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DOI
10.1016/j.energy.2018.09.005

Publication date
2018

Document Version
Final published version

Published in
Energy

Energy 164 (2018) 1161–1177

Contents lists available at ScienceDirect

Energy

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

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ARTICLE INFO

Article history:
Received 24 January 2018
Received in revised form
25 July 2018
Accepted 1 September 2018
Available online 7 September 2018

Keywords:
Climate change
Mitigation
Adaptation
Energy system model
Hydropower
Brazil

ABSTRACT

This paper performs a multi-model comparison to assess strategies for adaptation to climate change impacts in hydropower generation in Brazil under two Representative Concentration Pathways. The approach used allows for evaluating the interactions between climate change mitigation and adaptation strategies under low and high impact scenarios through 2050. Climate change impact projections of sixteen General Circulation Models indicate that a global high emissions trajectory scenario would likely yield more severe impacts on hydropower generation than a mitigation scenario. Adaptation modeling suggests that climate change impacts can be compensated by a wide range of alternatives, whose optimality will depend on the level of mitigation effort pursued. Our results show that climate change impacts would lead to even higher emissions in the absence of climate change mitigation policies. On the other hand, mitigation strategies to pursue lower emissions are maintained under climate change impacts, meaning that mitigation strategies are robust when faced with adaptation challenges. Mitigation efforts could yield a more diverse and less carbon intensive mix of technological options for adaptation. When analyzing investment costs to adapt to climate change impacts, in some cases mitigation can lead to a lower total investment level.

1. Introduction

Despite concerns about climate change and its impacts, energy system operators and planners have traditionally assumed that climate variables are stationary. Still both climate change itself as well as changes in climate variability may have serious consequences for energy production and consumption. Assessing vulnerabilities and incorporating them into long-term energy planning is, therefore, important for developing policies to cope with climate change challenges [1].

To this end, many studies have addressed the issue of climate change impacts on energy systems, and renewable energy in particular [2]. provide a review of such studies. More recently [3–7], assessed impacts of climate change from a global perspective, while [8–11] looked at specific countries or regions.

However, the work on climate change impact and adaptation worldwide seldom considers their interactions with climate change mitigation strategies. For instance, renewable based energy

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https://doi.org/10.1016/j.energy.2018.09.005
0360-5442/

systems are typically more vulnerable to climate change than those based on fossil fuels, since renewable energy relies on energy flows that are closely related to climate conditions [2]. Renewable energy systems are, thus, more exposed to the changes in climate they seek to avoid.

The implications of climate change depend not only on the actual change in physical climate, but also on human systems development trajectories [12]. On one hand, the magnitude of climate change depends on the carbon intensity of global development pathways. On the other hand, the systems affected by climate change are influenced by the same development pathway. This is particularly relevant for the energy sector given its role as the major source of greenhouse gases (GHG) emissions worldwide [13]. Future developments of the energy sector will depend on socioeconomic, technological and environmental variables, as well as public policies. As such, mitigation strategies will have a large influence not only on GHG emissions from energy use, but also on the shape and resilience of the energy system that will be exposed to future climate change impacts. Likewise, in a world with greater mitigation effort, adaptation strategies are expected to take a different form than those in a carbon-intensive world.

Brazil is a good case study given that its power sector is highly dependent on renewable sources, especially hydropower. Hydropower is the major power generation source in Brazil, having supplied, on average, 75% of the country's electricity over the last ten years [14]. Biomass is also relevant, reaching 25% of the country's primary energy supply in 2016 [14]. Given Brazil's reliance on renewables, some work on climate change impact assessment has been conducted for the country [15]. looked at climate change impacts on hydropower and biomass production [16]. assessed the impact of climate change on the untapped hydropower potential in the Amazon regions [17]. and [18] looked at impacts on wind power in Brazil. Few studies have gone further to address adaptation strategies [1], some of which included other economic sectors [19]. Here, these past efforts are extended by introducing a multi-model approach to assess climate change impacts and the interactions between mitigation and adaptation in Brazil. In addition, this paper provides an exploratory analysis of the implications of climate change impacts for mitigation and adaptation investments.

Thus, this work uses climate change impact scenarios for hydropower generation in Brazil to assess the interactions between climate change mitigation and adaptation strategies. Such assessment is conducted by comparing energy scenarios (up to 2050) provided by six integrated energy system models under two emissions pathways (RCP 8.5 and RCP 4.5) and two impact scenarios (low and high).

This paper is structured as follows: after this introduction, section 2 presents the methodological approach; section 3 describes the scenarios used; section 4 presents and discusses the results; finally, section 5 draws some conclusions and provides final remarks.

2. Methodological approach

Fig. 1 depicts the methodological procedure adopted in this study. The two Representative Concentration Pathways (RCPs) provide both the climate change mitigation and impact forcings. The climate change mitigation forcing determines the emission levels and the mitigation effort performed by Brazil to meet such levels, and will drive the simulations of Energy System Models (described in section 2.1). The climate change impact forcing is translated by General Circulation Models (GCMs), which provide the climatological consequences of the respective emission levels and their impacts on local climate variables (precipitation and temperature), and will drive the hydrological model (described in section 2.2) and the projections of impacts on hydropower generation.

Based on the mitigation forcings, two baseline scenarios for the evolution of the Brazilian energy system through 2050 were produced by six Energy System Models under a reference (RCP 8.5, hereafter named REF) and a mitigation policy (RCP 4.5, hereafter named POL45) context (see). The two baseline scenarios assume no impacts on hydropower production and serve as a benchmark for assessing climate change adaptation efforts. Based on these baseline scenarios, new scenarios were simulated by introducing a climate change impact shock in terms of lower electricity production at existing and planned hydropower plants. These scenarios maintain all assumptions from their respective baseline scenarios, except for hydropower generation. It should be noted that no other impacts on the energy system are assessed in this work. The approach is conceptually similar to a recent global analysis [20], although this paper brings the additional rigor of multiple energy system models whilst focusing solely on Brazil.

The climate change impacts were projected by the Global Water Availability Model (GWAM) using the results of sixteen CMIP5[1] GCMs for temperature and precipitation (BoR, 2016), under RCPs 8.5 and 4.5 radiative forcings (see section 2.2). Given the large range of GCM projections, two negative impact scenarios were used: low and high impact.

The comparison of the results between climate change impacts and no-impacts scenarios provide the basis for assessing climate change adaptation strategies under different mitigation efforts and impact severity levels.

2.1. Energy system models

Long-term energy scenarios were built using six integrated energy models: ADAGE [21], COPPE-COFFEE [22], GCAM [23], IMAGE [24], MESSAGE-Brazil [25], Phoenix_6LA [26] and TIAM-ECN [27,28]. The Energy System Models used here differ from each other in terms of their modeling approach, spatial resolution,[2] sectoral scope, degree of foresight and representation of technological options (type, availability and costs). The main features of each model are summarized in Appendix A.

Scenarios depend largely on premises about the future evolution of drivers for energy production and consumption, such as GDP, population, technological development, costs, behavior, trade, etc. The premises used in each model were not harmonized, except for hydropower installed capacity and electricity generation. Not harmonizing for other premises gives a large range of results and adaptation strategies, providing a wide spectrum of analysis and outcome possibilities, which are worth investigating. This approach has been used in previous model comparison studies, such as [29] for Asia, [30]; for major economies [31], for the United States, [32]; for Latin America, and [33] for India.

Likewise, the drivers that distinguish the two RCPs analyzed within each Energy System Model are not harmonized (see scenario description in Section 3.2). Indeed, each model projects different reference (REF) and policy (POL45) baselines. In addition to these two baseline scenarios, four climate change impact scenarios are built (one low and one high impact scenario for each baseline), totaling six scenarios. The purpose of the model comparison study here is to have a large spread of results in terms of carbon costs and budgets, reflecting a wide range of levels of effort

[1] Coupled Model Intercomparison Project. For more information refer to: http://cmip-pcmdi.llnl.gov/cmip5/.

[2] All Energy System Models used have a global scope, with varying spatial resolutions. The only exception is MESSAGE-Brazil, which is a country specific model.

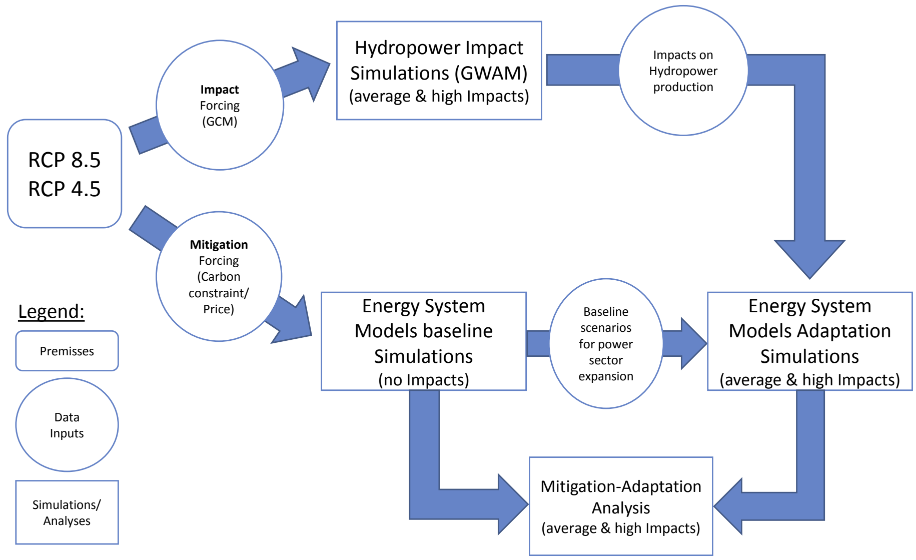

Fig. 1. Methodological procedure.

to reach a certain mitigation target.

