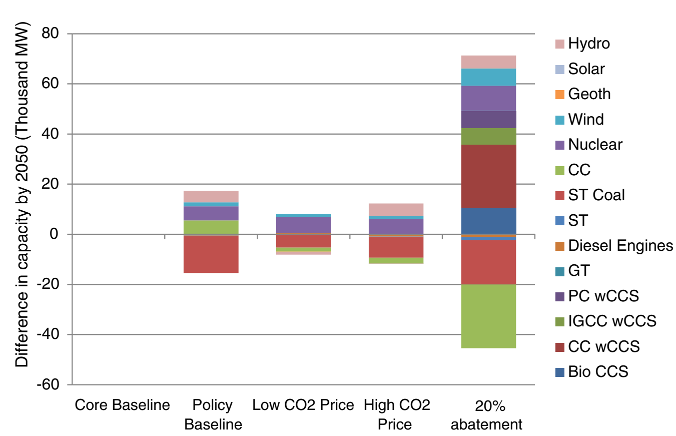

Fig. 8. Difference in installed capacity by 2050 relative to the Core baseline scenario.

Table 4
Share of accumulated electricity capacity additions by technology and scenarios up to 2050.

	Share of Accumulated Electricity Capacity Additions by Technology and Scenario up to 2050								
Scenario/Technology	Hydro	Wind	Nuclear	CC dual[a]	Coal[b]	Coal wCCS	IGCC wCCS	CC wCCS	Biomass wCCS
Core baseline	27%	5%	8%	29%	22%	0%	0%	0%	0%
Policy baseline	32%	7%	15%	35%	3%	0%	0%	0%	0%
Low CO2 price	25%	6%	16%	27%	16%	0%	0%	0%	0%
High CO2 price	33%	6%	15%	26%	12%	0%	0%	0%	0%
20% abatement	23%	10%	14%	5%	1%	6%	6%	23%	9%

[a]Combined cycle dual fired, mostly used with natural gas but sometimes with diesel oil.
[b]Supercritical coal fired.

rate of 5% used in this study results in an unfavorable cost-benefit ratio for the replacement of coal fired generation with natural gas, even under the High CO_2 price scenario. In other words, the present value of costs that would arise from the replacement of coal by natural gas is bigger than the carbon tax penalties to the higher emissions of coal fired plants.

Conversely, nuclear and wind capacity are sufficiently incentivized by the Low CO_2 price scenario and the implementation of hydro power plants is incentivized by the higher High CO_2 price scenario carbon prices. Fig. 8 below compares the installed capacity by the year 2050 in each scenario, relative to the Core baseline scenario.

We can see that there is an important reduction in coal fired plants installed capacity in the Policy baseline and 20% abatement scenarios, and this trend is more moderate in Low CO_2 price and High CO_2 price scenarios, as the installation of base load natural gas combined cycles is not as interesting in terms of cost-benefit ratio, as mentioned above. This situation is summarized in Table 4, where the share of total capacity additions by technology and scenario for the whole period is presented.

As for the fuels used for electricity generation, there is a substantial difference across scenarios, mainly due to the lower amount of coal used in all of them compared to Core baseline scenario, as shown in Fig. 9 below. Likewise, it can be seen that there is an increase in all scenarios in the use of wind and nuclear energy, and an increase of hydro in the Policy baseline, High CO_2 price, and 20% abatement scenarios. In the 20% abatement scenario, however, coal consumption increases, due to the assumed availability of CCS supercritical coal fired plants as well as IGCC with CCS technologies, both using coal. Since in the 20% abatement scenario the electricity demand is 20% higher than in the Core baseline or Policy baseline scenarios (as a measure to improve end use efficiency and reduce emissions due the use of Bio CCS), the fuel consumption is noticeably higher. Additionally, the expanded use of CCS technologies in the 20% abatement scenario decreases the overall efficiency of electricity generation, leading to an additional increase in fuel use for electricity generation.

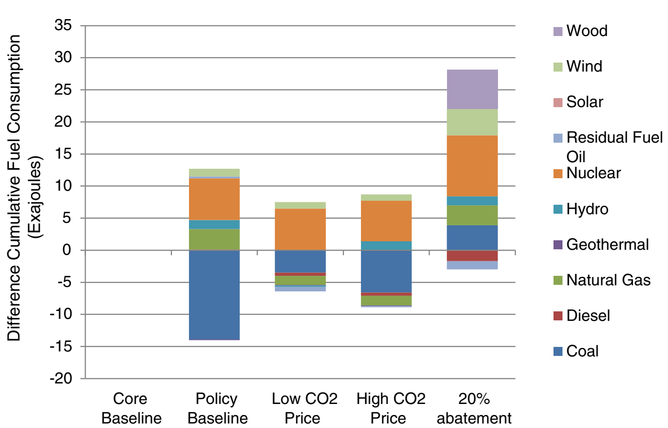

Fig. 9. Accumulated difference by 2050 in fuel use by scenario compared to Core baseline scenario.

