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Author(s):
Johnson, Nils; Krey, Volker; McCollum, David L.; Rao, Shilpa; Riahi, Keywan; Rogelj, Joeri

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Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants

Nils Johnson [a,*], Volker Krey [a], David L. McCollum [a], Shilpa Rao [a], Keywan Riahi [a,b], Joeri Rogelj [a,c]

[a] International Institute for Applied Systems Analysis (IIASA), Austria
[b] Graz University of Technology, Austria
[c] Institute for Atmospheric and Climate Science, ETH Zurich, Switzerland

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ABSTRACT

Limiting global warming to 2 °C will likely entail the complete phase-out of coal-based electricity generation without carbon capture and storage (CCS). The timing and rate of this phase-out will depend on the stringency of near-term climate policy and will have important implications for the stranding of coal power plant capacity without CCS. The objectives of this paper are to better understand the relationship between near-term climate policy and stranded coal capacity (assuming a long-term goal of limiting warming to 2 °C) and to explore strategies for reducing stranded capacity. Our analysis suggests that strengthening near-term climate policy (i.e., lowering the global greenhouse gas emission target in 2030) generally reduces stranded coal capacity and its costs. An effective strategy for reducing stranded capacity is to minimize new construction of coal capacity without CCS, which can be accomplished by reducing electricity demand through energy intensity improvements and/or by keeping existing plants operating through lifetime extensions. Another strategy, providing emission exemptions for pre-existing coal plants (i.e., grandfathering), would eliminate stranded capacity, but also decreases the likelihood of achieving the 2 °C target. Finally, the ability of CCS retrofits to significantly reduce stranded capacity depends on how quickly the technology can be deployed.

1. Introduction

Limiting the increase in mean global temperature to 2 °C relative to the pre-industrial level[1] will likely entail transforming the global energy system from one that relies on fossil fuels for ~80% of its total primary energy supply (TPES) to a system supplied predominantly by low carbon technologies, such as renewables, nuclear, and biomass with carbon capture and storage (CCS) [1] and [2,3]. Integrated assessment models (IAMs) and energy-economic models indicate that this transformation will require a phase-out of fossil-based electricity generation without CCS over the next century [4,5]. The timing and rate of this phase-out will depend on the implementation and stringency of climate policy and will have important implications for fossil-based power plant operators and utilities.

Given the large investments and long operating lifetimes (typically 30–50 years) associated with fossil-based power plants, the implications of climate policy for the stranding of fossil-based power capacity are particularly interesting. Stranded capacity is essentially the installed capacity that is not utilized when a plant is operating below the load factor for which it is designed. It generally occurs when the cost of electricity generation renders capacity uncompetitive in the electricity market. With climate policy, this can occur at fossil-based

* Corresponding author at: International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria. Tel.: +43 2236 807 490.
E-mail address: johnsonn@iiasa.ac.at (N. Johnson).

[1] This is roughly equivalent to achieving an atmospheric CO_2-equivalent (CO_2e) concentration of 450 ppm in 2100.

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plants when payments for CO_2 emissions increase operating costs. If severe, stranded capacity can warrant the premature retirement of existing power plants and can have significant financial implications for plant operators.

The risk of stranded capacity is particularly large for coal-based power plants without CCS as these carbon-intensive plants become uncompetitive in scenarios that limit warming to 2 °C and, thus, are phased out rapidly [2,6]. However, coal currently accounts for ~40% of global electricity generation [1] and, without stringent climate policy, its use is expected to increase over the next two decades, particularly in China and India, where coal currently accounts for about 80% and 70% of electricity generation, respectively [7]. Thus, given less stringent climate policy over the next two decades, commitments to new coal capacity are expected to increase, resulting in more risk of stranded capacity once policy shifts to support the long-term goal of limiting warming to 2 °C. Furthermore, the risk of stranded capacity is expected to be concentrated disproportionately in China and India, which has implications for the willingness of these countries to participate in global climate agreements. Although Rogelj et al. [8] briefly examined the impact of different short-term 2020 greenhouse gas (GHG) targets on the premature retirement of coal-based power plants, no previous research has thoroughly explored the impacts of climate policy on stranded capacity and its associated costs.