2.2. Hydrological model

To estimate climate change impacts on hydropower production for Brazil, an established top-down methodological approach was followed. The approach involves forcing a hydrological model with gridded GCM temperature and precipitation projections to determine runoff, which is then routed to estimate streamflow at hydropower dams of interest. This method has been employed and validated in previous global studies (e.g., [5,34]; here the inclusion of a detailed hydropower database for Brazil allows for a far more comprehensive assessment for this particular country. The following steps were taken. First, downscaled and bias corrected global, monthly temperature and precipitation time series were obtained at 0.5° grid square spatial resolution for sixteen CMIP5 GCMs (BoR, 2014). Next, these GCM projections were used to force the Global Water Availability Model (GWAM) [35], which simulates monthly runoff by tracking the soil water flux of each spatial grid. This runoff was then routed using the River Transport Model (RTM) [36], which uses cell-to-cell accumulation of runoff to generate streamflow.

The final step in preparing the data for hydropower simulation was to filter for grid locations where hydropower generation is expected. This was done using up-to-date information on Brazil's existing hydropower infrastructure as well as future expansion plans, which incorporate dams being constructed and planned at time of writing [37–43]. To simulate country-level hydropower generation, the technical, exploitable hydropower potential was computed at each filtered spatial grid (method described in Ref. [4]. Grid-level generation was then aggregated to get trajectories of hydropower potential for Brazil, in units of Exajoules. These trajectories were then smoothed using a ten-year moving window, ensuring capture of long-term trends in hydropower rather than inter-annual variation, which could be problematic for comparing GCM results at pre-specified points in time. The resulting projections of hydropower under climate change were used as input to the energy models.

Just two (CESM1_BGC and GFDL_CM3) of the sixteen candidate GCMs were selected for further analysis, as described in Section 3.1.

3. Scenarios

Observed and expected impacts of climate change will require adaptation efforts [13]. The impacts of climate change, however, do not depend solely on the global climate system's response to higher concentrations of GHGs in the atmosphere, but also on the development pathways that will take place over the next decades [12].

The scenarios assessed in this study are built so that the energy system exposed to climate change is consistent with the impacts associated with its GHG emissions. However, it should be noted that the effort to reach a given stabilization target (e.g. RCP 4.5) is a worldwide effort and not restricted to a single country. Thus, the scenarios produced here are based on the assumption that all countries contribute to GHG emissions mitigation (including Brazil) so that this effort results in the targeted global radiative forcing levels and, consequent magnitude of climate change.

The RCPs provide the target forcing for the mitigation efforts, as well as the changes in climate variables that lead to impacts on hydropower production. The next section presents the latter, describing the procedure used to choose the impact scenarios from the range of results based on sixteen GCM from CMIP5. Subsequently, section 3.2 describes the scenario protocol used in this model comparison study.

3.1. Climate change impacts

GWAM described in Section 2.2 was used to model electricity generation in all existing and planned hydropower plants under temperature and precipitation changes projected by 16 GCMs. The results shown in Fig. 2 indicate that there is a large spread of climate change impact projections resulting from all the GCMs analyzed. Despite such a wide range, the downward slopes of the median lines indicate that the impacts of climate change on hydropower production are likely to be negative in both RCPs and more severe in RCP 8.5. Two of the sixteen candidate GCMs were selected to represent a low impact and a high impact scenario. Having a large number of scenarios with small variations in the magnitude of the impacts make little difference in the adaptation runs and, thus, would not provide relevant information for the analysis. Furthermore, a positive impact (i.e. increase in hydropower production) scenario is not investigated, since there would

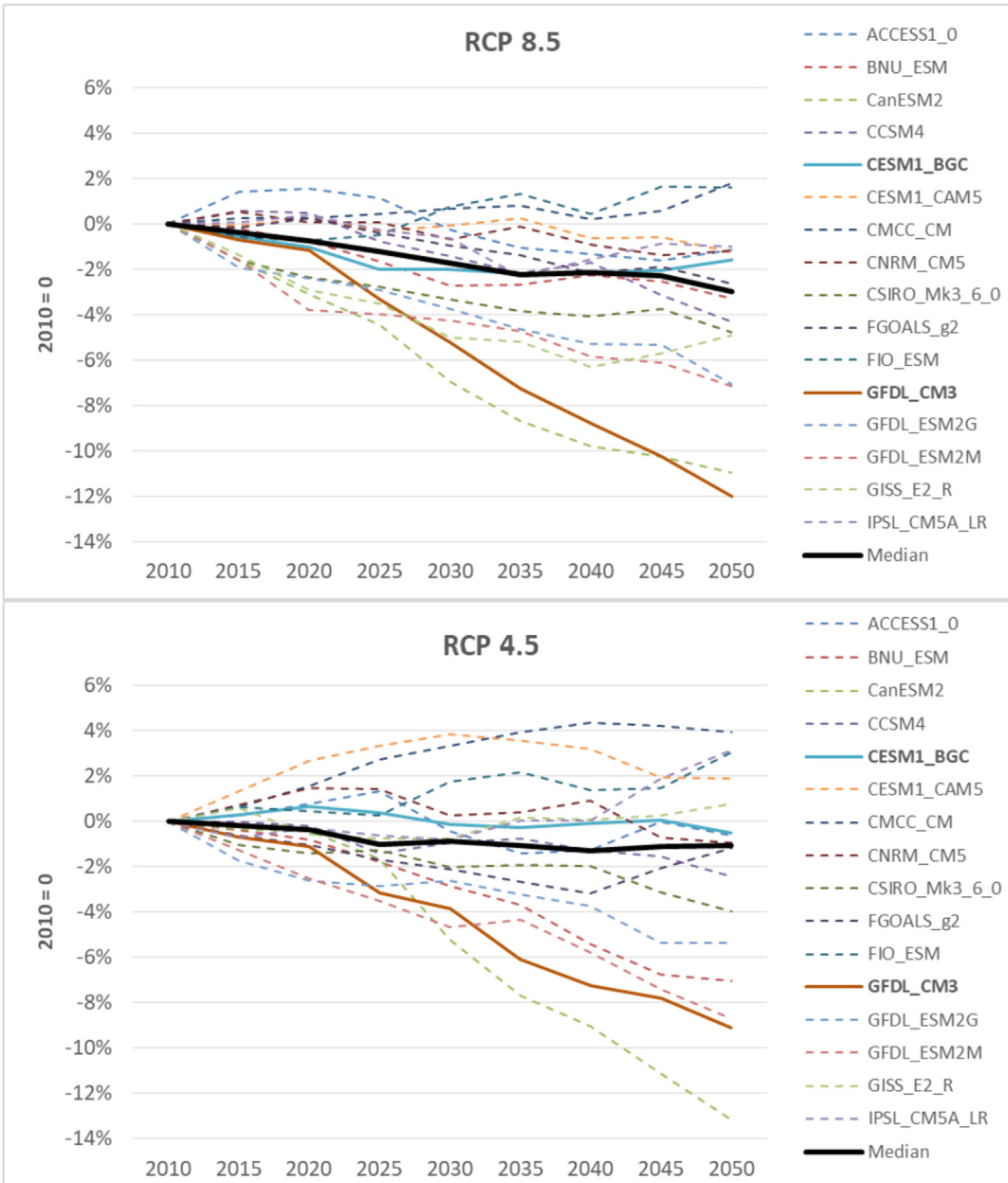

Fig. 2. Relative change in hydropower generation projected for all sixteen GCMs and their median (hydropower generation in 2010 = 0). Note: Median value and selected GCMs marked as solid lines.

be no adaptation effort in such a case.

The low impact scenario is represented by the GCM which follows the median closest[3] (CESM1_BGC, hereafter referred to as CESM). The high impact scenario is represented by the GCM for which the changes in hydropower generation are the most negative (GFDL_CM3, hereafter referred to as GFDL). In the latter, the GCM choice was made ensuring that the impacts must be distinct across RCPs to avoid ambiguity (i.e. the results for a RCP must be always better/worse than the other, regardless of which RCP, to avoid confusion as to which impact result is associated with each RCP).

[3] i.e. the GCM whose results minimized the sum of the squared difference to the median for both RCPs.

3.2. Scenario description

As already mentioned, two baseline scenarios were produced to serve as a benchmark for assessing the adaptation effort. These two baseline scenarios (REF and POL45) project the energy system through 2050 without considering any impact from climate change. They were built to be consistent with the mitigation effort associated with each RCP. REF is a no-mitigation policy baseline scenario (consistent with RCP 8.5), whereas POL45 is a mitigation baseline scenario in which energy models simulate mitigation policies compatible with RCP 4.5.

For population, models generally assume stabilization at different levels by 2050 (from 218 to 232 million people) and, in some cases, a peak and decrease after 2040. GDP assumptions vary significantly across models, ranging from a 2.2 to over a 4-fold increase from 2010 to 2050. In per capita terms, the spread of GDP assumptions is also large, nearly doubling in the lower case and increasing by 3.6 times by 2050, when compared to 2010. These GDP growth assumptions are lower than those used by a similar model comparison study by Ref. [44] for Brazil. This is, in some cases, the result of a revision given the recent economic crisis in the country [45].

The simulation of the POL45 baseline scenario by each Energy System Model is conducted according to different procedures and criteria. Some models use a global[4] emission constraint, while others use a carbon tax applied globally. Once again, not harmonizing the way the POL45 scenario is constructed can provide rich information on the evolution of the Brazilian energy system under a RCP 4.5 trajectory. In fact, it should be emphasized that the mitigation effort to reach radiative forcing similar to that of RCP 4.5 is a global one. Therefore, although some models may assume similar carbon emission trajectories/budgets or carbon prices globally, the values each model finds for Brazil depends on the representation of the country compared to and within the global energy system. This provides relevant information about a range of values of carbon budget and prices consistent with the role of Brazil in an optimal global mitigation effort to reach RCP 4.5 radiative forcing levels,[5] which can be used in future national assessments. Table 1 summarizes the modeling assumptions and procedures used to simulate the POL45 scenario, as well as some specific results for Brazil.