3.4. GHGs emissions

For GHGs emissions, all the scenarios analyzed show sustained growth rates ranging between 3.0% p.a. (Core baseline scenario) and 2.6% p.a. (Policy baseline scenario), except in the case of 20% abatement scenario, where emissions increase only by 0.09% p.a.. The elasticity of the increase in these emissions relative to GDP growth (whose interannual rate for the period is 3.1%) reveals values ranging between 0.84 (Policy baseline scenario) and 0.97 (Core baseline scenario). Reduction of GHGs emissions in the Policy baseline scenario reaches around 16% by the year 2050, relative to Core baseline scenario. Avoided emissions accumulated over the period total 1.584 million tons of CO_2e, which is equivalent to ten times the energy sector emissions recorded in the year 2010.

Emission reductions by 2050 in the Low CO_2 price scenario are smaller than that in the Policy baseline scenario, and this implies an emission reduction of around 9% relative to the Core baseline scenario by the end year. Avoided emissions in this period total 782 million tons of CO_2e (which is equivalent to five times the energy sector emissions recorded in 2010), relative to Core baseline scenario. Emission reductions in 2050 of the High CO_2 price scenario relative to Core baseline scenario reaches 11.3%, and accumulated avoided emissions total 1.044 billion tons of CO_2e (which is equivalent to more than six times the energy sector emissions recorded in 2010).

In the 20% abatement scenario, emissions in 2050 are 68% lower than that of same year in the Core baseline scenario; while the accumulated avoided emissions in the period 2010–2050 reach 5.152 billion tons of CO_2e, equivalent to thirty-three times the energy sector emissions recorded in 2010. CO_2 emissions are reduced in 2050 by 4.5% from 2010, through the inclusion of measures considered in the Policy baseline scenario for final demand sectors, and the incorporation of additional measures for final demand and electricity generation. However, the total level of GHGs emissions (Fig. 10) increase moderately, by 3.8% in 2050 above the level of emissions in 2010.

It is important to note that the penetration levels proposed for technologies such as CCS and BioCCS in the 20% abatement scenario reach the maximum theoretical potential[4] for Argentina for each of these technologies and practices; but these levels are not derived from a detailed analysis of the barriers (financial, political, technical) that could hinder their implementation. Without such an analysis, it is more prudent to consider that the implementation of these measures has a limited viability in the Argentinean context.[5] This scenario is presented for illustrative purposes and shows the difficulty of

[4] Own estimations, based on available biomass resources in Argentina (FAO, 2009).
[5] For example, implementing generation systems based on biomass requires a detailed analysis of the logistics and the spatial and temporal distribution of the available resource, which has not been carried out for the country.

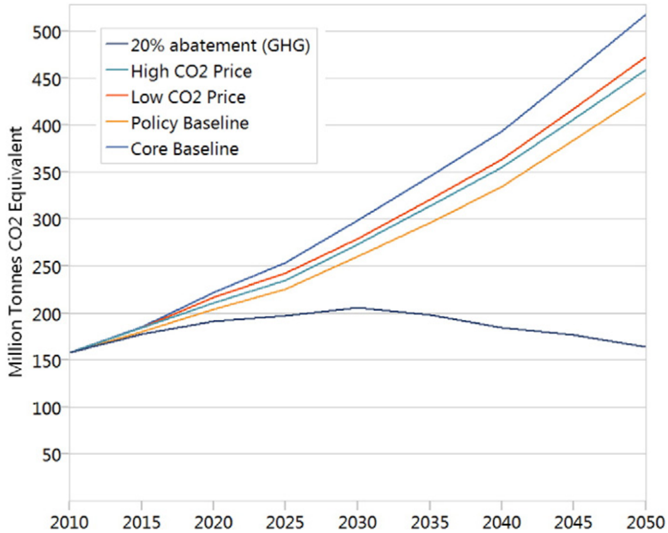

Fig. 10. CO_2e emissions in Argentinean Energy Sector under different scenarios.

posing, for a developing economy, emission-reduction targets comparable to those of developed economies.