In this study, we use the MESSAGE–MACRO integrated assessment model [9,10] and several climate policy scenarios, including a subset that was developed within the context of the AMPERE model inter-comparison project[2] [3], to explore the impact of the stringency of near-term climate policy on stranded power plant capacity. In particular, the paper focuses on conventional coal-fired power plants (i.e., coal combustion plants without CCS) since these plants have the largest carbon intensity and, thus, are the most likely to be stranded under policies seeking to remain below a 2 °C target.

The objectives of this paper are to better understand the relationship between near-term climate policy and stranded coal capacity assuming a long-term goal of limiting warming to 2 °C and to explore strategies for reducing stranded capacity. In Section 2, we describe the scenarios and technologies addressed in this paper and, in Section 3, explore when and at what rate coal-based power generation is phased out under different policy scenarios. In Section 4, we then quantify the magnitude and cost of the resulting stranded capacity in each scenario and, in Section 5, explore strategies for reducing stranded capacity. These strategies include: 1) focusing on energy intensity improvements (measured as final energy use per unit GDP); 2) extending the lifetime of existing power plants to reduce the need for new capacity; 3) providing emission exemptions for pre-existing plants (i.e., grandfathering) with an emphasis on the consequences for meeting the long-term 2 °C target; and 4) retrofitting plants with CCS.

2. Scenario implementation and technology descriptions

Scenarios with a range of GHG emission targets[3] in 2030 are used to explore the impact of near-term climate policy on stranded power plant capacity assuming a common long-term goal of limiting warming to 2 °C (Table 1). These scenarios represent seven discrete emission targets that span the range between the optimal and high short-term targets specified in the AMPERE project [3]. The lowest (i.e., optimal) target represents a stringent policy scenario in which immediate action is taken to meet the specified long-term climate objective, while the highest target is consistent with a 2030 target extrapolated from implementation of only the low-ambition unconditional Copenhagen pledges for 2020 [3]. Thus, higher near-term targets represent progressively less stringent climate policy (and mitigation) through 2030. However, it should be noted that even the least stringent near-term target (60.8 Gt CO_2e in 2030) still represents a 12% reduction in 2030 emissions relative to a scenario with absolutely no climate policy.

It should also be emphasized that all scenarios seek to achieve the same long-term objective, which is to limit the increase in global mean temperature relative to pre-industrial levels to below 2 °C in 2100. Thus, scenarios with less stringent near-term policy (i.e., reduced mitigation) until 2030 will require a more rapid transition to a low carbon energy system, and thus more aggressive mitigation after 2030, to meet the long-term objective [2,6]. All scenarios also assume that all mitigation technologies represented in the model are available (i.e., no restricted portfolio cases are considered) and that all countries participate in climate mitigation efforts at the same time (i.e., no delayed participation [12] or non-participation by certain regions). In addition, a low energy intensity (LowEI) scenario is examined in which the future energy intensity improvement rate is increased by about 50% relative to the reference scenario (RefEI).[4] The LowEI scenario is only examined with the least stringent near-term policy and is intended to assess the extent to which energy efficiency improvements can reduce stranded capacity in a weak policy environment.[5]

In the remainder of this paper, scenarios are identified by a combination of their energy intensity assumption and short-term target (e.g., RefEI-56.8), as summarized in Table 1. By default, all scenarios assume a power plant lifetime of 30 years and no grandfathering (i.e. plants are prematurely retired when carbon prices become sufficiently

[2] AMPERE is an acronym for "Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates". The AMPERE project explores several long-term GHG mitigation scenarios using a collection of IAMs with the objective of better understanding the uncertainties arising from differences among models. A major thrust of this project is to evaluate the impacts of various near-term GHG emission targets (for the year 2030) on the cost and feasibility of achieving long-term climate objectives ([3] in this issue).

[3] GHG emissions include all Kyoto gases (CO_2, CH_4, N_2O, and F-gases) emitted from fossil fuel and land-use sources. The global warming potentials used to translate non-CO_2 emissions to CO_2-equivalent (CO_2e) emissions are from the IPCC Fourth Assessment Report for a 100-year time horizon [11]. The newly added gas NF_3 is not included.

[4] Energy intensity improvement rates in the RefEI and LowEI scenarios are about 1.3%/year and 1.9%/year, respectively.

[5] Note that the GHG emission target in 2030 in LowEI-57.8 is less than the highest near-term target met by a RefEI scenario (60.8 Gt CO_2e/year). This is because, with low energy intensity, the largest emissions achievable in 2030 are 57.8 Gt CO_2e/year, even when the full century emission budget is unconstrained.

