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2015 Environ. Res. Lett. 10 125002

(http://iopscience.iop.org/1748-9326/10/12/125002)

IOP Publishing Environ. Res. Lett. 10 (2015) 125002 doi:10.1088/1748-9326/10/12/125002

Environmental Research Letters

CrossMark



RECEIVED
30 June 2015

REVISED
13 October 2015

ACCEPTED FOR PUBLICATION
29 October 2015

PUBLISHED
24 November 2015



LETTER

# The contribution of Paris to limit global warming to 2 °C

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**Keywords:** conference of Parties, climate change, mitigation, policy, integrated assessment model, INDC, energy

Supplementary material for this article is available online

## Abstract

The international community has set a goal to limit global warming to 2 °C. Limiting global warming to 2 °C is a challenging goal and will entail a dramatic transformation of the global energy system, largely complete by 2040. As part of the work toward this goal, countries have been submitting their Intended Nationally Determined Contributions (INDCs) to the United Nations Framework Convention on Climate Change, indicating their emissions reduction commitments through 2025 or 2030, in advance of the 21st Conference of the Parties (COP21) in Paris in December 2015. In this paper, we use the Global Change Assessment Model (GCAM) to analyze the near versus long-term energy and economic-cost implications of these INDCs. The INDCs imply near-term actions that reduce the level of mitigation needed in the post-2030 period, particularly when compared with an alternative path in which nations are unable to undertake emissions mitigation until after 2030. We find that the latter case could require up to 2300 GW of premature retirements of fossil fuel power plants and up to 2900 GW of additional low-carbon power capacity installations within a five-year period of 2031–2035. INDCs have the effect of reducing premature retirements and new-capacity installations after 2030 by 50% and 34%, respectively. However, if presently announced INDCs were strengthened to achieve greater near-term emissions mitigation, the 2031–2035 transformation could be tempered to require 84% fewer premature retirements of power generation capacity and 56% fewer new-capacity additions. Our results suggest that the INDCs delivered for COP21 in Paris will have important contributions in reducing the challenges of achieving the goal of limiting global warming to 2 °C.

## 1. Introduction

The international community is focused on limiting the global mean surface temperature increase relative to pre-industrial values to 2 °C. To that end, countries have committed to create an international climate agreement by the conclusion of the United Nations Framework Convention on Climate Change UNFCCC) Conference of the Parties (COP21) in Paris in December 2015. Leading up to COP21, industrialized as well as developing countries are submitting their Intended Nationally Determined Contributions (INDCs), indicating their emissions reduction commitments for the near term (to 2025 or 2030). For example, the USA has committed to reduce economy-wide greenhouse gas (GHG) emissions by 26–28% below 2005 levels in 2025. Likewise, the European Union (E.U.) has committed to reduce 2030 GHG emissions (excluding emissions from land-use changes) by 40% relative to 1990. Among developing countries, Mexico has committed to reduce GHG emissions by 22–40% from business as usual emissions in 2030 (UNFCCC 2015). Along similar lines, China has recently announced that it intends to achieve a peaking of $CO_2$ emissions from fossil fuels before 2030 and increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030 (The White House 2014). Other countries have either announced their contributions or are expected to announce them in the coming months (UNFCCC 2015).

Limiting global warming to 2 °C is a challenging goal and will entail a dramatic transformation of the global energy system. Emissions reduction commitments for the near term, such as those described above, raise an important question for international climate policy: What do such commitments and, by extension, the ensuing COP21 in Paris imply for the long-term costs and challenges of limiting global warming to 2 °C? In other words, what is the contribution of Paris?

The answer to this question hinges on the relationship between emissions and global mean temperature increase. Recent research has shown that the peak global mean surface temperature increase varies linearly with cumulative $CO_2$ emissions (IPCC 2014). This characteristic has led to the suggestion that global cumulative $CO_2$ emissions for the rest of this century could be used as a benchmark for climate policy aiming at limiting global warming.

The near-linear relationship between the global mean surface temperature increase and cumulative $CO_2$ emissions suggests that any near-term emissions mitigation that the Paris agreement facilitates would make achieving a long-term temperature target easier compared to a scenario in which countries undertake no near-term mitigation actions and postpone their actions into the future. This is simply because a cumulative emissions limit for the rest of this century implies a need for a corresponding cumulative emissions mitigation that becomes increasingly more challenging if its implementation is deferred. Thus, near-term emissions mitigation reduces the need for more drastic mitigation action in the long term.

We analyze the global energy system and economic cost implications of an INDC-based agreement that could emerge from COP21 by comparing three scenarios with a global cumulative $CO_2$ emissions budget constraint consistent with the 2 °C target. In the first, *Ideal* scenario, the global cumulative $CO_2$ emissions budget follows a globally cost-minimizing emissions pathway starting in 2021 (details in Methods section). This is the least-cost emissions path to meet the 2 °C target. In the second (*Paris*) scenario, we assume that at COP21 in Paris, countries agree to and implement emissions reductions through 2030 based on submitted INDCs. In the third, *No Paris*, or worst-case, scenario, we assume that the Paris negotiations collapse, and countries undertake no emissions mitigation until 2030. We assume further that in the second and the third scenarios, emissions reductions beyond 2030 are achieved according to globally optimal pathways.