In the electricity sector, the Policy baseline scenario could reduce accumulated electricity generation emissions by about 1 billion tons of CO_2e up to 2050, which means reaching 62% of the accumulated electricity sector emissions of the Core baseline scenario. In the 20% abatement scenario the electricity sector presents absolute negative values for the emissions (due to Bio CCS technology). Accumulated emissions savings in this scenario compared to the Core baseline scenario are 2.44 billion tons of CO_2e. This situation makes it possible to reach emissions for the whole energy sector by 2050 that are practically equivalent in absolute value to those of 2010. (See Fig. 11.)

3.5. Costs

The accumulated incremental costs of each scenario, compared with the Core baseline scenario, are presented in Table 5 below. In the Low CO_2 price and High CO_2 price scenarios the largest incremental costs are related to the transformation sector; while in the Policy baseline and 20% abatement scenarios, they are related to the demand sectors.

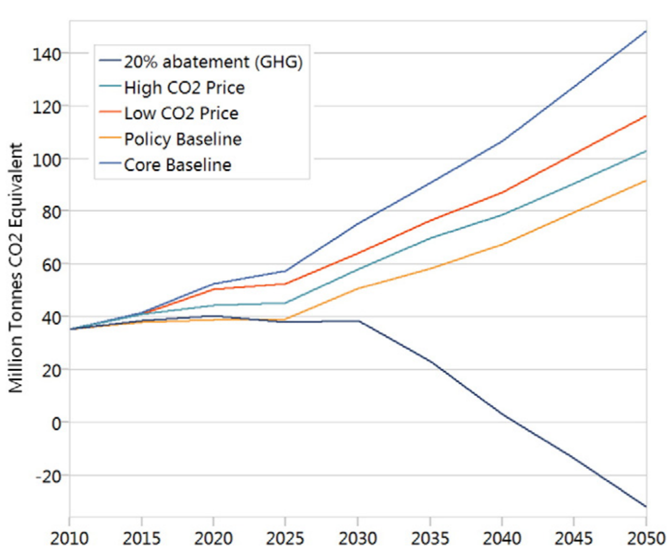

Fig. 11. Total emissions from electricity generation in all scenarios (only electricity).

In this last scenario, the emphasis is on investments to be made in the transport sector, linked mainly to the penetration of hybrid and electric vehicles. There is a cost per ton of avoided emissions in the Policy baseline and 20% abatement scenarios (14.4 and 44.6 US$/ton CO_2e avoided, respectively). However, in the case of the Low CO_2 price and High CO_2 price scenarios these costs are negative, as certain measures (such as eco-driving and freight from truck to train) have incremental costs that become negative when a carbon tax is applied.

In the Low CO_2 price and High CO_2 price scenarios less domestic production of primary resources and energy imports are required and therefore a negative cost is observed relative to the Core baseline scenario. A higher carbon tax in the High CO_2 price scenario leads to a lower benefit per unit CO_2 avoided, compared to the Low CO_2 price scenario due to the adoption of some electricity generation technologies (particularly hydro power plants) which have a higher cost than coal plants.

It can then be concluded that, despite considering price paths for CO_2, and following a strictly direct cost-benefit analysis criterion[6] for choosing the measures, the emission-saving potential in Argentina of CO_2 price scenarios is lower relative to the Policy baseline scenario. Consequently, choosing mitigation measures solely on the basis of a direct cost-benefit criterion, under these specific CO_2 price paths, implies that some measures may not be implemented because they imply net positive costs. Under these circumstances, measures that could have a positive economic impact on the rest of the economy are not included as the wider economic benefits, such as reducing unemployment, the health impacts benefits of cleaner renewable fuels, the diversification of the electricity matrix and security of supply, are disregarded as the economic benefits of these measures are not fully captured. An example of this could be the implementation of measures meant to improve thermal efficiency in residential buildings, which could lead to the development of a national industry and the creation of new materials and techniques produced for the domestic market, with the associated positive impacts this might have on the rest of the economy. Another example is the case of biofuels. Under the direct cost-benefit criterion, encouraging a higher penetration of biofuels in Argentina would not be feasible; however, the projects already implemented in the country have generated indirect benefits in regards to job creation, reduction of diesel imports, and improvements in security of supply, that a direct cost-benefit criterion is not considering (Bariloche Foundation, 2013).

In the electricity sector, the change between Core baseline and Policy baseline scenarios is the result of the implementation of supply diversification measures, requiring an incremental investment of 16.1 billion US$(2005) relative to Core baseline scenario. Such an estimate results from the comparison of accumulated cost overruns deriving from the implementation of the measures meant to reduce expansion based on coal and natural gas along the period 2010–2050 when no carbon tax is considered. These additional costs could be disaggregated into US$8.4 billion (2005) related to capital costs of capacity additions and US$7.7 billon (2005) related to the use of more expensive fuels (mostly natural gas replacing coal). The 20% abatement scenario implies an incremental investment effort of around US$55 billon (2005) above the Core baseline scenario. The greatest share of this economic effort falls on capital investments, reaching US$46.6 billion (2005).

