Environmental Research Letters

LETTER

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

Gokul C Iyer1, James A Edmonds1, Allen A Fawcett2, Nathan E Hultman1, Jameel Alsalam1, Ghassem R Asrar3, Katherine V Calvin1, Leon E Clarke1, Jared Creason1, Minji Jeong1, Page Kyle1, James McFarland1, Anupriya Muntra1, Pralit Patel1, Wenjing Shi1 and Haewon C McJeon2,3

1 Joint Global Change Research Institute, Pacific Northwest National Laboratory and University of Maryland, 5825 University Research Court, Suite 3500, College Park, MD 20740, USA
2 U.S. Environmental Protection Agency, 1200 Pennsylvania Avenue, NW (6207A), Washington, DC 20460, USA
3 School of Public Policy, University of Maryland, 2101 Van Munching Hall, College Park, MD 20742, USA

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 emis-
sions in 2030 (UNFCCC 2015). Along similar lines, China has recently announced that it intends to achieve a peaking of CO₂ 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 CO₂ emissions (IPCC 2014). This characteristic has led to the suggestion that global cumulative CO₂ 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 CO₂ 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 CO₂ emissions budget constraint consistent with the 2 °C target. In the first, Ideal scenario, the global cumulative CO₂ 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 4.05. GCAM is an open-source model primarily developed and maintained at the Pacific Northwest National Laboratory’s Joint Global Change Research Institute6.

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.
### 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 CO₂ emissions budget constraint over the century (table 1 and S1). In the first scenario (labeled *Ideal*), global emissions through 2030 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

---

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

| Scenario | Country/Region | Modeling assumptions | Outputs |
|----------|----------------|----------------------|---------|
|          |                | 2020 | 2025 | 2030 | Post-2030 | 2011-2100 cumulative CO₂ emissions | Global mean surface temperature increase in 2100 |
|          |                |      |      |      |          | [GtCO₂] | [°C] |
| Baseline | USA            |      |      |      |          | 4,750   | 3.4  |
|          | China          |      |      |      |          |         |      |
|          | Mexico         |      |      |      |          |         |      |
|          | EU             |      |      |      |          |         |      |
|          | Other Annex 1  |      |      |      |          |         |      |
|          | Other Non-Annex 1 |      |      |      |          |         |      |
|          | USA            |      |      |      |          | 1,300   | 2.0  |
|          | China          |      |      |      |          |         |      |
|          | Mexico         |      |      |      |          |         |      |
|          | EU             |      |      |      |          |         |      |
|          | Other Annex 1  |      |      |      |          |         |      |
|          | Other Non-Annex 1 |      |      |      |          |         |      |
|          | USA            |      |      |      |          | 1,300   | 2.0  |
|          | China          |      |      |      |          |         |      |
|          | Mexico         |      |      |      |          |         |      |
|          | EU             |      |      |      |          |         |      |
|          | Other Annex 1  |      |      |      |          |         |      |
|          | Other Non-Annex 1 |      |      |      |          |         |      |

*aSee table S1 for detailed modeling assumptions.  
*bIncludes CO₂ emissions from fossil fuels, industry, and land-use changes. Numbers are rounded to the nearest 50.  
*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).*
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 CO2 emissions budget constraint of 1300 GtCO2, 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 CO2 emissions from fossil fuels, industry, and land-use changes (LUCs) and do not include non-CO2 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-CO2 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 CO2 emissions from LUCs, face the same carbon price. CO2 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 CO2 emissions from fossil fuels and industry only.

Previous research has shown that scenarios achieving cumulative CO2 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 CO2 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 CO2 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 CO2 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, CO2 emissions budgets, non-CO2 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 CO2 emissions budget

Through 2030, the Paris scenario involves substantial reductions in CO2 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
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 CO2 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 CO2 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
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

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

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

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
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 CO₂ 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 CO₂ 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 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.
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 emission 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 economic 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.

References

Clarke J F and Edmonds J 1993 Modelling energy technologies in a competitive market Energy Econ. 15 123–29

Clarke L, Edmonds J, Krey V, Richels R, Rose S and Tavoni M 2009 International climate policy architectures: overview of the EMF 22 International Scenarios Energy Econ. 31 566–81

Clarke L et al 2014 Assessing Transformation Pathways Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed O Edenhofer et al (Cambridge: Cambridge University Press)

Edmonds J, Clarke J, Dooley J, Kim S and Smith S 2004 Stabilization of CO2 in a B2 world: insights on the roles of carbon capture and disposal, hydrogen, and transportation technologies Energy Econ. 26 517–57

Edmonds J, Clarke L, Lurj J and Wise M 2008 Stabilizing CO2 concentrations with incomplete international cooperation Clim. Policy 8 355–76

Edmonds J and Reilly J 1985 Global Energy: Assessing the Future (Oxford: Oxford University Press)