## 2. Methods

### 2.1. The global change assessment model

In this study, we use the Global Change Assessment Model (GCAM) version 4.0[5]. GCAM is an open-source model primarily developed and maintained at the Pacific Northwest National Laboratory's Joint Global Change Research Institute[6].

GCAM combines dynamic-recursive models of the global energy, economy, agriculture, and land-use systems (Edmonds and Reilly 1985, Sands and Leimbach 2003, Edmonds *et al* 2004, Kim *et al* 2006) with a reduced-form atmosphere-carbon-cycle-climate model, the Model for the Assessment of Greenhouse-Gas Induced Climate Change (Wigley and Raper 1992, Wigley 2008, Meinshausen *et al* 2011). Outcomes of GCAM are driven by assumptions about population growth, labor participation rates, and labor productivity in 32 geopolitical regions, along with representations of resources, technologies, and policy. GCAM operates in five-year time steps from 2010 (calibration year) to 2100 by solving for the equilibrium prices and quantities of various energy, agricultural, and GHG markets in each time period and in each region. GCAM tracks the emissions of 16 GHGs endogenously based on the resulting energy, agriculture, and land use systems.

The energy system formulation in GCAM comprises detailed representations of extractions of depletable primary resources such as coal, natural gas, oil, and uranium along with renewable sources such as bioenergy, hydro, solar, and wind (at regional levels). GCAM also includes representations of the processes that transform these resources to final energy carriers, which are ultimately used to deliver goods and services demanded by end users in buildings, transportation, and industrial sectors. Each technology in the model has a lifetime, and, once invested, technologies operate till the end of their lifetime or are shut down if the variable cost exceeds the market price. The deployment of technologies in GCAM depends on relative costs and is achieved using an implicit probabilistic formulation that is designed to represent decision making among competing options when only some characteristics of the options can be observed (Clarke and Edmonds 1993, McFadden 1980, Train 1993).

[5] The most recent release version of the model can be downloaded online at: http://www.globalchange.umd.edu/models/gcam/.

[6] The full documentation of the model is available at the GCAM wiki (http://wiki.umd.edu/gcam/index.php?title=Main_Page), and the description in this section is a summary of the wiki documentation.

**Table 1.** Scenarios explored in this paper.

<table>
<tr><th rowspan="3">Scenario</th><th rowspan="3">Country/Region</th><th colspan="4">Modeling assumptions[a]</th><th colspan="2">Outputs</th></tr>
<tr><th rowspan="2">2020</th><th rowspan="2">2025</th><th rowspan="2">2030</th><th rowspan="2">Post-2030</th><th>2011-2100 cumulative $CO_2$ emissions[b]</th><th>Global mean surface temperature increase in 2100[c]</th></tr>
<tr><th>[$GtCO_2$]</th><th>[°C]</th></tr>
<tr><td rowspan="6">Baseline</td><td>USA</td><td rowspan="6" colspan="4">No explicit climate policy</td><td rowspan="6">4,750</td><td rowspan="6">3.4</td></tr>
<tr><td>China</td></tr>
<tr><td>Mexico</td></tr>
<tr><td>EU</td></tr>
<tr><td>Other Annex 1</td></tr>
<tr><td>Other Non-Annex 1</td></tr>
<tr><td rowspan="6">Ideal</td><td>USA</td><td rowspan="6">Copenhagen</td><td rowspan="6" colspan="3">Global carbon price to achieve global cumulative $CO_2$ budget constraint</td><td rowspan="6">1,300</td><td rowspan="6">2.0</td></tr>
<tr><td>China</td></tr>
<tr><td>Mexico</td></tr>
<tr><td>EU</td></tr>
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<tr><td rowspan="6">Paris</td><td>USA</td><td rowspan="6">Copenhagen</td><td colspan="2">INDC</td><td rowspan="6">Global carbon price to achieve global cumulative $CO_2$ budget constraint</td><td rowspan="6">1,300</td><td rowspan="6">2.0</td></tr>
<tr><td>China</td><td colspan="2">USA-China joint announcement on climate change</td></tr>
<tr><td>Mexico</td><td colspan="2">INDC</td></tr>
<tr><td>EU</td><td colspan="2">INDC</td></tr>
<tr><td>Other Annex 1</td><td colspan="2">Comparable to USA</td></tr>
<tr><td>Other Non-Annex 1</td><td colspan="2">Comparable to China</td></tr>
<tr><td rowspan="6">No Paris</td><td>USA</td><td rowspan="6" colspan="3">No explicit climate policy</td><td rowspan="6">Global carbon price to achieve global cumulative $CO_2$ budget constraint</td><td rowspan="6">1,300</td><td rowspan="6">2.0</td></tr>
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<tr><td>Other Non-Annex 1</td></tr>
</table>

[a] See table S1 for detailed modeling assumptions.