4. Cross-model comparison

In this section, we offer another perspective on the results from the LEAP model through a cross-model comparison involving two integrated assessment models, TIAM-ECN and GCAM. TIAM-ECN and GCAM are partial equilibrium, optimization/market-equilibrium models, which vary considerably not only with LEAP (simulation model), but also between themselves, in terms of the objective function, technological detail,

[6] This implies the exclusion of indirect effects on the rest of the economic system (spillover effects), or the existence of so-called market failures regarding prices.

technological cost and availability, demand representation, amongst other aspects. The different methodologies and approaches to the scenarios lead to different responses to carbon prices and energy policy in terms of energy structure.

As was stated in Section 2, the LEAP model considered a limited set of mitigation measures. By contrast, TIAM-ECN and GCAM models consider a larger set of potential mitigation measures. As such, the LEAP results could thus be interpreted as a lower estimate for the emissions reductions potential (and perhaps more cognizant of current policy directions and politico-economic constraints), whereas TIAM-ECN and GCAM represent a theoretical upper estimate that could be achieved with available technologies under specific economic conditions.

Such a comparison also permits a deeper understanding of the functionality of the models, the drivers of uncertainty associated with projections, and as such the limitations of the models and their respective outputs. For detailed model descriptions of the integrated assessment models we refer to publications by their respective modeling teams: TIAM-ECN (Rösler et al., 2014; van der Zwaan et al., 2013a,b) and GCAM (Calvin et al., 2011).

This cross-model comparison aims to examine the differences across models in key input parameters and results, including the evolution of GDP, population, primary energy, final energy, electricity supply breakdown, and CO_2 emissions. The cross-model comparison will focus on the Core baseline scenario and high carbon tax growth path (High CO_2 price scenario). A brief examination of the key differences of the 20% abatement scenario with respect to the High CO_2 price scenario across the different models follows this analysis.

4.1. GDP and population

For two key parameters, GDP and population growth, there is very little variation between the models (see Fig. 12). LEAP and TIAM-ECN use the same data sources for these variables. There is no variation between the scenarios as these variables are exogenous to the models. We refer to van Ruijven et al. (2016–in this issue) for a detailed description of sources of data and harmonization of the models.

4.2. Primary energy

In terms of primary energy (see Fig. 13), there is good consistency between TIAM-ECN and GCAM, however these models both have approximately 2.1–2.9 EJ less primary energy demand in 2050 compared with LEAP in both scenarios. This absolute difference is largely attributable to a difference in final energy, which is explored in the next Section (4.3).

In LEAP no change in energy consumption is observed in the carbon tax scenario. By contrast, the application of a carbon tax in TIAM-ECN results in a decrease of approximately 14% compared to the baseline scenario by 2050, due to a shift from fossil fuels to RE in the energy supply sector, energy savings as well as an uptake in energy efficiency measures in energy consumption. Similarly in GCAM, the carbon tax results in approximately a 4% decline in energy consumption in 2050 as the carbon tax increases the cost of energy, driving down demand. GCAM exhibits an upward sloping development due to a significant uptake of CCS, which has lower efficiency compared to non-CCS energy conversion technology.

4.3. Final energy

A 1.9–3.5 EJ difference in final energy (see Fig. 14) is observed in both scenarios in 2050 between the integrated assessment models (TIAM-ECN, GCAM) and LEAP, despite the fact that GDP and population development are largely harmonized. These differences arise due to different expectations regarding demand growth and efficiencies, including differences in efficiency developments over time in the baseline scenario.

There is general agreement across models that a reduction in final energy demand under the carbon tax scenario is to be expected, although the impacts are less pronounced for the LEAP model. This is largely due to the integrated assessment models introducing a real energy system wide carbon tax, whereas in LEAP only specific measures with negative Net Present Value (NPV) are included. The main drivers for a reduction in final energy under the carbon tax scenario in TIAM-

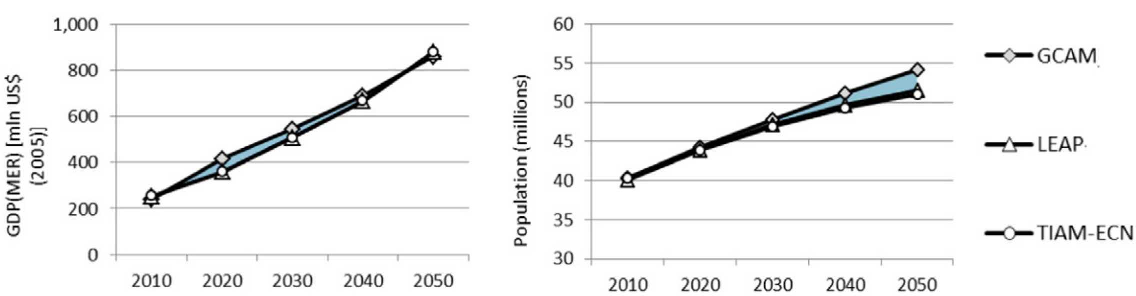

Fig. 12. Evolution of GDP (left) and population (right).