EIA 2015 International Energy Statistics (www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=7) (accessed 24 June 2015)

Eom J, Edmonds J, Krey V, Johnson N, Longden T, Luderer G, Riahi K and Van Vuuren D P 2015 The impact of near–term climate policy choices on technology and emission transition pathways Technol. Forecast. Soc. Change 90 73–88

Fuss S et al 2014 Betting on negative emissions Nat. Clim. Change 4 850–53

Gough C and Upah P 2011 Biomass energy with carbon capture and storage (BECCS or Bio-CCS) Greenhouse Gases: Sci. Technol. 1 324–34

Hultman N, Malone E L, Runci P, Carlock G and Anderson K L 2012 Factors in low–carbon energy transformations: comparing nuclear and bioenergy in Brazil, Sweden, and the United States Energy Policy 40 131–46

IEA 2014 World Energy Investment Outlook (Paris: International Energy Agency)

IPCC 2014 Climate change 2014: synthesis report Contribution of Working Groups I, II and III 2014 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed R K Pachauri and L A Meyer (Geneva: Intergovernmental Panel on Climate Change)

Iyer G, Clarke L, Edmonds J, Flannery B, Ultman N, McJeon H and Victor D G 2015a Improved representation of investment decisions in assessments of CO2 mitigation Nat. Clim. Change 5 436–40

Iyer G, Hultman N, Eom J, McJeon H, Patel P and Clarke L 2015b Diffusion of low–carbon technologies and the feasibility of long–term climate targets Technol. Forecast. Soc. Change 90A 103–18

Iyer G, Hultman N, Fetter S and Kim S H 2014 Implications of small modular reactors for climate change mitigation Energy Econ. 45 144–54

Jakob M, Luderer G, Steckel J, Tavoni M and Monjon S J 2012 Time to act now? Assessing the costs of delaying climate measures and benefits of early action Clim. Change 114 79–99

Kim S, Edmonds J, Lurj J, Smith S and Wise M 2006 The ObjECTS framework for integrated assessment: hybrid modeling of transportation Energy J. 27 63–91

Kriegler E et al 2015 Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy Technol. Forecast. Soc. Change 90 24–44

McFadden D 1980 Econometric models for probabilistic choice among products J. Bus. 53 513–29

Meinshausen M, Raper S C B and Wigley T M L 2011 Emulating coupled atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6—Part 1: Model description and calibration Atmos. Chem. Phys. 11 1417–56

Moss R H et al 2010 The next generation of scenarios for climate change research and assessment Nature 463 747–56

O’Neill B C, Kriegler E, Riahi K, Ebi K L, Hallegatte S, Carter T R, Mathur R and Van Vuuren D P 2013 A new scenario framework for climate change research: the concept of shared socioeconomic pathways Clim. Change 122 387–400

Peck S C and Wan Y S 1996 Analytic solutions of simple optimal socioeconomic pathways Energy J. 123 9–71

Rogelj J, McCollum D L, Reisinger A, Meinshausen M and Riahi K 2015 Post-2020 climate agreements in the major economies assessed in the light of global models Nat. Clim. Change 5 119–26

Riahi K et al 2015 Locked into Copenhagen pledges—Implications of short–term emission targets for the cost and feasibility of long–term climate goals Technol. Forecast. Soc. Change 90A 8–23

Rogelj J, McCollum D L, Reisinger A, Meinshausen M and Riahi K 2013 Probabilistic cost estimates for climate change mitigation Nature 493 79–83

Sands R and Leimbach M 2003 Modeling agriculture and land use in an integrated assessment framework Clim. Change 56 145–210

Tavoni M et al 2015 Post-2020 climate agreements in the major economies assessed in the light of global models Nat. Clim. Change 5 119–26

The White House 2014 U.S.–China Joint Announcement on Climate Change (www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change) (accessed 30 July 2015)

Thomson A M et al 2011 RCP 4.5: a pathway for stabilization of radiative forcing by 2100 Clim. Change 109 77–94
Train K 1993 *Qualitative Choice Analysis: Theory, Econometrics, and an Application to Automobile Demand Choice Analysis* (Cambridge, MA: MIT Press)

UNEP 2014 *The Emissions Gap Report 2014* (Nairobi: United Nations Environment Programme (UNEP))

UNFCCC 2015 *INDCs as Communicated by Parties* ([www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx](http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx)) (accessed 30 July 2015)

Wigley T M 2008 MAGICC/SCENGEN 5.3: User Manual Version 2 (Boulder, CO: National Center for Atmospheric Research)

Wigley T M and Raper S C B 1992 Implications for climate and sea level of revised IPCC emissions scenarios *Nature* 357 293–300

Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith S J, Janetos A and Edmonds J 2009 Implications of limiting CO₂ concentrations for land use and energy *Science* 324 1183–86