[b] Includes $CO_2$ emissions from fossil fuels, industry, and land-use changes. Numbers are rounded to the nearest 50.

[c] Temperature increases are calculated using the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC6.8) (Meinshausen *et al* 2011). Increases are calculated with respect to pre-industrial average (1750–1849).

### 2.2. Experimental design

The reference scenario (labeled *Baseline*) is based on reference assumptions in Thomson *et al* (2011), except as noted. The *Baseline* scenario depicts a world in which the global population reaches a maximum of 9.5 billion in 2070 and then declines to 9 billion in 2100, while global gross domestic product (GDP) grows by an order of magnitude between 2010 and 2100, and primary energy consumption almost doubles between 2010 and 2100. Further, this scenario excludes all policies explicitly designed to limit GHG emissions, and, therefore, fossil fuels continue to dominate global energy consumption. Most of the increase in demand for energy occurs in the fast-growing Non-Annex 1 regions. While assumptions about population and GDP are exogenous and fixed across scenarios explored in this study, energy demand and prices are endogenous to the model and may vary across scenarios.

We explore three emissions mitigation scenarios with a cumulative $CO_2$ emissions budget constraint over the century (table 1 and S1). In the first scenario (labeled *Ideal*), global emissions through 2020 follow Copenhagen commitments (Riahi *et al* 2015) (section S1), and subsequent emissions reductions are assumed to be achieved cost-effectively by employing a globally optimal price on carbon starting in 2021 and rising exponentially thereafter, consistent with a present-discounted-cost-minimizing price pathway (Peck and Wan 1996).

In the second scenario (labeled *Paris*), global emissions through 2030 are modeled based on recently submitted INDCs and announcements made in the first quarter of 2015 by major economies (namely, the USA, the E.U., Mexico, and China), along with assumptions about comparable levels of effort by the rest of the world (section S1). The assumption is that countries agree to reduce emissions through 2025 or 2030 at COP21 in Paris, based on submitted INDCs. We assume that countries achieve emissions reductions through 2030 by means of a uniform price on carbon across all sectors of the economy. Further, we also assume that carbon prices between 2025 and 2030 increase exponentially. It is important to note that in reality, many countries are expected to implement their INDCs by employing a range of policies, not just economy-wide carbon prices. For example, the USA is expected to reduce overall GHG emissions by a range of sector and GHG-specific policies, including the Clean Power Plan, vehicle fuel economy standards, policies to reduce hydrofluorocarbons and methane emissions, and more. We do not explicitly model such policies in the USA or other countries; we focus on overall emissions instead. While the choice of near-term policies could influence the nature and magnitude of challenges of post-2030 mitigation, it would not materially affect the qualitative insights of this analysis. Beyond 2030, emissions reductions in the *Paris* scenario are achieved by employing a globally optimal price on carbon starting in 2031 and rising exponentially thereafter.

In the third scenario (labeled *No Paris*), we assume that countries fail to agree upon any emissions reduction targets for the near term and do not undertake any emissions mitigation action until 2030. The cumulative emissions budget constraint is then achieved by employing a globally optimal price on carbon starting in 2031 and rising exponentially thereafter. This scenario is useful to understand the 'contribution' of near-term mitigation actions, including the INDCs and the ensuing COP21, in terms of the challenges of limiting global warming to 2 °C and provides a point of departure for comparison.

In the *Ideal*, *Paris*, and *No Paris* scenarios, we impose a 2011–2100 cumulative $CO_2$ emissions budget constraint of 1300 $GtCO_2$, a budget that is consistent with a 50% probability of limiting net anthropogenic warming to 2 °C (IPCC 2014) (section S2)[7]. It is important to note that the global cumulative budget constraint is based only on $CO_2$ emissions from fossil fuels, industry, and land-use changes (LUCs) and do not include non-$CO_2$ emissions. However, individual country targets through 2020 in the *Ideal* scenario and through 2030 in the *Paris* scenarios are modeled in accordance with the submissions to UNFCCC and may or may not include LUC emissions and non-$CO_2$ emissions. For instance, in the *Paris* scenario, the USA's 2025 emissions are represented as a 27% reduction in *all* GHG emissions with respect to 2005 levels, consistent with its INDC. On the other hand, the E.U.'s 2030 constraint does not include LUCs (UNFCCC 2015). Throughout, we assume that all GHGs, excluding $CO_2$ emissions from LUCs, face the same carbon price. $CO_2$ emissions from LUCs are assumed to face a price that is 10% of the price on other gases. The latter assumption is made to avoid rapid transitions in land use to bioenergy production and afforestation (Wise *et al* 2009). In addition, since the focus of our study is on the energy system, we present results for $CO_2$ emissions from fossil fuels and industry only.