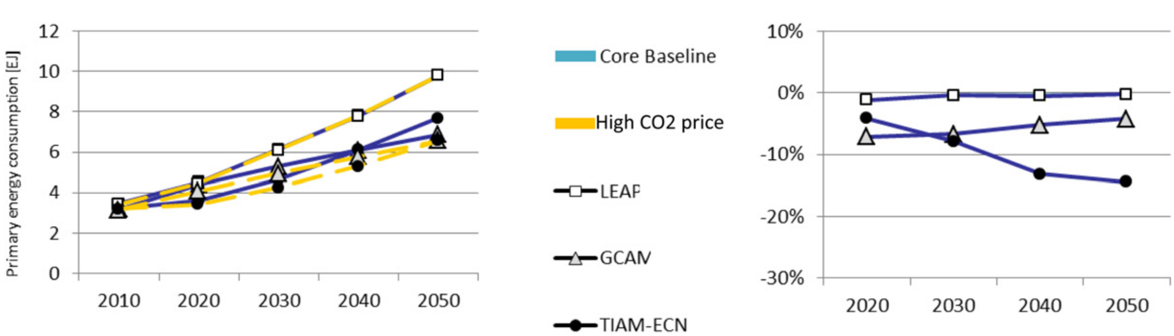

Fig. 13. Absolute primary energy consumption in core baseline and carbon tax (High CO_2 price) scenarios (left), as well as variation over time between core baseline and carbon tax scenario (right).

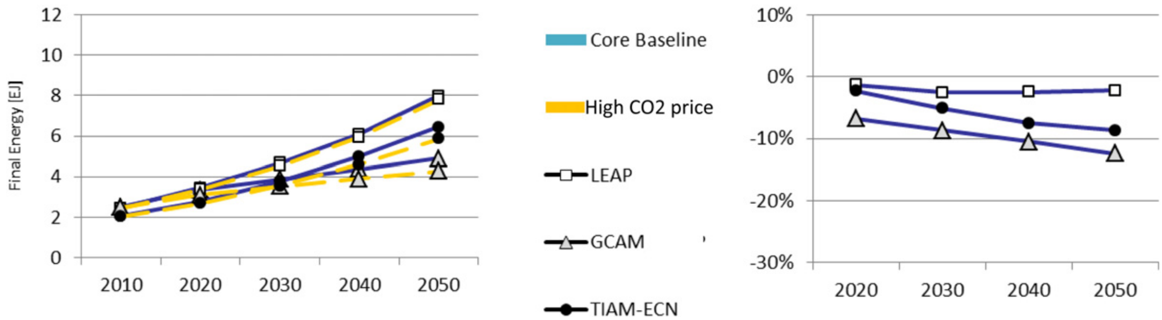

Fig. 14. Absolute final energy variations across models in the core baseline and High carbon tax scenarios (left), and % variation in the same scenarios (right).

ECN is due to a shift towards electricity, which has a greater efficiency, and which also contributes towards a reduction in final energy consumption. Also in the transport sector under TIAM-ECN, more efficient engines lead to lower final energy consumption. For GCAM, the reduction is price-induced, as it was with primary energy, and includes both shifts to more efficient energy carriers and reductions in demand.

4.4. Electricity generation

The baseline electricity generation mix is relatively similar until 2030, but between 2030 and 2050 a large divergence is seen in the models (see Fig. 15). In the core baseline scenario in 2050, the total electricity generation projected is relatively consistent between the models. None of the models have nuclear generation playing a significant role. Aggregate fossil fuel generation (oil, gas, coal) in the baseline is also fairly consistent, with approximately 60–80% of electricity generated from fossil fuels in all three models in 2050. The major variation in the baseline scenario is in the level of coal, and renewable energy production. LEAP contains larger shares of coal in the baseline scenario, whereas TIAM-ECN and GCAM foresee a gas dominated power sector. LEAP also foresees greater hydro power utilization than the integrated assessment models. GCAM is more optimistic about non-hydro renewables than the other two models. LEAP imposes a limit on natural gas expansion that the integrated assessment models do not. Reasons for the divergence include different assumptions on imports, domestic production, global coal availability, prices, amongst others.