Table 1
Summary of scenario abbreviations.

Energy intensity	Short-term target in 2030 (Gt CO_2e/year)	Equivalent scenario in AMPERE [3]
RefEI	51.4	450-FullTech-OPT
	52.9	450-FullTech-LST
	54.8	N/A
	56.8	N/A
	57.8	N/A
	58.8	N/A
	60.8	450-FullTech-HST
LowEI	57.8	450-LowEI-HST

large).[6] Scenarios that evaluate different plant lifetimes (30, 40, and 50 years) are identified by the plant lifetime and scenarios that examine different assumptions regarding the market penetration of CCS retrofits are identified as "Bound" or "Unbound".

The MESSAGE–MACRO integrated assessment model combines a global (multi-sector, multi-region, multi-gas) systems engineering optimization model (MESSAGE) [10] with an aggregated macro-economic model (MACRO) [9] and a simple climate model (MAGICC) [14–17]. MESSAGE is a linear optimization model that minimizes the total discounted energy system cost over the time horizon from 1990 to 2110 using perfect foresight (for more information on MESSAGE-MACRO, see the supplementary material). The optimal scenario (RefEI-52.4) is run with the default setup using perfect foresight over the full century while the other scenarios with near-term targets use a two-phase approach that mimics limited foresight to 2030 [18]. In the first stage, a perfect foresight scenario is run over the full century with a long-term emission budget that allows the model to hit the near-term emission target in 2030. This first run is used to fix the solution through 2030, and then another perfect foresight scenario is run with a smaller long-term budget that achieves the long-term target. Since the long-term budget used in the first phase exceeds the budget used in the second phase, capacity expansions are planned prior to 2030 without anticipation of the rapid shift in climate policy and the large reduction in coal electricity that will be necessary after 2030 to meet the long-term target. Thus, the model assumes that utilities and plant operators have limited foresight of no more than 10 years when planning during the 2021–2030 period.

The myopic, or limited foresight, setup mimics policy scenarios in which there is uncertainty regarding long-term climate policy after 2030 and, thus, plant operators must make near-term planning decisions based on current carbon prices and their expectation of future climate policy. Given more policy certainty and, thus, more foresight, it should be noted that plant operators would likely make different decisions. However, the different 2030 emission targets examined in this paper essentially represent a range of possible near-term planning responses given different expectations of long-term climate policy. For example, RefEI-60.8 and RefEI-52.9 are scenarios in which planning decisions before 2030 are made with expectations of long-term (2000–2100) cumulative CO_2 emission budgets of ~2500 Gt and ~1600 Gt, respectively. For comparison, note that the AMPERE project assumes a cumulative CO_2 emission budget of 1500 Gt for limiting warming to 2 °C in 2100 [3], which is consistent with the budget achieved in the perfect foresight (RefEI-51.4) scenario.

Of particular relevance to this paper is the method with which MESSAGE tracks new power plant capacity and the vintage structure of existing plants, which both have consequences for plant retirement and, thus, stranded capacity. The required new electricity capacity for each power plant technology in each time period is calculated based on the endogenously optimized generation mix (i.e., how much electricity must be produced by each technology), the exogenously-specified maximum load factor of each technology, and the existing capacity from previous time periods, which is tracked based on the exogenously-specified technology lifetime.[7] Under perfect foresight and the objective of minimizing total system cost, the model will generally attempt to build the least new capacity required in each period to meet electricity demand (i.e., it will maximize the load factor). However, in scenarios with myopic foresight, MESSAGE may find itself with over-capacity of certain technologies and determine that it is optimal to operate them at partial load and, thus, strand capacity. Once new capacity is installed, it is maintained in the model for its specified lifetime, after which it is retired.

The analysis of stranded capacity in this paper focuses on conventional coal (i.e., combustion) power plants without CCS since these plants are most rapidly phased out with stringent climate policy.[8] In MESSAGE, conventional coal power plants are represented by three individual technologies: 1) subcritical plants *without* flue gas desulphurization (FGD) and nitrogen oxide (NOx) removal, 2) subcritical plants *with* FGD and NOx removal, and 3) advanced supercritical coal plants *with* FGD and NOx removal. The availabilities, costs, efficiencies, and maximum load factors of these technologies vary through time and by region. Thus, global means for the cost, efficiency, and load factor parameters are calculated after running each scenario and account for the deployment in each region (see supplementary material). Plant output includes both electricity and heat. In the remainder of this paper, results are aggregated for the three technologies and referred to as conventional coal without CCS.