The energy system models used in this study project a range of cumulative emissions in Brazil of 19000–28500 $MtCO_2$ from fossil fuel burning and industrial processes from 2010 through 2050 under the POL45 scenario, with many models being close to the average of 23475 $MtCO_2$. However, these values in terms of percentage reductions from the REF baseline scenario have a much wider spread. This means that, although models relatively agree on the accumulated emission levels allocated to Brazil in an RCP 4.5 trajectory, they do not agree so much on the level of effort that this implies when comparing to a business as usual course for the energy system. This is also evident from the wide range of associated carbon prices. Such a large spread of results cover a wide range of possible futures so as to have a wide range of possible adaptation/mitigation outcomes to compare from.

Having these two baseline scenarios as a no-climate-change-impact benchmark, two additional impact scenarios were projected for each RCP: a low (CESM) and a high impact (GFDL) scenario. These four scenarios with climate change impacts (two RCPs x two GCMs) were simulated maintaining all assumptions from their respective baseline scenarios, except for hydropower installed capacity and power generation. The results of these scenarios in terms of power generation capacity addition and production can be compared to the baseline to assess the adaptation effort when facing the respective level of climate change impact. Table 2 summarizes all scenarios analyzed and includes the results for total hydropower generation and variation to a no-climate-impact baseline.

Table 1
Modeling assumptions for the POL45 Baseline scenario.

Model	POL45 scenario modeling procedure	Accumulated CO_2 Emissions[1] in Brazil through 2050 (Mt CO_2) and % reduction to REF	Associated Carbon Price in 2020 and 2050 (2005 USD/ tCO_2)[2]
ADAGE	Carbon tax applied globally on fossil fuel and industrial emissions	28384 11%	30–97
COFFEE	Global emission constraint to match GHG emission pathway of RCP4.5 under SSP2	21661 26%	9–22
GCAM	Carbon tax applied globally on fossil fuel and industrial emissions to match RCP 4.5 emissions	24383 12%	8–34
IMAGE	Carbon tax applied globally on all GHG emissions	23164 13%	5–28
MESSAGE-Brazil	Emissions Constraint for Brazil based on accumulated emissions through 2050	24361 6%	n.a. [3]
Phoenix	Global emissions constraint to match cumulative CO_2 emissions of RCP 4.5 under SSP2	19211 19%	7–63
TIAM-ECN	Global emissions constraint to match GHG emissions pathway of RCP4.5	23164 37%	94–117

Note: [1] Emissions from fossil fuels and industry only; [2] associated carbon prices rise roughly linearly in all models; [3] values not available because shadow-prices are consistent with an accumulated budget, not year-specific emissions.

4. Results

The following sections present the results for the energy system models runs under the scenarios described above. First, the baseline scenarios are discussed, in order to provide a reference background for the adaptation strategies which are discussed subsequently. An analysis of cost differences among scenarios is then performed and, finally, the implications of these results are discussed.

4.1. Baseline scenarios

The baseline scenarios (REF and POL45) project two pathways for the evolution of the Brazilian energy system, without assuming any impacts from climate change. The REF scenario projects an energy system in which no additional mitigation effort is made, except for policies that are already implemented. The POL45 scenario describes an evolution of the Brazilian energy system that is compatible with the country's role in a global trajectory that reaches radiative forcing levels of RCP 4.5.

Primary energy consumption increases through 2050 in the REF scenario in all models in absolute terms (1.6–3-fold) and in per capita terms (1.3–2.6-fold). Primary energy intensity, on the other hand, decreases in all models, except for COFFEE.[6] Primary energy intensity in the POL45 scenario is even lower in all models, once again except for a slight increase in COFFEE.

This lower energy intensity, in turn, is accompanied by a small increase in carbon intensity of primary energy consumption in the REF scenario in most models (exceptions are COFFEE and IMAGE). The consumption of oil, coal and natural gas increases in absolute

[4] In the case of MESSAGE-Brazil a national constraint, given its national scope.

[5] It should be noted that there are many allocation methods based on considerations like fairness, historic responsibility, grandfathering, per capita conversion, among others [71]. Different allocation methods would yield different emission budgets, trajectories and/or carbon prices for Brazil than the ones used here [72].

[6] The slight increase in primary energy consumption in COFFEE (26% increase from 2010 to 2050) is mostly because of higher penetration of biomass, which uses more primary energy for the same amount of energy service.

Table 2
Summary of scenarios analyzed.

Scenario Name	Description	Accounting for climate change effects? [Y/N]	Unit	Hydropower generation (TWh/year)/Percentage Change from Baseline (results from GWAM) 2010	2020	2030	2040	2050
REF	No policy baseline	No	TWh/year	404.09	521.31	564.09	574.07	581.52
REF_GFDL	No policy High Impacts	Yes	%	0.0%	−1.3%	−4.9%	−8.3%	−11.9%
REF_CESM	No policy Low Impacts	Yes	%	0.0%	−1.2%	−1.6%	−2.4%	−1.4%
POL45	RCP4.5 baseline	No	TWh/year	404.09	521.31	564.09	574.07	581.52
POL45_GFDL	RCP 4.5 High Impacts	Yes	%	0.0%	−1.3%	−3.7%	−7.2%	−9.1%
POL45_CESM	RCP 4.5 Low Impacts	Yes	%	0.0%	0.5%	0.0%	−0.1%	−0.3%

terms in all models in the REF scenario, accompanied by increases in mostly biomass and hydro.[7] Models agree that oil will remain an important energy carrier in the future, but that its relative importance will be lower despite the large oil reserves in the country. In the POL45 scenario, the carbon intensity of primary energy decreases in all models from 2010 to 2050, except for ADAGE, for which there is a small increase, but less than in the REF scenario. Still, the consumption of fossil fuels rise through 2050 in all models, but to lower extent when compared to the REF scenario. Nuclear increases in all models and scenarios, but to varying extents.

Fig. 3 shows the results for electricity generation through 2050 in all models for the two baseline scenarios. Results show a large variation across models in total power generation, as well as the technological options used, other than hydropower. The large variation in total electricity generation across models is a result of the wide range of energy consumption drivers, such as GDP and energy intensities.

Electricity generation more than doubles by 2050 in most models (except MESSAGE-Brazil and Phoenix) in both baseline scenarios. Per capita electricity consumption increases in both baseline scenarios in all models. In the POL45 scenario, electricity consumption grows more slowly than in the REF scenario, suggesting that the models do not employ electrification (e.g., in transportation) to mitigate emissions and reach an RCP 4.5 trajectory.

In the harmonized hydropower expansion plan used in all models, hydropower remains the major source of electricity generation in the baseline scenarios, despite losing relative importance. The larger expansion in hydropower generation occurs early in the period (by 2020), when large hydropower plants currently under construction become operational. Still, most models project a diversification of the power generation mix by 2050, despite the projected increase in hydropower.

In the REF scenario, most models increase deployment of fossil fuel based power generation through 2050, especially after 2030. This includes, mainly, natural gas, but also coal and, in some models oil. Nuclear power generation increases in the REF scenario in all models. Renewable energy penetration in the REF scenario can be significant in some models, mostly based on biomass. Although there is a small penetration of wind and solar in some models, these options do not play an important role in power generation in the REF scenario in any model.

Regarding the power sector, the strategies to reach lower emission levels in the POL45 scenario differ for each model. Generally speaking, lower emission levels are achieved by a combination of lower electricity consumption and changes in the power generation mix. In some models, mitigation is mostly achieved by lower electricity consumption, while maintaining a power generation mix similar to that of the REF scenario. Other models show more substantial changes in their power generation mix. In general, model runs for the POL45 scenario show a lower penetration of coal, usually associated with Carbon Capture and Storage (CCS) or compensated by a higher penetration of renewable energy sources such as biomass, solar and wind. Nuclear power is also an alternative in some models to reach lower emission levels.

In the next section, the baseline scenarios will be compared to scenarios with a high and a low impact in hydropower generation in order to assess the adaptation strategies projected by each model under different mitigation constraints.

4.2. *Climate change adaptation strategies under mitigation constraints*

The results for climate change adaptation are presented in terms of variation to the respective baseline scenario to control the analysis for variations across Energy System Models. Since the impacts on hydropower directly affect the power sector, results are only presented for electricity generation. Despite the models being energy system models, thus providing insights into the complex relationships between all energy producers and consumers, second order impacts (i.e. impacts to other non-electrical energy sectors) will be described on an individual model basis at the end of this section, when applicable.

Fig. 4 shows the variation in total power generation in 2050 for each model as the result of introducing the climate impact shocks.[8] Optimal adaptation strategy varies across models, whose results are discussed for each Energy System Model below. The variations in the baseline projections are repeated in the adaptation simulations, indicating a wide range of adaptation strategies. The results, however, tend to follow each model's power sector expansion plan under the different GHG stringency levels.

Given the lower impacts projected for RCP 4.5, the aggregate adaptation effort is lower in the POL45 scenario for both high and low impact cases. In other words, the additional electricity generation needed to compensate for the loss in hydropower is lower in POL45 scenarios. The climate change low impact scenarios (CESM) show small impacts, especially in the POL45_CESM scenario. Under the high impacts GFDL projections, the contribution of hydropower generation to Brazil's power needs in 2050 decreases from 582 TWh/year to 512 TWh/year and 529 TWh/year, for RCP 8.5 and RCP 4.5, respectively. This leaves a wide gap to be met by alternative technologies. In 2050 in the CESM projections, hydropower decreases to 573 TWh/year and 580 TWh/year in RCP 8.5 and RCP 4.5, respectively.

Looking at the results for specific models, ADAGE shows that hydropower generation loss is replaced by oil, natural gas and coal, regardless of the mitigation policies by 2050. It should be noted

[7] It should be emphasized that the hydropower production trajectory is harmonized across models.

[8] The detailed results are presented in Appendix B.