In the carbon tax scenario, the models react in markedly different ways. Whereas LEAP shows mainly a shift from coal to wind, nuclear, hydro and oil; TIAM-ECN predicts increased coal with CCS, renewables (in particular solar PV), and energy efficiency measures, whereas GCAM sees a significant role for CCS, in particular biomass with CCS. GCAM also finds that with higher carbon prices that it is easier to decarbonize electricity than other fuels, so end-users switch to electricity in these scenarios driving up demand. The models all agree that absolute and proportional shares of aggregate fossil fuel generation decline under the carbon tax.

4.5. CO_2 emissions from fossil fuel combustion and process related industrial emissions

Baseline emissions (see Fig. 16) are reasonably consistent between LEAP and TIAM-ECN, with each model showing 513 and 532 Mt CO_2 per year by 2050 respectively. This is more than a doubling of emissions from 2010. GCAM has a lower amount of 363 Mt CO_2 per year by 2050. There is a significant variation in the resulting CO_2 emissions between the models in the high carbon tax scenario (High CO_2 price). Emissions under the LEAP model are reduced by 64 $MtCO_2$ per year by 2050 (11.3% reduction compared with baseline scenario), TIAM-ECN predicts approximately 202 Mt CO_2 per year reduction (37%), and GCAM foresees emissions being driven to almost zero (94.5% reduction).

Firstly, comparing LEAP with TIAM-ECN, the general trend is similar, however under TIAM-ECN greater energy savings and efficiency measures are introduced, as reflected by lower primary energy consumption in the High CO_2 price scenario, and a stronger decline in fossil fuel use in TIAM-ECN between the two scenarios. Due to a different methodological approach and model, a more pronounced demand response in TIAM-ECN can be seen compared to LEAP under this scenario. For example, in the industry sector TIAM-ECN shows under the carbon tax scenario a reduction in final energy in the industry sector of approximately 7%, whereas LEAP does not consider any changes.

Comparing LEAP with GCAM, the significant deployment of CCS enabled by high a carbon tax (High CO_2 price scenario) in GCAM results in much lower CO_2 emissions than in LEAP. GCAM has fairly optimistic assumptions about the cost of CO_2 capture and the availability of CO_2

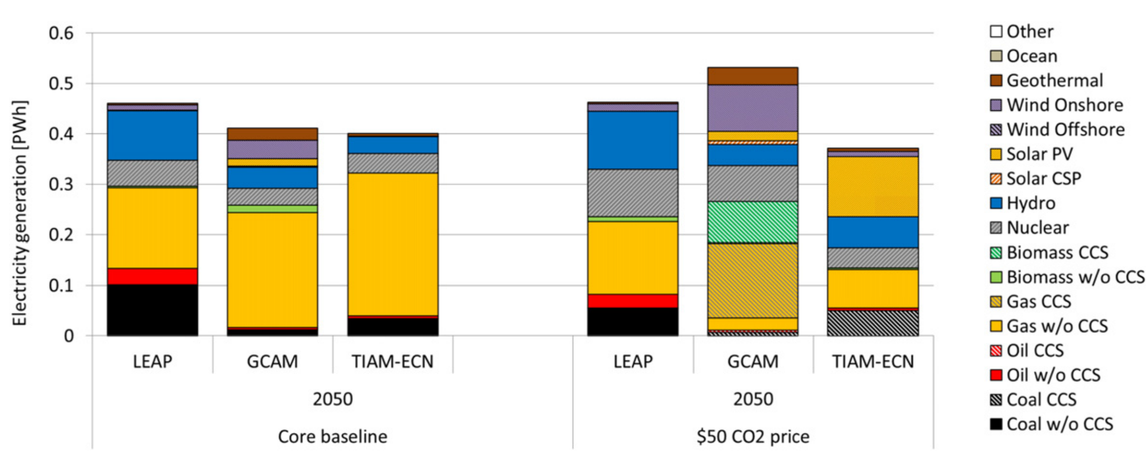

Fig. 15. Electricity generation mix under core baseline and High CO_2 price scenarios in 2050.