3. Phase-out of coal-based power generation

The stringency of near-term climate policy will impact the timing of the phase-out of fossil-based electricity generation

[6] The standard lifetime for coal power plants in MESSAGE is 30 years, which is consistent with the typical financing period for these plants [13]. Although plants can operate for much longer periods, additional capital investment is generally required to renovate and/or replace old components and this cost is not included in the capital and annual O&M costs in MESSAGE. Moreover, given the 30-year financing period, it can be argued that shutting down a plant after 30 years does not result in any stranded capital investment since the initial capital cost has been fully paid at this time.

[7] In the historic period (1990–2005), the electricity generation by each technology and by region is calibrated to IEA data [19,20]. The vintage of capacity installed pre-1990 is also tracked in each region by exogenously specifying the total installed capacity in 1985 and a growth rate that identifies how quickly capacity expands up to the 1985 value in each region [21].

[8] Integrated gasification combined cycle (IGCC) coal plants, both with and without CCS, and conventional coal plants with CCS are also represented in MESSAGE, but were not considered in this analysis. A negligible amount of IGCC without CCS is installed (<12 GW) over the century and coal plants with CCS are built after 2030 and are well-utilized. Thus, coal plants with CCS do not suffer from significant stranded capacity.

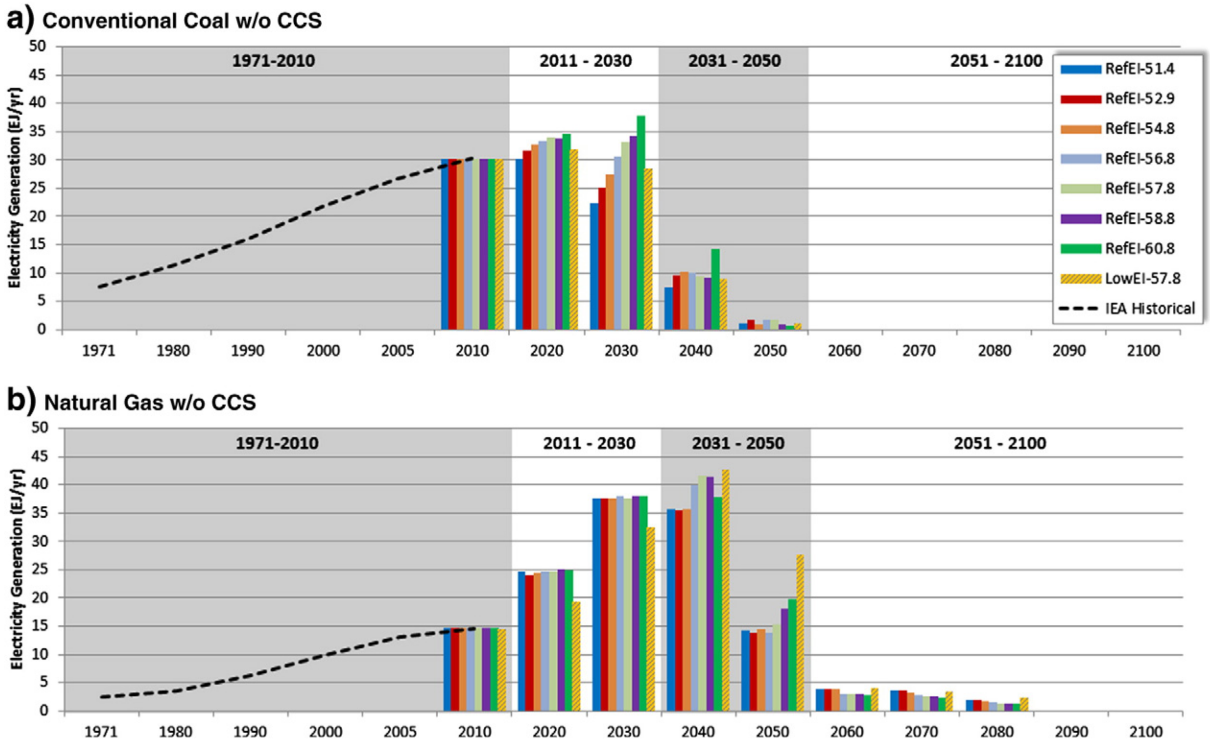

Fig. 1. Electricity generation in each scenario for a) conventional coal power plants without CCS and b) natural gas power plants without CCS (Values are representative of each period (e.g., 2040 represents the period from 2031 to 2040)). Historical data is from IEA [22,23].