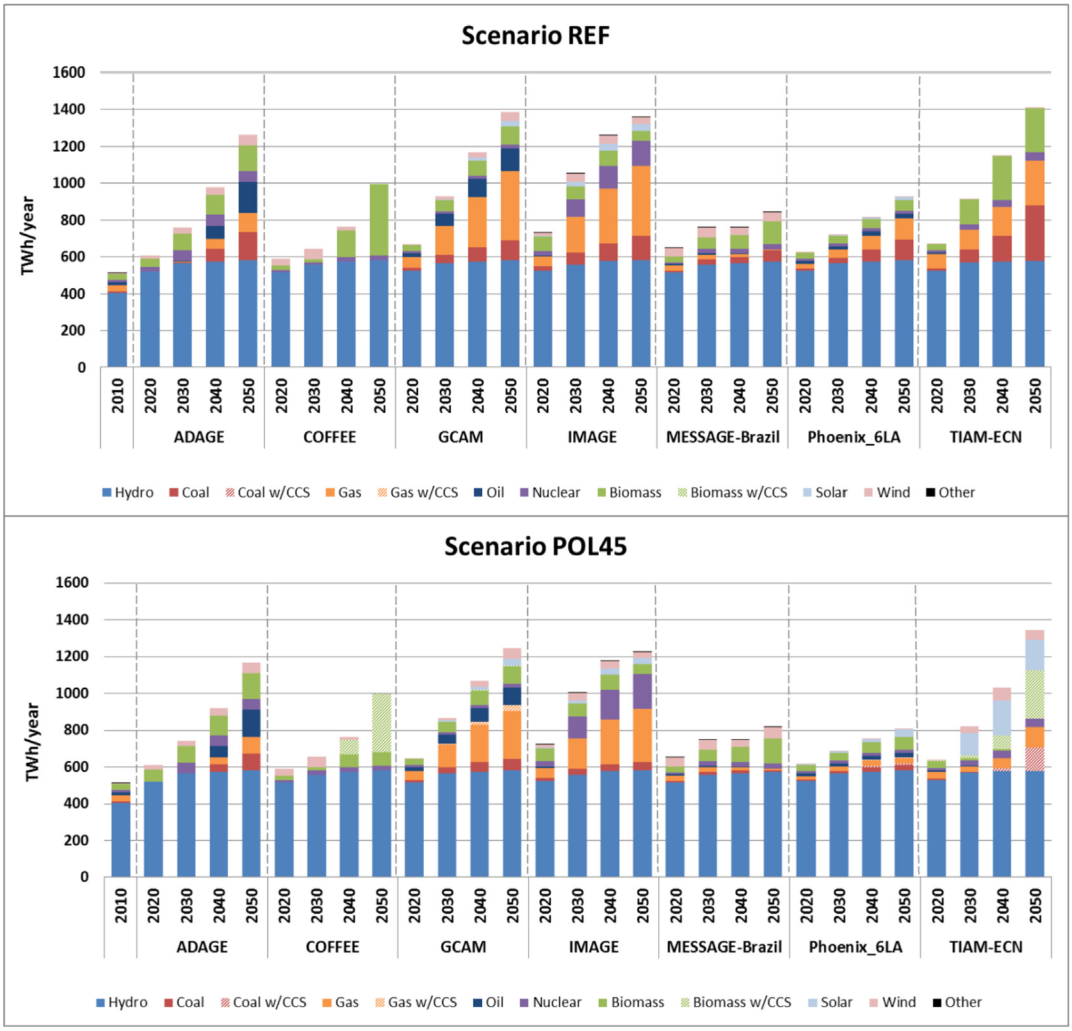

Fig. 3. Electricity Generation in Baseline Scenarios. Note: Historical values presented for 2010 (EPE, 2016).

that in the shorter term (2020–2030), adaptation may anticipate the entrance of some nuclear, biomass and wind. The major difference in adaptation strategy between REF and POL45 is a lower electricity consumption in the latter. ADAGE is a Computable General Equilibrium (CGE) model, in which price signals can lower the demand for electricity as a way to reduce emissions. Thus, the difference in adaptation strategies are in line with the differences in the results found by ADAGE for the baseline scenarios.

The results for the COFFEE model show that hydropower generation loss is largely replaced by a combination of biomass power plant technologies (mostly bagasse and woody biomass) in all scenarios by 2050. Across scenarios, results from COFFEE place Brazil as a major producer and a net exporter of biofuels, both first and second generation. However, biofuel production is affected differently in adaptation scenarios in terms of order of magnitude and share: ethanol production increases, which leads to larger bagasse availability for the power sector; advanced biofuels (mostly diesel and kerosene) production decreases, shifting some of the biomass toward electricity generation. It should also be noted that other sources, such as coal, natural gas and nuclear power are anticipated as a replacement for hydropower loss along the trajectory.

In the GCAM model, the hydropower shortfall is met predominantly by natural gas technologies for adaptation scenarios, with the remainder being met by a well-diversified portfolio comprising oil, coal, biomass, wind, solar and nuclear technologies. Interestingly, the same is true when climate policy is adopted. However, whilst expansion of fossil technologies remains dominant under RCP 4.5 scenarios, carbon capture and storage accounts for 18% of fossil generation by 2050 compared to zero uptake under the REF scenario group by 2050. These policy responses, combined with lower demands under POL45 scenarios, curtail growth in power sector CO_2 emissions by more than half relative to the REF scenario by 2050.

For climate impacts in the adaptation scenarios for IMAGE model, hydropower losses are compensated by natural gas, nuclear, bio-energy, solar and wind in the short term (<2030) and by natural gas, nuclear, solar and wind in the long term (<2050). The reduction in hydropower leads to a reduction of coal because of the loss of flexible load hours provided by hydropower. This loss of flexible capacity needs to be compensated by other flexible technologies such as gas which results in a tiny reduction of coal power that provides base load hours. In the mitigation (POL45) scenarios, roughly a similar impact is seen; however, the hydropower loss and its replacement add up to less generation than in the REF scenarios. The effect on electricity demand reduction is limited and roughly

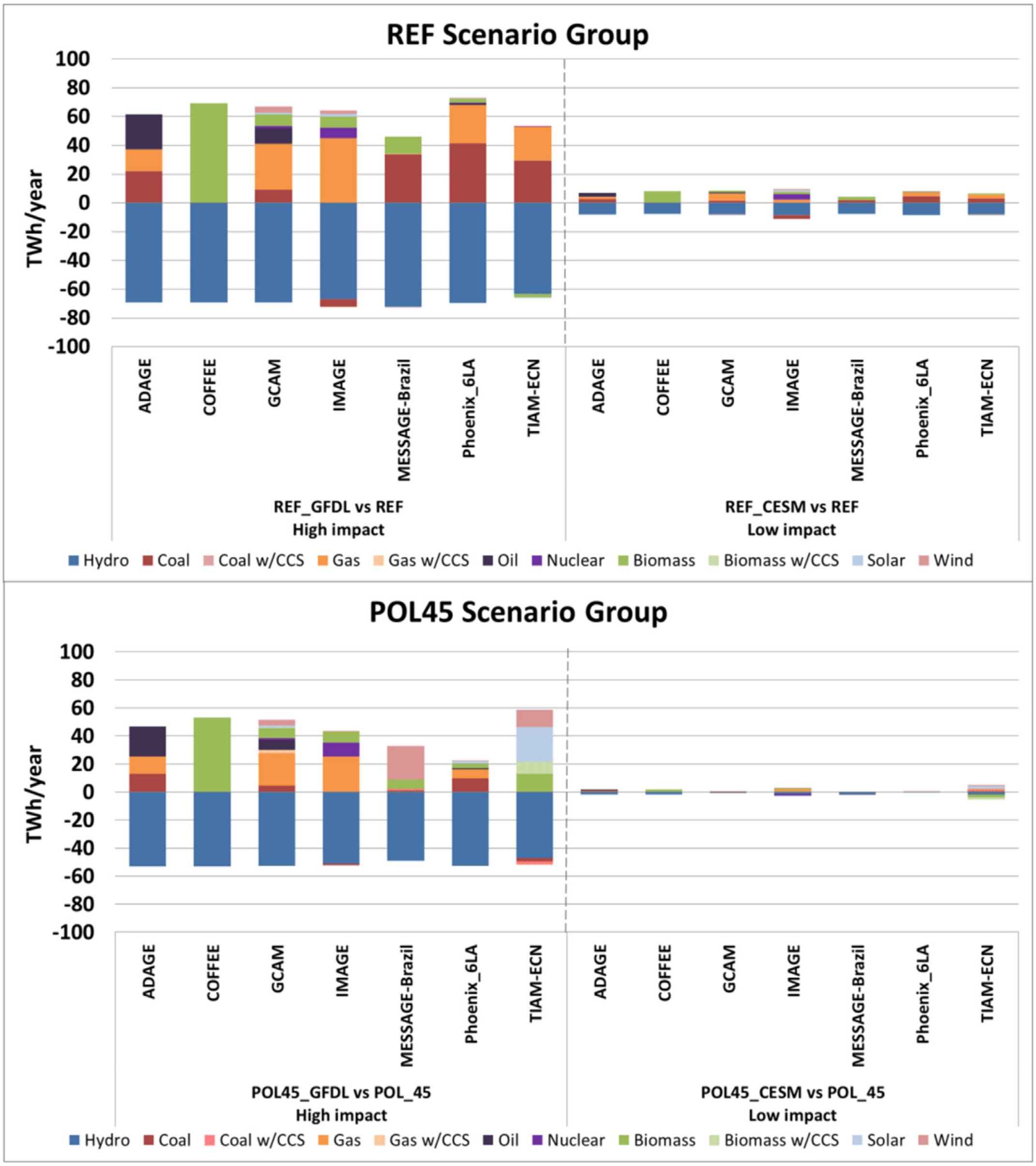

Fig. 4. Change in Electricity Generation in Climate Change Scenarios in 2050 (Climate impact scenarios minus Baseline Scenarios). Note: please refer to detailed results in Appendix B.

the same for both RCPs.