Previous research has shown that scenarios achieving cumulative $CO_2$ emissions budgets similar to the one explored in this study are characterized by substantial net negative emissions, especially after 2050 (Kriegler *et al* 2015). Negative emissions can be achieved, for example, through afforestation or the use of sustainable bioenergy with $CO_2$ capture and storage (BECCS). In some previously modeled scenarios, BECCS technology is deployed at scales so large that the global system has not only ceased to introduce $CO_2$ into the atmosphere but has reached the point at which the global system is removing carbon at rates similar to all present-day fossil fuel emissions (Riahi *et al* 2015). Such scenarios meet an end-of-century emissions limit goal by first exceeding the limit and later on removing the excess emissions using BECCS. While negative emissions energy technologies such as BECCS exist and have been demonstrated (Gough and Upham 2011), questions remain as to the ability of societies to deploy BECCS at the scales needed to remove excess emissions from an overshoot trajectory and, additionally, the environmental consequences of overshoot scenarios compared to scenarios that never exceed the cumulative target (Fuss *et al* 2014, Eom *et al* 2015). To avoid such concerns, we limit the deployment of negative emissions technologies so that global $CO_2$ emissions are never net negative throughout the century (figures S1 and S2) (UNEP 2014). This makes our results more conservative.

Finally, it should be noted that although it might be possible to construct scenarios with varying assumptions about near-term emissions trajectories, $CO_2$ emissions budgets, non-$CO_2$ emissions, and negative emissions, the broad qualitative insights of this analysis will not be affected.

## 3. Results and discussion

### 3.1. Emissions pathways to achieve the cumulative $CO_2$ emissions budget

Through 2030, the *Paris* scenario involves substantial reductions in $CO_2$ emissions from fossil fuels and industry, relative to the *Baseline* (figure 1(a)). However, near-term emissions in the Paris scenario are higher compared with the *Ideal* scenario, which is

[7] This budget takes into consideration the effects of non-$CO_2$ emissions on climate forcing. See section S2 for more details.

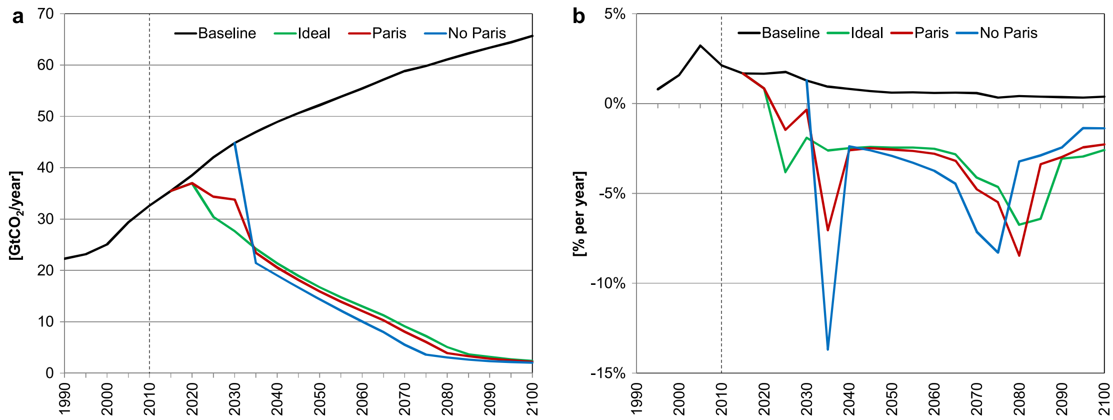


**Figure 1.** (a) Global $CO_2$ emissions from fossil fuels and industry and (b) annual rate of change in emissions. Global GHG pathways are presented in figure S3.

constructed to implement Copenhagen Commitments through 2020, with subsequent emissions reductions being achieved by means of a globally optimal carbon price (figure S1). To the extent that the emissions pathway of the *Paris* scenario does not align with the *Ideal* scenario, emissions mitigation in the *Paris* scenario is suboptimal.

Consequently, in order to catch up with the cost-effective pathway of achieving the cumulative $CO_2$ emissions budget, emissions in the *Paris* scenario decrease at a faster rate (5% per year on average) during the period from 2030–2040 compared with the *Ideal* scenario (3% per year). Nevertheless, the post-2030 emissions reductions in the *Paris* scenario are significantly slower compared to the *No Paris* scenario, in which emissions continue to rise between 2020–2030, requiring reductions at 8% per year, on average, between 2030–2040.

The above rates of emissions decline, particularly the ones in the *Paris* and the *No Paris* scenarios, are considerably higher than historical rates. Emission decline rates of about 2% per year have been observed in France between 1980–2000 due to the scaling up of nuclear power, in Sweden during the 1974–2000 period due to a shift in energy policies as a response to the oil crisis (about 2–3% per year), and in Denmark due to the rapid deployment of wind technologies (Riahi *et al* 2015). While these rates are broadly consistent with the global rates in the *Ideal* scenario, it is important to note that they were achieved at the national scale. Similar decline rates at the global scale would involve substantial challenges, including coordinated efforts by emitting countries with different national circumstances, priorities, and preferences (Riahi *et al* 2015). Further, such challenges would be greater in the *Paris* and *No Paris* scenarios, which involve higher decline rates. As we discuss further, such accelerated emissions reductions are accompanied by dramatic transformations of the energy system within a short period of time.