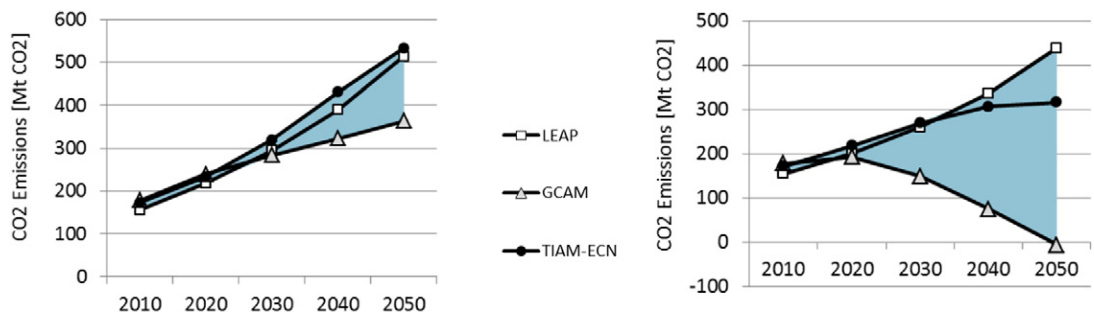

Fig. 16. Energy and industry emissions under core baseline (left) and High carbon tax (right) scenario.

storage reservoirs. Additionally, GCAM allows for global trade of bioenergy, thus Argentina does not have to produce all of its energy locally. These assumptions allow the model to deploy CCS on fossil fuels and biomass with CCS at a large scale, generating negative emissions in the electricity sector. Electrification of the energy demand sectors, such as transport, residential, commercial, and industry, contributes to their decarbonization.

4.6. 20% Abatement (GHG) scenario

In the 20% abatement (GHG) scenario, the models describe pathways to achieve a 20% emissions reduction, compared with 2010 emissions (see Fig. 17). Although LEAP does not reach this target (increase of 3.8% compared to 2010, see Section 3.4), it includes ambitious reductions, comparable to TIAM-ECN and GCAM results in this scenario, and as such there are some useful insights to be found from comparing the results despite this limitation, in that the models seek to significantly reduce emissions by a similar order of magnitude.

Under the 20% abatement scenario, with exogenous GDP and population growth, the integrated assessment models react in a similar manner to the High CO_2 price scenario in terms of primary energy and final energy curtailment (whereas LEAP increases primary energy consumption by almost 30%). For GCAM, this is not especially surprising, given that in High CO_2 price scenario the high carbon tax results in an almost complete decarbonization of the energy sector. This difference in behavior highlights, as for the High CO_2 price scenario, a stronger demand response of the integrated assessment models, as well as more optimistic efficiency gains.

Of particular interest in this scenario is the fundamental transformation of the electricity generation sector. In all three models, there is a significant deployment of CCS technology on conventional (fossil) energy sources, as well as an up-scaling of nuclear and wind in the case of LEAP. The continued importance of coal, natural gas and oil, even under this ambitious scenario, is consistent between the three models.

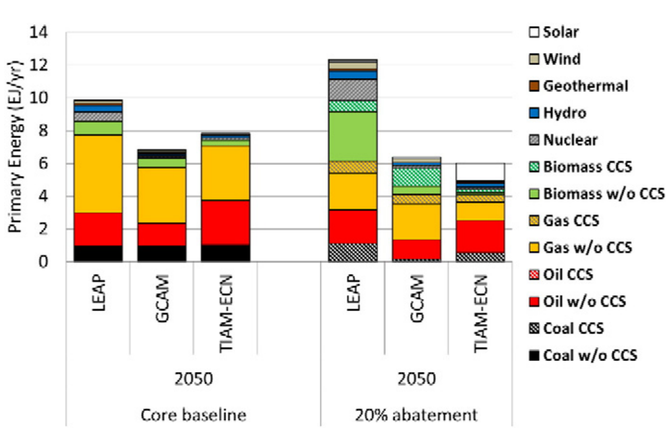

Fig. 17. Primary energy mix under core baseline and 20% abatement scenarios in 2050, described in terms share of primary energy sources.

5. Discussion, conclusions and policy implications

In this paper, in order to facilitate evidence based climate mitigation policy, the LEAP, TIAM-ECN and GCAM models were applied to evaluate the impact of a variety of climate change control policies on the energy sector of Argentina over the 2010–2050 period. A policy baseline, carbon price (low and high) scenarios, and an emissions abatement scenario were analyzed by the different models. The LEAP simulation model also described a highly policy relevant scenario (Policy baseline), in which Argentina implements the most feasible mitigation measures currently under consideration by official bodies and energy academic institutions. The results of this modeling exercise provides policy makers with relevant quantitative information on primary energy consumption, final energy consumption, electricity sector development, CO_2 emissions savings, amongst others.

Several key insights for the medium and long term (up to 2050) from the analysis can support effective policy making and strategy development, and the preparation of Argentina's INDC.