MESSAGE-Brazil shows that hydropower generation loss by 2050 under the impact scenarios without mitigation efforts (REF) is partially replaced by coal, biomass (sugarcane bagasse) and, less importantly, natural gas. In scenarios with mitigation efforts (POL45), the hydropower loss is partially replaced by wind power generation and biomass (sugarcane bagasse), besides a small addition of coal (with CCS). In both scenario groups, hydropower loss was not fully replaced by other sources due to energy efficiency measures that reduced electricity demand.

In the Phoenix model, the loss of hydropower generation is lower than the total generation replacement in the climate impact scenarios. This results from the model shifting towards other inputs in the production sectors and/or changes in Brazil's net electricity exports. Under the adaptation scenarios by 2050, hydropower generation loss is met predominantly from coal and natural gas, and with less participation from biomass, nuclear, solar, wind and oil sources. Assuming mitigation efforts, (POL45 scenario group), the hydropower loss is partially replaced by coal (with and without CCS), natural gas (with and without CCS), biomass (without CCS), solar, wind, nuclear and oil sources. However, the penetration of these adaptation measures are much lower than in the REF scenario group, providing an example of Brazil's response beyond the electricity sector to the impacts from lower hydropower generation.

Lastly, in TIAM-ECN climate impact shocks on hydropower are compensated in the REF scenario group by an increase in electricity generation from coal (without CCS) and natural gas until 2050. Some energy efficiency compensates for the loss in hydropower in the REF scenarios. In the mitigation scenarios (POL45), the power system adaptation mix is drastically different, moving to a more diverse mix of renewable energy, including solar PV, biomass (with and without CCS) and wind. Conversely to the REF scenarios, the mitigation scenario (POL45) hardly reports absolute reductions in power generation triggered by unavailability of hydropower plants due to climate change impacts. This is caused by high energy efficiency standards and the importance of electricity for decarbonizing energy demand sectors.

4.3. Adaptation costs

The impacts of climate change on hydropower will generate the need for adaptation strategies which will, in turn, require investments in new power generation capacity. In this section, the investment costs are compared among scenarios. Two comparisons are made: one comparing climate change impact scenarios to their respective baselines; and one comparing the different trajectories for each RCP.

The first analysis assesses the investment costs to adapt to climate change impacts. This provides a measure of how much more expensive the power generation system expansion is when assuming the occurrence of climate change. Indeed, the modeling of optimal energy system expansion does not usually consider the possibility of climate change effects and may therefore understate the costs. This analysis provides a quantification of the additional cost, assuming impacts on hydropower only.

The second analysis assesses investment cost differences between the results of REF and POL45, for the low and high climate change impact scenarios (CESM and GFDL, respectively). This analysis can provide some insights into the difference in the investment burden of mitigating *versus* adapting. In other words, it attempts to assess whether it is more costly to not act to reduce emissions and endure higher impacts or to mitigate and face lower impacts.[9]

The costs were calculated assuming standard investment cost for all models (see Appendix C). In the presentation of our investment cost model-specific discounting of investments is neglected, which is in line with similar analyses as performed by Refs. [46,47]. Models that do not report power generation capacity had their capacity addition calculated from the reported power generation, using standard capacity factor values (see Appendix C). It should be noted that the total costs of adaptation also includes operation and maintenance costs, fuel cost and eventual costs to other sectors. However, coordinating these cost comparisons among a large set of models is not a trivial task, since not all models report the same parameters in the same way. All comparisons are made in terms of the additional (or the reduction in) total accumulated investment, in 2005 USD. Additionally, due to the large uncertainties in both the cost analysis and the range of outcomes from all models, a stochastic sensitivity analysis was performed (see Appendix C).

Fig. 5 presents the investment cost increase of climate change impact scenarios in relation to their baseline in 2030 and 2050. The incorporation of climate change impacts in power system expansion plans leads to increasingly higher costs towards mid-century. The exception are models, which, in some cases, adapts by reducing the demand for electricity as a response to price signals. This result, however, does not imply lower costs for the economic system or, more broadly, for society's well-being.

As expected, higher impacts (e.g. those of GFDL) lead to higher additional investments in electricity generation capacity. In 2050, average additional investment costs for RCP 8.5 and RCP 4.5, respectively, are 13.2% and 8.9% and higher in GFDL, compared to 1.8% and −0.2% in the CESM scenarios. Also, as the magnitude of impact increases, so does the range of values for additional investment costs, meaning that the uncertainty increases as impacts become more severe. These results are coherent with the findings of the stochastic analysis (Appendix C), in which the standard deviation increases for each time step.

Fig. 6 attempts to shed some light into the issue of whether it is more costly to mitigate or adapt. It compares, for each GCM (GFDL and CESM), the investment cost differences between the POL and REF scenarios assuming, in each case, the climate change impacts associated with the respective radiative forcing level (RCP). Positive values indicate that the POL scenario is more expensive than the REF.

The spread of results is large, mostly due to the results of specific models. Excluding TIAM-ECN, which stands as an outlier, the results point towards a general trend of lower investment costs in the POL45 scenarios when compared to the REF scenarios. This provides some evidence to the fact that, in the presence of climate change impacts, mitigating can lead to a lower investment burden. Though not exclusively, this is especially the case of models in which emission reductions are achieved through lower electricity consumption.

However, the mitigation strategy will largely influence the differences in investment cost. For instance, for the outlier TIAM-ECN, the costs in the POL45 scenarios are much higher than those of REF. The reason is that the model projects a high penetration of solar PV and biomass with CCS in POL45 scenarios, both of which have high capital costs. Nevertheless, most models (5 out of 7 models) project lower investments in the POL45, relative to the REF, in part due to energy efficiency on the demand side.

When comparing the REF and POL45 scenarios, the differences in the results for low and high impacts (CESM *vs.* GFDL) are not large, meaning that mitigation strategies are the main driver of investment cost differences. Still, results indicate that the larger the impacts, the less favorable is the adaptation investment when compared to mitigating GHG emissions.

It should be noted that the analysis does not include other costs, such as those for fuels. Fuel costs can vary significantly across models, sectors and time periods. Given that in POL45 the models tend to reduce fossil fuel consumption, fuel costs should be lower in these scenarios, favoring mitigation strategies[10].

5. Discussion

Climate change is likely to cause impacts on energy systems. Looking at Brazil, given its large reliance on hydropower, this study has assessed impacts based on projections of a set of 16 GCMs on the production of hydro-based electricity in the country. As can be seen from Fig. 2 there is large uncertainty in the range of impact outcomes from GCM results. Still, also some common observations can be made. The results for RCP 4.5 provide a wider range of possible impacts of climate than in the RCP8.5 case. Also, in RCP 4.5 a larger number of cases the impacts of climate change on hydropower at the national scale are beneficial.[11] It can therefore be expected that a RCP 8.5 scenario would yield more severe impacts on hydropower generation in Brazil than RCP 4.5.

Results indicate that the adaptation effort would be lower in an RCP 4.5, given the lower magnitude of impacts. The lower impact scenarios (those using the results of CESM) provide little room for

[9] It should be emphasized that reaching a lower radiative forcing level is a global effort. Reducing emissions in Brazil alone will not guarantee any level of climate stabilization. In this paper we assume that all countries cooperate in a global endeavor to reduce emissions.

[10] The exception here is the costs of biomass, which may be relevant in some models. However, most models do not report these costs, jeopardizing the comparison.

[11] Although regional impacts within the country can be expected in most cases.

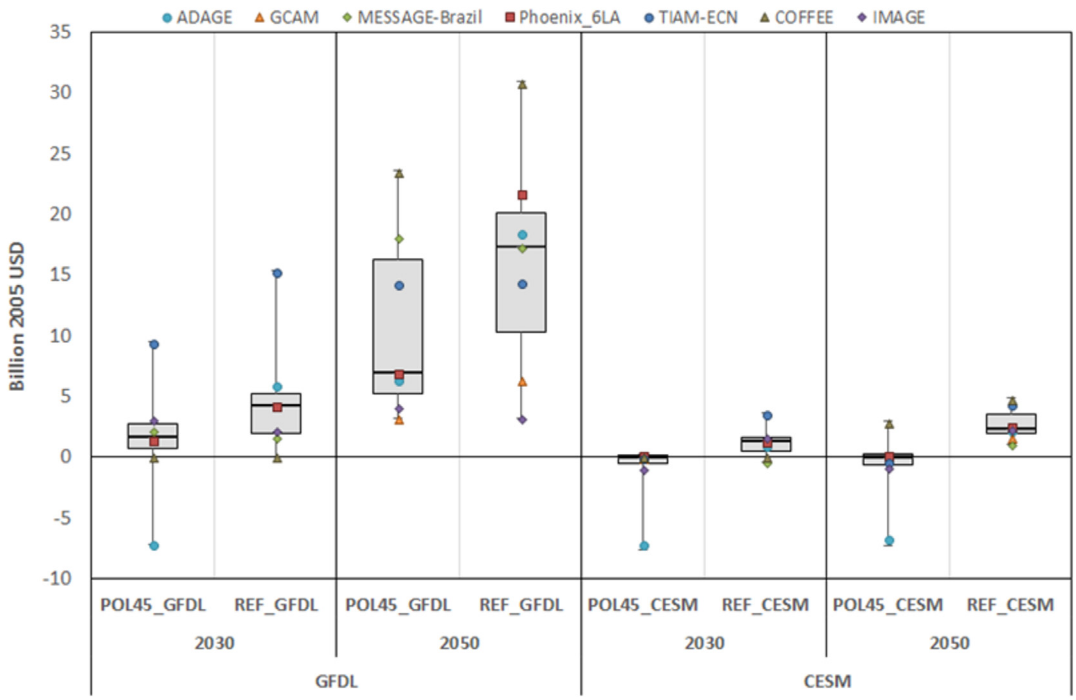

Fig. 5. Additional cost of climate change impact scenarios when compared to the corresponding baseline (REF and POL45).