### 3.2. Energy system transformations to achieve the cumulative $CO_2$ emissions budget

In the *Baseline*, the energy system is dominated by fossil fuels (figure 2(a)). Near-term emissions reductions through 2030 in the *Ideal* scenario are achieved by reducing fossil fuel-based energy consumption and increasing the deployment of low-carbon technologies such as nuclear and renewables (figure 2(b)). In addition, the increased deployment of low-carbon technologies raises energy prices, inducing energy conservation and reduction in energy demand.

With higher emissions through 2030 compared to the *Ideal* scenario, the near-term energy system transformation is less pronounced in the *Paris* scenario (figure 2(c)). However, the accelerated emissions reduction during the period from 2030–2040 is achieved by faster deployment of low-carbon technologies and reduction in energy demand. By extension, in the *No Paris* scenario, which requires even faster emissions reductions during this period, the deployment of low-carbon technologies is even more rapid, and reduction in energy demand greater (figure 2(d)).

Such transformations in the energy system are accompanied by changes in the type and scale of investments in the energy sector. Of particular interest is the pattern of investments in the electricity generation sector—a pivotally important sector in most assessments of climate change mitigation (Clarke *et al* 2014). Near-term emissions reductions through 2030 in the *Ideal* and *Paris* scenarios involve some premature retirements of fossil fuel-based power plants (that is, retirements before natural shutdown at the end of their lifetime) and investments in low-carbon technologies relative to the *Baseline* scenario (figure 3). Since emissions during this period in the *Paris* scenario are higher compared to the *Ideal* scenario, the above changes are less pronounced.

Beyond 2030, accelerated emissions reductions in the *Paris* scenario require accelerated premature retirements of fossil fuel-based capacity compared with the *Ideal* scenario. For example, in the *Ideal*

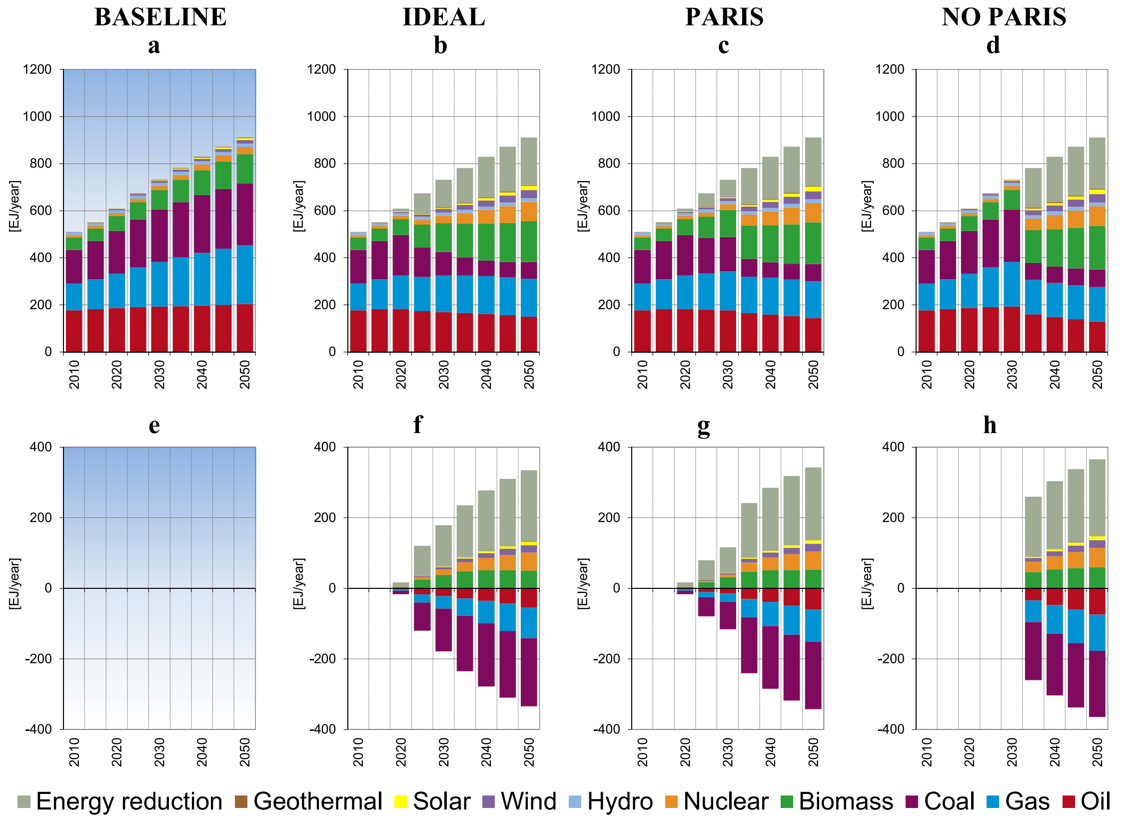


**Figure 2.** (a)–(d): Primary energy consumption by fuel in the scenarios explored in this study. (e)–(h) are changes in primary energy consumption relative to the *Baseline* scenario.

scenario, the installed capacity of coal in 2030 is about 710 GW. In the following five years, that is, between 2031–2035, about 38% (270 GW) of this capacity is prematurely retired. In contrast, in the *Paris* scenario, premature retirements during the same period increase to 72% (900 GW of the 1250 GW capacity in 2030). The residual demand is then satisfied by rapid deployment of low-carbon technologies. For example, in the *Ideal* scenario, about 515 new nuclear power plants (1000 MW each) are built during the five-year period from 2031–2035. In contrast, in the *Paris* scenario, 790 new nuclear power plants (54% more than the *Ideal* scenario) are built during the same period.