without CCS and the rate at which it occurs. It is expected that a more rapid rate of phase-out will result in more stranded capacity since recently built plants will need to be retired prematurely. Fig. 1 illustrates the electricity generated by conventional coal and natural gas power plants without CCS in the seven RefEI scenarios and one LowEI scenario. The differences in the generation pathways of the two technologies highlight why stranded capacity is expected to be more significant for conventional coal power plants than for natural gas power plants.

In the scenario with the most stringent near-term policy (RefEI-51.4), coal-based generation remains at the 2010 level until 2020, gradually declines after 2020, and then is phased out completely after 2050. As near-term climate policy becomes less stringent (i.e. the 2030 emission target increases), electricity generation from coal increases in the 2011–2030 period. However, in all scenarios except the ones with the highest targets (RefEI-60.8 and RefEI-58.8), generation begins to decline after 2020 and is phased out completely after 2050. LowEI-57.8 follows a similar generation pathway, but the increase in the 2011–2020 period is less than expected given the target. In RefEI-60.8, global coal-based generation continues to expand until 2030 and then is rapidly phased out over a very short period (~10 years) with less than 1 EJ/year of global generation after the 2031-2040 period.

In contrast, natural gas-based generation until 2030 does not significantly vary between the RefEI scenarios, despite the different policy regimes. Even after 2030, significant generation from natural gas continues for two decades and is not phased out completely until after 2080. Although the low energy intensity scenario requires less natural gas-based generation through 2030, more natural gas is used in the 2031–2050 period. These deployment patterns indicate that natural gas-based electricity generation is used as a bridging technology to achieve emission reductions in the mid-term [4]. Because the phase-out of natural gas-based electricity occurs later in time and is more gradual, plant operators, as modeled by MESSAGE, have more foresight in planning new capacity and can, thus, minimize stranded capacity. Fig. 1 also indicates that limiting warming to 2 °C in 2100 requires that *both* natural gas and coal-based electricity generation without CCS are completely phased out by the end of the century.

To better understand the likelihood of stranded capacity, not only the timing, but also the rate of phase-out is important since a more rapid phase-out should result in more stranded capacity. Fig. 2 illustrates the required annual change in conventional coal capacity without CCS for the periods from 2011 to 2030 and from 2031 to 2050.[9] As near-term climate policy becomes less stringent, fewer reductions in coal capacity are required during the 2011–2030 period and capacity even increases in the scenarios with high 2030 emission targets. However, fewer reductions in the 2011–2030 period must be offset by much

[9] The required reduction in conventional coal capacity is calculated by converting the difference in electricity generation over each period to capacity assuming an average load factor of 80% for all plants. The annual value is then estimated by dividing the period length. It indicates how much capacity would need to be reduced to avoid stranded capacity, not the actual capacity reductions occurring in each scenario. These periods were selected because they represent the two 20-year periods in which the transition to stringent climate policy occurs and, thus, are the periods when unanticipated reductions will occur.