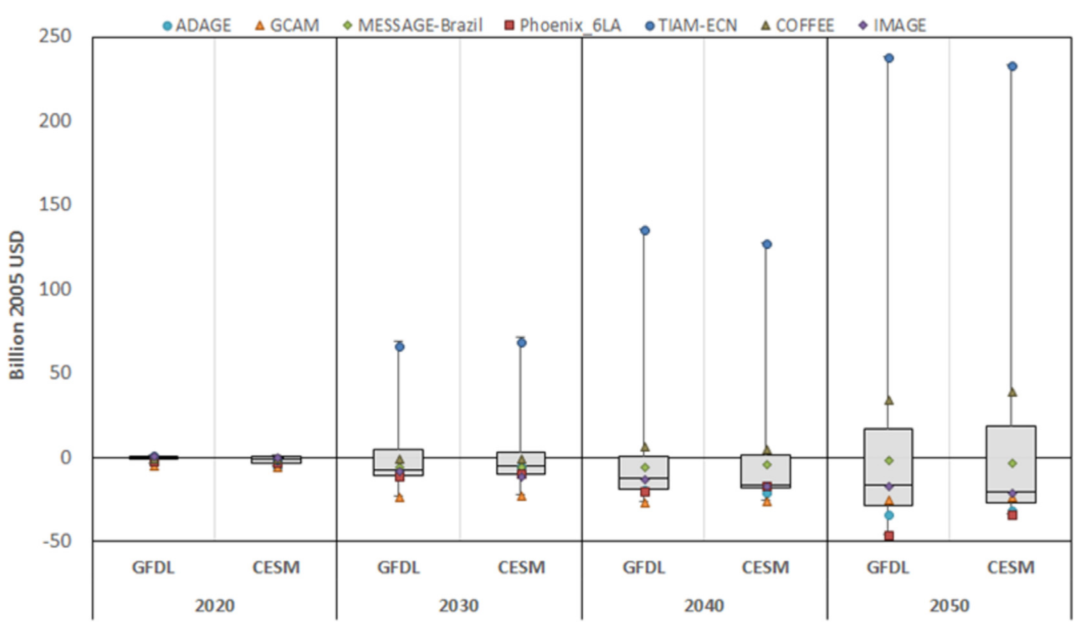

Fig. 6. Investment cost differences between REF and POL45 scenarios for low and high impacts (negative/positive values indicate REF scenario has higher/lower investment costs).

analysis, since the adaptation effort is relatively small. Indeed, if mitigation efforts are successful in avoiding severe climate change impacts, little adaptation would be needed.

Results also show that the mitigation effort pursued (more or less stringent, according to each RCP's trajectory) has an effect on the adaptation strategy within each model. This indicates that climate change impacts can be compensated by a wide range of alternatives, whose optimality will depend on the level of mitigation effort pursued. This result is observed despite the fact that baseline projections and adaptation strategies in terms of changes in the energy system vary across models.

A detailed analysis of results for each model provides insights into the possible adaptation strategies under different mitigation constraints. Some models see lower energy consumption as part of the adaptation strategy. This can be the result of energy efficiency improvements and/or a lower consumption due to a smaller activity effect (e.g. in the case of CGE models).

Such analysis shows that the optimal strategies that the energy system models use to reduce emissions are the same used to cope with the loss in hydropower generation. This indicates that mitigation strategies to pursue lower emissions are maintained under climate change impact shocks. In other words, mitigation strategies are robust when faced with adaptation challenges under a large variety of scenario results.

In the REF scenario group (RCP 8.5), adaptation is mostly based on fossil fuels. This means that, in the absence of mitigation efforts, climate change impacts could increase emissions even further and lead to more severe climate change impacts. Adaptation in the POL45 scenarios, on the other hand, generally is based on a more diverse and less carbon intensive mix of technological options, both within and across models. There is, however, no general consensus across models as to which is the best adaptation strategy.

Adaptation strategies for RCP 4.5 scenarios include renewable energy, CCS and lower electricity consumption. On one hand this can be expected since these scenarios are driven by a carbon constraint or price, explicitly making non-emitting technologies more attractive. On the other hand, given model's renewable energy resources availability, technical and operational constraints, it could be the case that models would fail to adapt using only low carbon technologies. This is, however, not verified.

Scenarios without stringent emission reductions will result in clear climate impact [48]. Therefore, such baseline scenarios should consider climate impacts and subsequent adaptation action as a reference. By not accounting for the costs caused by climate change impacts in the calculation, mitigating always leads to higher costs, as the avoided adaptation and damage costs are not accounted for. A fair comparison should consider both sides of the coin. When including investment costs to adapt to climate change impacts, in some cases mitigating can lead to a lower total investment burden.

It should be noted too, that accounting for climate impacts is not only important for renewable energies (e.g. hydropower), but also for thermal power generation (e.g. from nuclear and fossil fuels), which may require large quantities of cooling water.

Introducing climate change impacts into long-term energy system scenarios, however, is subject to a large amount of uncertainty. The GCMs assessed in this study indicate that there is a large range of future climate possibilities, which lead to a variety of adaptation strategies and costs. Still, results show that risking a more severe climate change, such as in an RCP 8.5, increases the uncertainty about which are the best adaptation alternatives and their associated costs.

Despite the large uncertainty in system wide assessments, including a climate change impact risk analysis on specific energy projects is extremely important. In the case of Brazil, this is especially relevant for large-scale hydropower plants planned for the Amazon region, where most of the country's remaining hydro potential is, given their large social and local environmental costs.

In fact, regardless of the uncertainty in GCM climate projections, recent severe drought in Brazil led to a nation-wide water shortage that severely impacted hydropower generation for extended periods, forcing near-constant operation of open cycle gas power plants causing electricity price spikes and GHG emissions increase [49,50]. There is evidence that the increase in severe drought occurrence and duration may be the new normal in at least some regions of Brazil due to the increased warming observed since 1961 [51]. This calls for the need to include climate change adaptation strategies into the planning of the energy sector in Brazil.

6. Final remarks

This paper presents a model comparison study in which the interactions between strategies for climate change mitigation and adaptation are investigated for Brazil. Impacts on hydropower production – the major source of electricity generation in Brazil – and associated adaptation strategies under mitigation constraints were assessed in energy scenarios through 2050, generated by six integrated energy models. These models simulated combinations of two emissions mitigation pathways (RCP 8.5 and RCP 4.5) and two impact scenarios (low and high).

Results of 16 GCMs indicate that the global emissions trajectory of the RCP 8.5 scenario would probably yield more severe impacts on hydropower generation in Brazil than the RCP 4.5 scenario. The median value of impact projections for RCP 8.5 is three times higher than that of RCP 4.5 in 2050. The adaptation strategies to cope with these impacts vary across models. In the absence of climate change mitigation policies, climate change impacts would generally yield even higher emissions, as adaptation strategies would stimulate fossil fuel based electricity generation. In this case, by 2050 emissions increase from a range of 2911–4274 tCO_2/year (REF scenario) to a range of 2920–4280 tCO_2/year and 2964–4318 tCO_2/year for the low and high impact scenarios, respectively (REF_CESM and REF_GFDL). Mitigation efforts could reduce the magnitude of impacts, besides leading to a more diverse and less carbon intensive mix of technological options. Finally, the POL45 scenario results provide evidence of the feasibility of adapting to eventual climate change impacts using available low carbon technologies.

Future studies could expand the analysis described in this paper to include other climate change impacts in energy production and consumption. Also, a more detailed analysis of second-order effects on other energy and economic sectors could improve our understanding of the interactions between climate change mitigation and adaptation.

The cost analysis presented in this paper is restricted to investment costs. A more thorough analysis of costs across the entire energy sector and economy is an important subject for future research. Although this may be difficult to coordinate in a multi-model comparison study, given the many differences that exist between distinct types of models, energy system modelers can adopt the procedure used here to improve their scenario building procedure by accounting for interactions between mitigation and adaptation.

Acknowledgements

The research that allowed the publication of this paper has been produced with the financial assistance of the U.S. Agency for International Development and U.S. Environmental Protection Agency in the context of the LAMP project 66027 and 69336 (under Interagency Agreements DW8992395101 and DW08992459801). The contents of this publication are the sole responsibility of the authors and can in no way be taken to reflect the views of the U.S. government. The authors would like to thank the feedback and efforts from all CLIMACAP and LAMP project partners for enabling the research results reported in this article.

We acknowledge the support of the Brazilian National Research Council (CNPq) in doing this research. We would like to thank Roberto Schaeffer, Leon Clarke, Stephanie Waldhoff and Camila Ludovique Callegari for their support.