The degree of difficulty involved in such changes can be better appreciated by comparing the above results with historical rates of deployments in the electricity generation sector. In the *Paris* scenario, the average rate of capacity additions between 2031–2035 (430 GW/year) is 1.4 times the rate in the *Ideal* scenario and about 2.5 times the rate between 2000–2012 in electricity generation across the globe (170 GW/year, according to data from EIA (2015)). This corresponds to about a trillion U.S. dollars' (USD) worth of capital investments (figure S4), which is about 1.5 times the rate of capital investments during the same period in the *Ideal* scenario and about four times the average rate of capital investments in electricity generation between 2000–2012 (267 billion USD/year; EIA (2014)).

Changes that are so dramatically different from the past are possible in simulation models with full technological flexibility. However, in reality, such changes could be seriously challenged by a range of socioeconomic, behavioral, and institutional factors, including the lack of capital, infrastructures, institutional frameworks, public perceptions, and social acceptance (Iyer *et al* 2015a, Iyer *et al* 2014, Moss *et al* 2010, O'Neill *et al* 2013, Hultman *et al* 2012), and could lead to extremely high costs and even infeasibilities (Iyer *et al* 2015b). This suggests that if real-world factors are taken into account, the challenges of rapid premature retirements of fossil fuel-based capacity and dramatic increases in low-carbon capacity deployments in a short period of time in the *Paris* scenario could be substantially greater than what is implied by our analysis.

The magnitude of such challenges will be even greater for the *No Paris* scenario. For example, in the *No Paris* scenario, almost 90% of coal-fired power plants in 2030 are prematurely retired during the period from 2031–2035. During the same period, about 1150 new nuclear power plants (1000 MW each; 124% more than the *Ideal* scenario) are built. In addition, the average rate of capacity additions (610 GW/year) is twice the rate in the *Ideal* scenario and more than thrice the rate between 2000–2012 in electricity generation across the globe. Likewise, capital investments per year during this period are as high as 1420 billion