If the most feasible mitigation measures being considered by Argentina were implemented, they will have a strong mitigation impact compared to business-as-usual. According to the LEAP model, it was shown that the implementation of this set of mitigation measures, generates a CO_2e reduction potential of 16% compared to the business-as-usual scenario, at a total incremental economic cost of 22.8 billion US$(2005) to 2050.

Measures such as eco-driving in public and freight transport, and a freight transport mode change from truck to train, are cost-effective mitigation options even in the absence of ambitious climate control policy, according to the LEAP simulation. This means that even with a low carbon tax these measures generate environmental and economic benefits to society, and thus further analysis is recommended for eventual implementation.

There is a large range of variability in the predictions of the impacts of certain climate control policies. The comparison between TIAM-ECN and GCAM resulted in a large variation in emissions under the carbon tax scenarios. For these two models, this illustrates the challenges associated with long-term impact projections of carbon tax policy. Under a High CO_2 price, TIAM-ECN and GCAM models predict approximately 37% and 94% reductions by 2050 compared to the Core baseline scenario, respectively. These models typically assume advanced technologies are available at relatively low (nth of a kind) costs. Additionally, these models generally assume implementation and trade barriers are overcome, allowing a more rapid (or inexpensive) transition to a low carbon economy. In comparison, in LEAP an approach based on a limited set of mitigation options selected through a techno-economic analysis yielded more conservative results, with an 11.3% reduction by 2050 compared to business-as-usual under the same scenario.

Climate control policies will have a large impact on the penetration of some technologies, and little impact on others. In terms of technology pathways, the models all agree that natural gas will remain an important part of the electricity mix, however coal could play a more important

Table 5
Accumulated incremental costs relative to core baseline scenario. Period 2010–2050. Discounted at 5% in billion US dollars (2005).

Incremental costs relative to core baseline	Policy baseline	$10 CO_2 price	$50 CO_2 price	20% abatement (GHG)
Demand				
Residential	8.96	0.16	0.16	26.3
Commercial and Services	0	0	0	1.32
Manufacturing Industries	0	0	0	5.29
Transport	4.24	1.96	1.95	135.79
Transformation				
Electricity Selfproduction	2.91	2.91	2.91	2.91
Electricity Utilities[a]	5.53	5.65	7.42	43.72
Biodiesel Plants	0.4	−0.07	−0.07	1.78
Ethanol Destillery	0.7	−0.01	−0.01	−0.04
Resources				
Production	76.14	−17.38	−14.15	180.29
Imports	−58.99	−47.57	−49.28	−113.03
Exports	−16.48	−2.24	−1.52	−54.42
Environmental Externalities	0	−3.67	−24.68	0
Net Present Value	22.8	−60.3	−80.3	229.9
GHG Savings (Mill. Tonnes CO_2 eq).	1584	782.1	1043.7	5152.6
Cost of Avoided CO_2 (U.S. Dollar/Tonne CO_2 Eq.)	14.4	−77.1	−76.9	44.6

[a] Capital investment costs based on CEAC (2012) and IEA (2010).

role moving forward, depending on assumptions regarding natural gas supply and prices. The models also agree that reaching a more stringent emissions reductions targets is feasible through the implementation of CCS, but they differ as to which fuel and at what cost this technology will be deployed.

More research is needed to understand the impacts of specific policies on energy supply and demand. Looking at the three model results, there is less agreement between the simulation model and optimization models regarding absolute primary and final energy consumption projections, and associated response to carbon taxes, with the optimization models predicting stronger energy savings and efficiency measures. There are important differences in assumptions and methodological approach between the LEAP simulation model, which benefits from closer analysis by local stakeholders, and optimization models, which may capture additional interactions and automatically include additional mitigation measures. Additional research to understand the impacts of different policies will improve the accuracy of both simulation and optimization models. From a technical perspective, future work could potentially focus on taking advantage of the different approaches of the models by incorporating the reductions in energy demand observed in the TIAM-ECN and GCAM models into LEAP to examine detailed changes within LEAP that would be consistent with the values in TIAM-ECN and GCAM, which reflect more fuel switching and energy efficiency measure uptake than were used in this particular application of the LEAP model.

The results of this study have an inherently longer term perspective (up to 2050). In the short and medium term, policy makers should undertake a deeper analysis of specific policies, such as the implementation of the ProBiomass program, support for nuclear plants, wind farms and hydroelectric plants, to understand the wider economic implications, and to capture all of the economic co-benefits, identify country-specific challenges, and prepare public actors (state-owned utilities, regulators) and private actors (manufacturing firms, consumers) for the transformation towards an energy sector under climate control policies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2015.03.021.

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