Appendix A. Main features of the energy system models use in this study

Model Type/ Feature	ADAGE	GCAM	PHOENIX	IMAGE	COFFEE	TIAM-ECN	MESSAGE-Brazil
Basic model features							
Economic Coverage and Feedback	General Equilibrium	Partial Equilibrium	General Equilibrium	Partial Equilibrium	Partial Equilibrium	Partial Equilibrium	Partial Equilibrium
Model Type	Optimization	Simulation	Optimization	Simulation	Optimization	Optimization	Optimization
Foresight	Recursive-dynamic	Myopic	Myopic	Myopic	Intertemporal optimization	Intertemporal optimization	Intertemporal optimization
Calibration to base-year shares	Calibrated to base-year production	Calibrated discrete-choice model	Calibrated production function	Calibrated discrete-choice model	No base year calibration		No base year calibration
Representation of key regional resources							
Solar power supply	Nested CES function with elasticity of substitution between fixed factor and the rest	Regional supply curves	Fixed factor in GCE	Regional supply curves	Regional supply curves	Regional supply curves	Sub-National supply curves
Wind power supply	Nested CES function with elasticity of substitution between fixed factor and the rest	Regional supply curves	Fixed factor in GCE	Regional supply curves	Regional supply curves	Regional supply curves	Sub-National supply curves
Bioenergy	Biofuel: endogenous land competition; Bioelctricity: Nested CES function with elasticity of substitution between fixed factor and the rest	Endogenous land competition	Endogenous land competition	Regional supply curves	Regional supply curves	Regional supply curves	Sub-National supply curves
CO_2 storage supplies	No	No limits	Fixed factor in GCE	Regional supply curves	Regional supply curves	Regional production limits	Sub-National supply curves
Expansion and share constraints for key technologies and representation of technological change							
Hydroelectric power	Fixed Path according to Climate Change Scenarios	Fixed Path according to Climate Change Scenarios	Fixed Path according to Climate Change Scenarios	Fixed Path according to Climate Change Scenarios	Fixed Path according to Climate Change Scenarios	Fixed Path according to Climate Change Scenarios	Fixed Path according to Climate Change Scenarios
Coal-fired power	No constraints on expansion; exogenous technological change	No constraints on expansion; No technological change	No constraints on expansion; Endogenous technological change	No constraints on expansion; Endogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change
Natural gas fired power	No constraints on expansion; exogenous technological change	No constraints on expansion; No technological change	No constraints on expansion; Endogenous technological change	No constraints on expansion; Endogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change
CCS in electricity generation	Not available	No constraints on expansion; No technological change	No constraints on expansion; Endogenous technological change	No constraints on expansion; Endogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change
Nculear	No constraints on expansion; exogenous technological change	No constraints on expansion; No technological change	No constraints on expansion; Endogenous technological change	No constraints on expansion; Endogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change
Biomass	No constraints on expansion; exogenous technological change	Constrained by land use allocation to biomass (i.e., must compete with other uses of land, including agriculture); No technological change.		Constrained by land use allocation to biomass (i.e., food production first); Endogenous technological change.	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change
Solar	No constraints on expansion; exogenous technological change	Capacity Model; No technological change	No constraints on expansion; Endogenous technological change	No constraints on expansion; Endogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change
Wind	No constraints on expansion; exogenous technological change	Capacity Model; No technological change	No constraints on expansion; Endogenous technological change	No constraints on expansion; Endogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change	Growth Constraint; Exogenous technological change

Note: based on [52].

Appendix B. Detailed Results for Adapation – Changes in Electricity Generation in Climate Change Scenarios (vs. Baseline) in 2050 (TWh/yr).

		Hydro[1]	Coal	Coal w/CCS	Gas	Gas w/CCS	Oil	Nuclear	Biomass	Biomass w/CCS	Solar	Wind	Other
REF_GFDL vs REF	ADAGE	−69.36	22.02	0.00	15.06	0.00	24.39	0.00	0.00	0.00	0.00	0.00	0.00
	COFFEE	−69.37	0.00	0.00	0.00	0.00	0.00	0.00	69.37	0.00	0.00	0.00	0.00
	GCAM	−69.42	9.17	0.00	31.88	0.00	10.89	1.35	8.16	0.00	1.50	3.93	0.00
	IMAGE	−67.14	−5.47	0.00	45.03	0.00	0.00	7.32	7.65	0.00	1.98	2.47	0.00
	MESSAGE-Brazil	−72.49	33.68	−0.01	0.30	0.00	0.00	0.00	12.13	0.00	0.00	0.00	0.00
	Phoenix_6LA	−69.73	41.39	0.00	26.77	0.00	1.16	0.29	2.70	0.00	0.71	0.17	0.00
	TIAM-ECN	−63.55	29.39	0.00	23.64	0.00	0.00	0.00	−2.52	0.00	0.00	0.00	0.00
REF_CESM vs REF	ADAGE	−8.08	2.55	0.00	1.74	0.00	2.82	0.00	0.00	0.00	0.00	0.00	0.00
	COFFEE	−7.98	0.00	0.00	0.00	0.00	0.00	0.00	7.98	0.00	0.00	0.00	0.00
	GCAM	−8.33	1.39	0.00	5.11	0.00	0.73	0.06	1.16	0.00	−0.03	−0.03	0.00
	IMAGE	−8.73	−2.49	0.00	2.24	0.00	0.00	3.73	1.83	0.00	0.94	0.97	0.00
	MESSAGE-Brazil	−7.98	1.78	0.00	0.03	0.00	0.00	0.00	2.56	0.00	0.00	0.00	0.00
	Phoenix_6LA	−8.57	4.43	0.00	2.89	0.00	0.14	0.04	0.33	0.00	0.01	0.02	0.00
	TIAM-ECN	−8.00	3.20	0.00	2.57	0.00	0.00	0.00	0.71	0.00	0.00	0.00	0.00
POL45_GFDL vs POL_45	ADAGE	−52.97	12.87	0.00	12.57	0.00	21.31	0.00	0.00	0.00	0.00	0.00	0.00
	COFFEE	−52.97	0.00	0.00	0.00	0.00	0.00	0.00	52.97	0.00	0.00	0.00	0.00
	GCAM	−52.76	4.73	0.07	22.74	2.35	7.16	1.32	7.15	0.30	1.58	4.05	0.00
	IMAGE	−51.12	−1.08	0.05	25.04	0.00	0.00	10.26	7.87	0.00	0.06	0.43	0.00
	MESSAGE-Brazil	−49.19	1.16	1.16	0.00	0.00	0.00	0.00	6.53	0.00	0.00	24.12	0.00
	Phoenix_6LA	−52.45	9.75	0.08	6.25	0.06	0.68	0.27	3.29	0.00	1.72	0.15	0.00
	TIAM-ECN	−47.15	−2.12	−2.12	−0.36	0.00	0.00	0.00	12.80	9.00	24.38	12.62	0.00
POL45_CESM vs POL_45	ADAGE	−1.81	0.46	0.00	0.45	0.00	0.77	0.00	0.00	0.00	0.00	0.00	0.00
	COFFEE	−1.80	0.00	0.00	0.00	0.00	0.00	0.00	1.80	0.00	0.00	0.00	0.00
	GCAM	0.00	−0.07	0.00	−0.05	0.02	−0.09	0.02	0.06	0.00	0.01	0.08	0.00
	IMAGE	−1.39	−0.08	0.00	2.01	0.00	0.00	−1.22	0.66	0.00	−0.03	0.03	0.00
	MESSAGE-Brazil	−1.80	−0.04	−0.04	0.00	0.00	0.00	0.00	0.17	0.00	0.00	−0.27	0.00
	Phoenix_6LA	0.15	−0.03	0.00	0.00	0.00	0.04	0.00	−0.01	0.00	−0.51	0.01	0.00
	TIAM-ECN	−1.79	0.80	0.79	0.80	0.00	0.00	0.00	−1.79	−1.79	1.69	0.73	0.00

Note: [1] Hydropower generation has been harmonized, but it can vary slightly across models due to issues such as model structure, aggregation, operational constraints, reporting, etc.

Appendix C. Stochastic Sensitivity Analysis

The deterministic cost analysis of section 4.3 uses the investment cost parameters presented in Table C1. For CGE models that do not report installed capacity, the capacity factors of Table C1 were used to calculate generation capacity from electricity generation projections.

Table C1
Performance and investment costs characteristics of power generation technologies

Option	Operational Capacity factor	Investment Cost (US$/kW)				
		2010	2020	2030	2040	2050
Oil	0.50	1400	1400	1400	1400	1400
Gas	0.50	1000	1000	900	900	900
Gas w/CCS	0.85	3000	3000	2800	2500	2300
Coal	0.80	3000	3000	2700	2250	2250
Coal w/CCS	0.80	5500	4700	4700	4000	4000
Biomass	0.60	3500	3500	3500	3500	3500
Biomass w/CCS	0.80	5500	5500	5000	4500	4500
Nuclear	0.90	4000	4000	4000	4000	4000
Wind	0.30	1800	1700	1600	1500	1400
Solar/PV	0.30	4000	3500	2000	1500	1200
Solar/CSP	0.60	6000	6000	4500	4000	3500

Sources: [53–55].

This section explores the methodological procedure and results of the stochastic sensitivity analysis of the investment cost analysis, as shown in Section 4.

Methodology

The main objective of the stochastic analysis is to help verifying how the uncertainties and fluctuations of the input data, especially related to the cost of energy technologies, may affect the overall findings of the deterministic analysis performed by each model in this study.

The stochastic analysis was performed using the Crystal Ball® software, which is useful for making forecasts from the variability of input parameters of a deterministic model, by a Monte Carlo approach. This program has been used in public health [56], environmental impact assessment [57–59], risk analysis [60] and cost analysis (Rochedo and Szklo, 2011).

The Crystal Ball® uses a Monte Carlo sampling approach, supported also by the Latin hypercube (Rochedo and Szklo, 2011). Thus, it was possible to sample about 10,000 values for each case study at intervals that cover the full range of variation of the parameters.

The first step of the methodological procedure is to determine the variation profile of each selected parameter, in this case, the investment cost of energy technologies. For this, an extensive review of the literature data was performed [40,61–70]. Thus, it was possible to determine the profile, mean value and standard deviation for each route. Whenever data availability was an issue, the approach used in this study was to select another technology as proxy and assume a similar distribution and coefficient of variation. Results of this analysis, which is the main input for the stochastic analysis, are summarized in Table C2.

cumulative investment in 2050 for each model and each scenario analyzed in this study, resulting in 42 profiles. Therefore, each model is analyzed in an isolated and independent manner. Results are present in terms of the mean value, standard deviation, median and confidence levels of 25% and 75%.