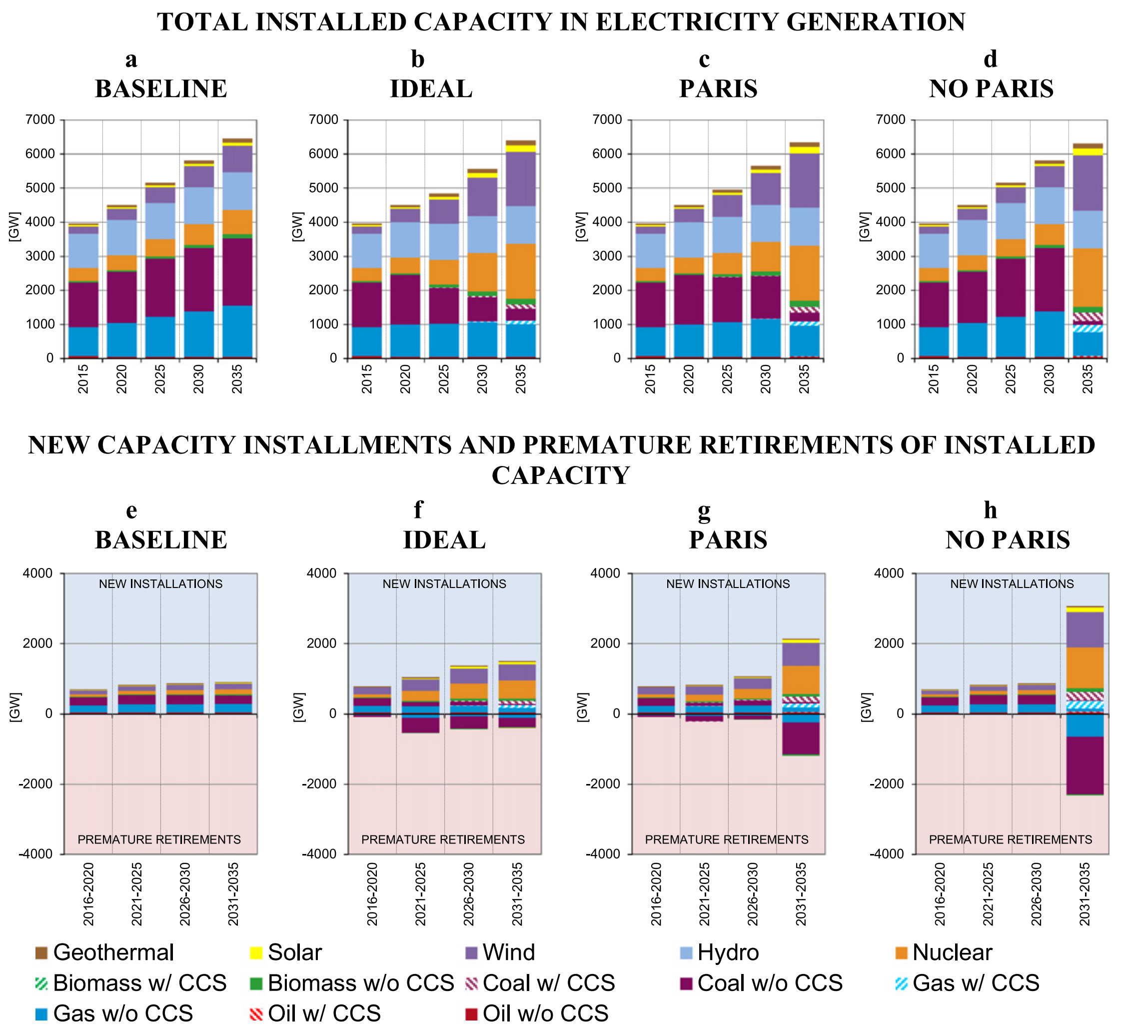


**Figure 3.** (a)–(d): Total installed capacity; (e)–(h) represent new capacity installments and premature retirements (retirements before natural shutdown at the end of lifetime) of installed capacity in the electricity generation sector.

USD/year (more than twice the *Ideal* scenario and more than five times the 2000–2012 average).

The above results suggest that even though all of the mitigation scenarios explored in this study involve substantial challenges, if countries fail to commit to reduce emissions in the near-term at the Paris Conference, the challenges will be exacerbated by the need for rapid mobilization of capital, investments in infrastructure, institutional capacity-building, and developing public and social acceptance within a short period of time in order to get back on track to the cost-effective pathway of achieving 2 °C. In other words, a successful agreement in Paris will be crucial in reducing the magnitude of the challenges involved in the transformations required to limit global warming to 2 °C cost-effectively.

### 3.3. Costs of achieving the cumulative $CO_2$ emissions budget

With greater emissions reductions and energy system transformations compared to the *No Paris* scenario, the near-term costs through 2030 for the *Paris* and *Ideal* scenarios are higher (figure 4). For example, capital investments in 2030 for the *Paris* scenario are 36% greater than the *No Paris* scenario. With more stringent emissions reductions, investments for the *Ideal* scenario are even greater (by 88%).

However, the post-2030 costs for the *Paris* and *Ideal* scenarios are considerably lower (figure 4 and S5). For example, capital investments in 2035 for the *Paris* scenario are lower than the *No Paris* scenario by 31%. Likewise, mitigation costs in 2035 are 36% lower. Furthermore, such reductions are greater for the *Ideal* scenario: Capital investments and mitigation costs for the *Ideal* scenario are lower than the *No Paris* scenario by 53% and 38%, respectively.

While these results are consistent with previous work on delayed mitigation and staged accession to climate cooperation, it should be noted that our results on the costs of achieving the cumulative $CO_2$ emissions budget are based on one model, and a range of technological, social, and political factors create uncertainties in cost estimates (Edmonds *et al* 2008, Clarke *et al* 2009, Jakob *et al* 2012, Rogelj *et al* 2013, Tavoni *et al* 2015, Riahi *et al* 2015, Kriegler *et al* 2015,

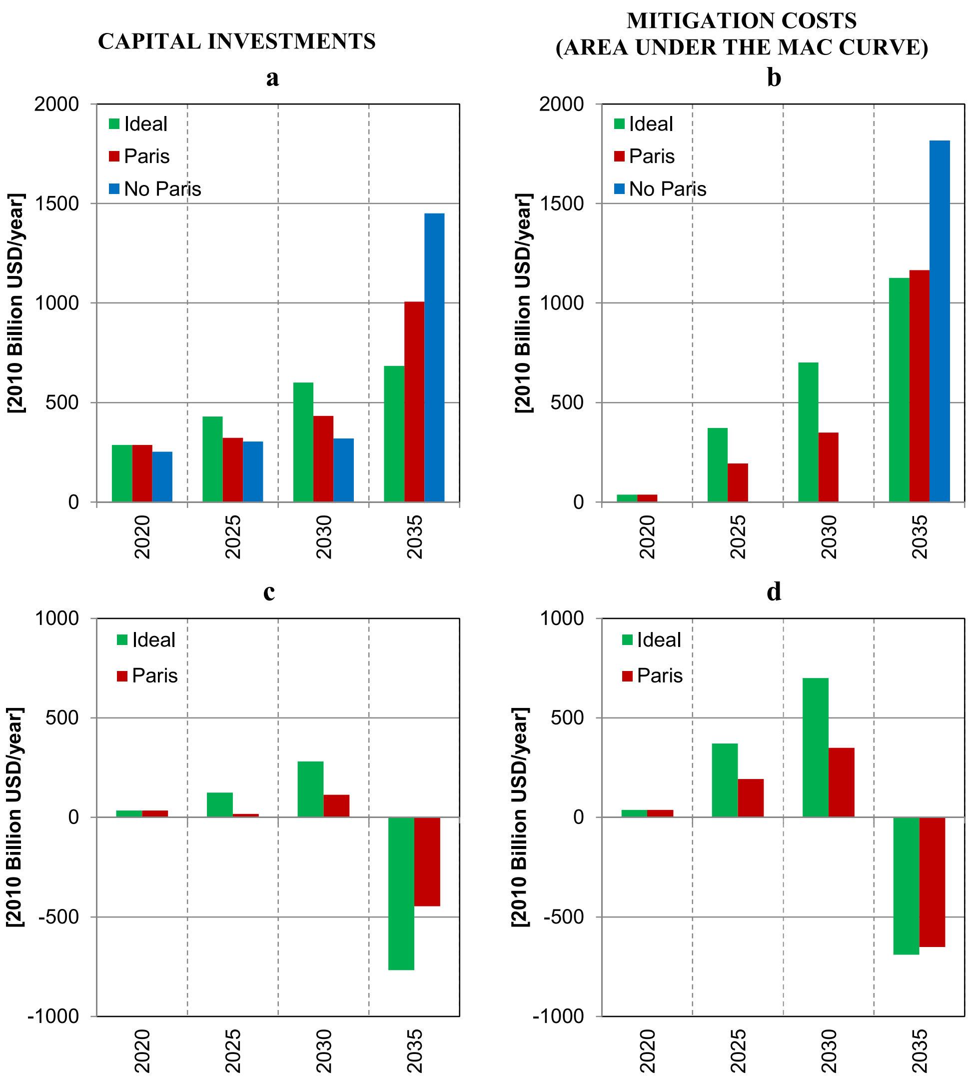


**Figure 4.** (a) Capital investments in the electricity generation sector; (b) global mitigation costs (calculated as the area under the marginal abatement cost curve); (c) and (d) differences with respect to the *No Paris* scenario.

UNEP 2014). Nevertheless, our results indicate the 'contribution' of near-term mitigation actions, including recently submitted INDCs and, by extension, the ensuing COP21 in Paris for global mitigation costs of limiting global warming to 2 °C: a successful agreement in Paris will involve some upfront costs in the near term; however, it will also lead to substantial reductions in the long-term costs of transforming the global energy system to the scenario in which countries do not undertake any mitigation in the near-term. And such reductions will be greater if countries undertake more stringent near-term emissions reductions. Moreover, these considerations are independent of the overall assessment of the benefits of avoided climate change, which might be large relative to the costs discussed here (Pizer *et al* 2014).

## 4. Conclusions

This paper uses GCAM, a global integrated assessment model, to conduct an ex-ante analysis of the impact of INDCs on the challenges of achieving a cumulative $CO_2$ emissions budget consistent with limiting global warming to 2 °C with a 50% probability.

On the one hand, our analysis shows that INDC emissions levels through 2030 are higher than a scenario following the least-cost (and immediate) pathway to 2 °C. This in turn necessitates faster emissions cuts beyond 2030 in order to get back on track, resulting in accelerated premature retirements of fossil fuel- based power supply and increases in investments in low-carbon energy supply, particularly during the decade between 2030–2040. For instance, we find that with presently announced INDCs, catching up with the cost-effective pathway will require three times as many premature retirements of fossil fuel- based power plants and 50% more low-carbon capacity additions in the electricity generation sector during the period from 2031–2035 compared to the idealized least-cost pathway. In this sense, although achieving a stringent cumulative $CO_2$ emissions budget is challenging in itself, the current pathway requires greater effort post-2030.

On the other hand, however, these challenges should be viewed in light of the alternative. The economic challenges of staying on a 2 °C pathway are greatly amplified if countries do not undertake any emissions reductions in the near term. In such a case, catching up with the cost-effective pathway will require about six times as many premature retirements of fossil fuel-based power plants and more than twice as much low-carbon capacity additions. It is important to note that the numerical results of our analysis are likely to change as more INDCs are included in the analysis. Nevertheless, our results suggest that a successful international agreement to undertake near-term emissions reductions at the ensuing COP21 in Paris will be valuable in reducing the challenges of the dramatic long-term energy system transformations required to limit global warming to 2 °C.

## Acknowledgments

Analysis of mitigation potential and levels of national mitigation action related to the conclusions of this paper was supported by the U.S. Department of State (IAA 19318814Y0012) and the U.S. Environmental Protection Agency (IAA DW–8992406301). NEH was supported by the William and Flora Hewlett Foundation. The assessments of newly submitted INDCs are continuously updated at http://www.globalchange.umd.edu/. The views and opinions expressed in this paper are those of the authors alone and do not necessarily state or reflect those of the United States Government, the Department of State, or the Environmental Protection Agency, and no official endorsement should be inferred.

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