Given the different power technology expansion in each case, each case (model and scenario pair) presented a distribution profile. Most of the cases were better fitted by a normal distribution, with the most notable exception in the case of the IMAGE model, which presented a lognormal profile. The IMAGE model also presented the largest relative standard deviations of all models. On the other hand, TIAM-ECN presented the lowest relative value for standard deviation on climate policy scenarios, which is partially explained by the fact that TIAM-ECN presented the largest values for investment cost at the median value. It is also worth noting that the median value for each case is roughly the same value observed in the deterministic analysis in section 4.3.

Table C2
Distribution profile of investment cost of energy technologies

Technology	Mean	Standard Deviation	Coef. of Variation	Distribution	R^2	p-value
Oil	1400	704	0.503	Normal	Note 1	
Gas	1000	409	0.409	Normal	0.9179	0.011
Gas/CCS	3000	1326	0.442	Normal	Note 2	
Coal	3000	1509	0.503	Normal	0.9659	0.0001
Coal/CCS	5500	2431	0.442	Normal	0.9481	0.0002
Biomass	3500	1760	0.503	Normal	Note 1	
Nuclear	4000	4801	1.200	Lognormal	0.9611	0.0001
Wind	1800	208	0.115	Lognormal	0.8159	0.0099
Solar/PV	4000	1101	0.275	Normal	0.9781	0.0064
Solar/CSP	6000	1496	0.249	Lognormal	0.6582	0.0064
Biomass/ccs	5500	2431	0.442	Normal	Note 2	

Notes: 1 - The coefficient of variation and distribution profile of Coal was used as proxy.
2 - The coefficient of variation and distribution profile of Coal/CCS was used as proxy.

The probabilistic analysis performed in this study can be split in two broad categories:

- Independent Analysis: considering each isolated model results, on which only the uncertainty related to the cost of the energy technologies was assessed.
- Combined Analysis: which considers each model's result as equiprobable, providing a common cost estimate across all models.

For the Combined Analysis, both investment analysis performed in Section 4.3 was considered. The first, related to the additional cost of climate change impact scenarios when compared to the corresponding baseline. The second, considering the investment cost differences between REF and POL45 scenarios, for low and high impacts (Fig. 6).

Results

Results of the stochastic sensitivity analysis in the Independent Analysis available in Table C3. This table presents the profile for the

The results for the Combined Analysis are presented in Table C4 and Table C5. In this analysis, all model results for expansion of power technologies are jointly assessed to determine a single cost estimate for each scenario. The approach used in this step was to consider each individual model result as equiprobable, resulting in a 14.28% probability of occurrence for the result of each model. In other words, for each scenario, there is 14.28% chance that the expansion observed in each model of a given power technology (e.g. Solar PV or Wind) is considered to be most likely to occur.

Despite the larger complexity of the Combined Analysis, relative to the Independent Analysis, this approach allows for the combined assessment of the results of all models. Not only that, but also allows for an in-depth analysis of the cost uncertainty of mitigation and adaptation scenarios. Additionally, it is possible to assess how each individual model behaves, relative to this combined profile.

Table C3
Probabilistic cumulative investment cost in 2050 for individual models for each scenario

Scenario	Model	Mean	St. Dev.	Median	P25	P75
REF	ADAGE	248.9	60.4	247.3	216.8	298.0
REF	GCAM	50.2	15.9	50.8	42.0	64.2
REF	MESSAGE-Brazil	123.1	33.9	122.0	105.0	151.7
REF	Phoenix_6LA	81.6	21.8	80.5	70.0	100.3
REF	TIAM-ECN	262.6	71.3	257.6	223.1	323.2
REF	COFFEE	163.8	77.9	166.0	122.5	229.6
REF	IMAGE	298.8	96.2	281.9	251.1	346.1
REF_GFDL	ADAGE	267.3	64.3	266.3	232.5	319.6
REF_GFDL	GCAM	56.5	18.2	57.1	46.9	72.4
REF_GFDL	MESSAGE-Brazil	140.5	38.7	139.4	120.2	173.3
REF_GFDL	Phoenix_6LA	103.4	28.7	101.9	88.2	127.6
REF_GFDL	TIAM-ECN	277.1	75.4	271.2	235.2	340.4

Table C3 (*continued*)

Scenario	Model	Mean	St. Dev.	Median	P25	P75
REF_GFDL	COFFEE	195.0	93.1	198.1	145.9	273.4
REF_GFDL	IMAGE	302.0	100.2	283.8	253.1	348.5
REF_CESM	ADAGE	251.1	60.9	249.6	218.9	300.5
REF_CESM	GCAM	51.8	16.7	52.5	43.3	66.7
REF_CESM	MESSAGE-Brazil	124.2	34.2	123.0	105.9	153.1
REF_CESM	Phoenix_6LA	84.1	22.5	82.9	72.2	103.5
REF_CESM	TIAM-ECN	267.0	72.5	262.0	226.6	328.1
REF_CESM	COFFEE	168.6	80.3	170.8	126.1	235.9
REF_CESM	IMAGE	301.1	98.3	283.3	252.6	348.1
POL45	ADAGE	227.0	59.7	223.3	195.8	270.8
POL45	GCAM	29.6	6.4	28.5	26.3	33.3
POL45	MESSAGE-Brazil	121.5	35.8	121.3	102.5	151.2
POL45	Phoenix_6LA	50.4	14.9	49.9	42.2	63.1
POL45	TIAM-ECN	499.3	85.2	500.7	458.4	569.6
POL45	COFFEE	204.1	79.3	205.5	163.5	265.8
POL45	IMAGE	281.2	125.8	252.6	220.9	324.5
POL45_GFDL	ADAGE	233.3	57.4	232.4	202.5	279.2
POL45_GFDL	GCAM	32.7	7.3	31.6	29.0	37.0
POL45_GFDL	MESSAGE-Brazil	139.7	37.9	139.4	119.3	170.9
POL45_GFDL	Phoenix_6LA	57.4	16.4	56.7	48.4	71.5
POL45_GFDL	TIAM-ECN	513.7	87.4	515.8	469.6	585.7
POL45_GFDL	COFFEE	228.0	81.0	228.4	188.0	291.4
POL45_GFDL	IMAGE	285.3	132.3	254.3	221.8	327.8
POL45_CESM	ADAGE	220.3	55.0	217.3	190.8	263.3
POL45_CESM	GCAM	29.5	6.4	28.5	26.3	33.2
POL45_CESM	MESSAGE-Brazil	121.6	35.8	121.4	102.6	151.3
POL45_CESM	Phoenix_6LA	50.6	14.9	50.1	42.4	63.3
POL45_CESM	TIAM-ECN	498.9	85.0	500.2	458.3	569.1
POL45_CESM	COFFEE	207.0	79.4	208.4	166.4	268.9
POL45_CESM	IMAGE	280.3	125.0	251.8	220.3	323.8

Table C4 presents the stochastic results from the additional cost of climate change impact. Results in Table C4 can be directly compared to the value in Fig. 5. Once again, it is possible to note that, at median values, the high impact scenario (GFDL) results in larger investment costs than the lower impact scenario (CESM). The stochastic results also corroborate the original findings of the study that dealing with the impacts in the REF case requires a larger investment than the POL45, due to the larger extent of the impact in the reference case.

Additionally, it is possible to state with a large amount of certainty (roughly 70% for all cases) that in 2050 the two impact scenarios resulted in an additional investment needed by the power sector to deal with the lower hydropower availability. It is worth noting that some models react by reducing the demand for electricity as a response to price signals, which could result in a lower investment.

In turn, results in Table C5 are comparable to the results in Fig. 6. The values represent the additional investment cost of climate policy scenario (POL45) relative to the reference scenario (REF), under the same GCM. Results for both GCM are best represented by a normal distribution with relatively large standard deviations. The median value is largely pushed by the largely positive results of TIAM-ECN, which is the only model that presented a large expansion of biomass power with CCS and an increased a capacity addition between the scenarios. Meanwhile, most models presented lower investments in the POL45, relative to the REF, in part due to energy efficiency on the demand side. Thus, the mean value of the stochastic sensitivity analysis presents an additional cost to mitigation, despite the result of 5 out of 7 models. If you would discard TIAM-ECN results as an outlier, the median value would be in the range of −6 to −7 for both GCM models.

Table C4
Probabilistic additional cost of climate change impact scenarios when compared to the corresponding baseline (REF and POL45)

Policy Scenario	GCM Model	2030					2050				
		Mean	St. Dev.	Median	P25	P75	Mean	St. Dev.	Median	P25	P75
REF	GFDL	5.1	67.2	4.3	34.4	−10.4	23.0	133.3	18.7	81.1	−11.7
REF	CESM	1.4	65.2	2.5	31.8	−12.5	6.4	121.6	8.6	65.0	−20.0
POL45	GFDL	0.3	72.1	−0.5	30.7	−14.8	13.4	176.1	14.6	96.6	−21.6
POL45	CESM	−1.1	74.1	−0.2	32.0	−14.3	5.1	177.5	4.0	86.2	−31.0

Table C5
Probabilistic investment cost differences between REF and POL45 scenarios for low and high impacts

GCM Model	2030					2050				
	Mean	St. Dev.	Median	P25	P75	Mean	St. Dev.	Median	P25	P75
GFDL	1.3	69.4	−0.2	−31.6	32.4	41.9	158.8	38.9	−37.0	112.8
CESM	3.0	69.6	2.0	−28.1	33.7	43.7	153.7	36.4	−34.9	111.9

Finally, it is worth highlighting that both analysis, stochastic (Independent and Combined) and Deterministic, performed in this study only assessed investment costs of power technologies. As such, investment in other sector, such as primary energy production and biofuels, and other relevant cost (operation and maintenance, fuel, etc) are not included in this study. Thus, these results do not provide a full view of the cost relation between different levels of mitigation and adaptation. Additionally, the investment cost analysis performed in this study was made *ex-post* to the models results. This means that it is not completely integrated with the outcome of each model, therefore the probability of a higher investment cost did not affect the expansion results of each model. This should be considered, since the model's results would most likely change due to the changes in the power technologies investment costs.

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