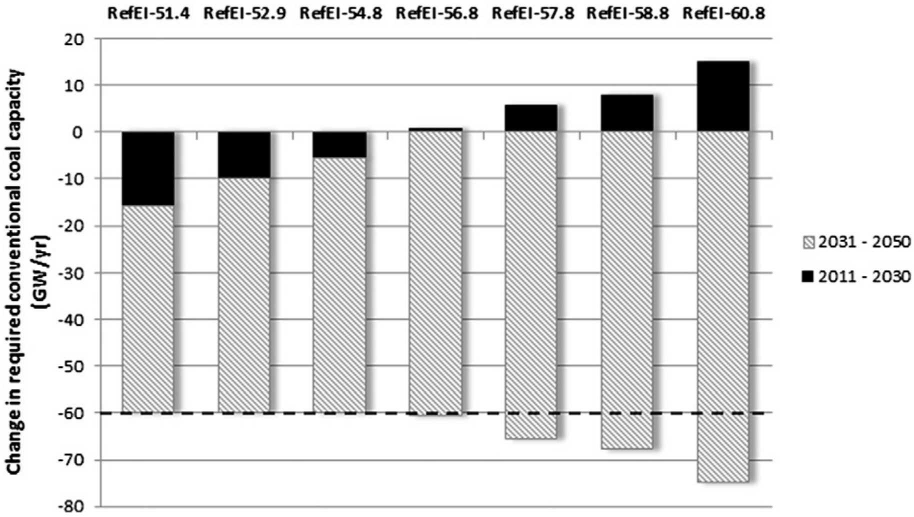

Fig. 2. Change in required conventional coal capacity without CCS in 2011–2030 and 2031–2050 (black dashed line indicates total 2011–2050 change).

larger reductions during the 2031–2050 period since all scenarios completely phase out conventional coal after 2050 and, thus, achieve the same required retirement rate over the period from 2011 to 2050 (~60 GW/year). In essence, reducing the stringency of near-term policy delays reductions in coal capacity and, thus, increases the reductions required in the 2031–2050 period and the risk of stranded capacity. However, the rate of reduction shown in Fig. 2 includes both capacity that is retired at the end of its design lifetime as well as capacity that is retired prematurely. It is this latter type of capacity retirement that constitutes stranded capacity and which will be explored in more depth in the next section.

4. Stranded coal capacity and costs

Although the timing and rate of the phase-out of conventional coal electricity generation without CCS hint that significant coal capacity will be stranded in these scenarios, the actual stranded capacity also depends on how quickly plants that have fulfilled their full design lifetimes can be retired.[10] If the rate of planned retirement matches the rate of required capacity reduction, then stranded capacity will not materialize. However, if planned retirement is insufficient, then capacity, and even entire plants, must be retired prematurely, resulting in stranded capacity.

4.1. Magnitude of stranded capacity

At the global level, the total installed capacity and total electricity generation in each period can be used to calculate a mean actual load factor for conventional coal plants which can then be compared with the potential load factor as an indicator of stranded global capacity (Fig. 3). In the next two decades (2011–2030), stranded capacity is expected to be small regardless of near-term policy since the actual load factor is only slightly smaller than the range for the potential load factor. However, more stranded capacity is expected during this period with more stringent policy in the near-term. In contrast, the load factors in the following two decades (2031–2050) suggest that stranded capacity will increase significantly as near-term climate policy becomes less stringent.

The actual stranded capacities in the RefEI scenarios are consistent with the expectations suggested by the mean actual load factors.[11] In general, as the stringency of climate policy declines and annual GHG emissions in 2030 increase, the stranded capacity in the 2011–2030 period decreases and the stranded capacity in the 2031–2050 period increases (Fig. 4). In the first two decades, stranded capacity increases with the stringency of near-term policy because more stringent policy requires greater reductions in conventional coal capacity in the near-term, which cannot be entirely achieved given existing capacity commitments. In contrast, less stringent near-term policy decreases stranded capacity in the first two decades, but also results in additional coal capacity commitments in 2030 and, thus, increases the urgency with which coal must be phased out in the following two decades. As a result, stranded capacity increases in the following two decades as near-term policy stringency declines. In the scenario with the least stringent policy (RefEI-60.8), the stranded capacity is equivalent to the premature retirement of about 2.8 500-MW power plants every month worldwide over the 20-year period from 2031 to 2050.

Fig. 4 indicates that the stringency of near-term climate policy entails a trade-off between stranding capacity in the near-term (2011–2030) and in the mid-term (2031–2050). Up to a 2030 emission target of ~55 Gt CO_2e, the stranded capacity in each period roughly balances, resulting in the mean value over the entire 40-year period remaining relatively flat (red dotted line). This finding suggests that some weakening of near-term policy may have little impact on stranded conventional coal capacity. However, mean stranded capacity more than doubles in the scenarios with the least stringent policy (RefEI-58.8 and RefEI-60.8).

[10] In MESSAGE, conventional coal plants have a default lifetime of 30 years.

[11] Actual stranded capacity is calculated for each coal technology and in each period by estimating the capacity needed to generate the projected heat and electricity outputs assuming that the plants are operating at the potential global load factors listed in the supplementary material. This capacity is then subtracted from the total installed capacity in the energy system to identify the stranded capacity.

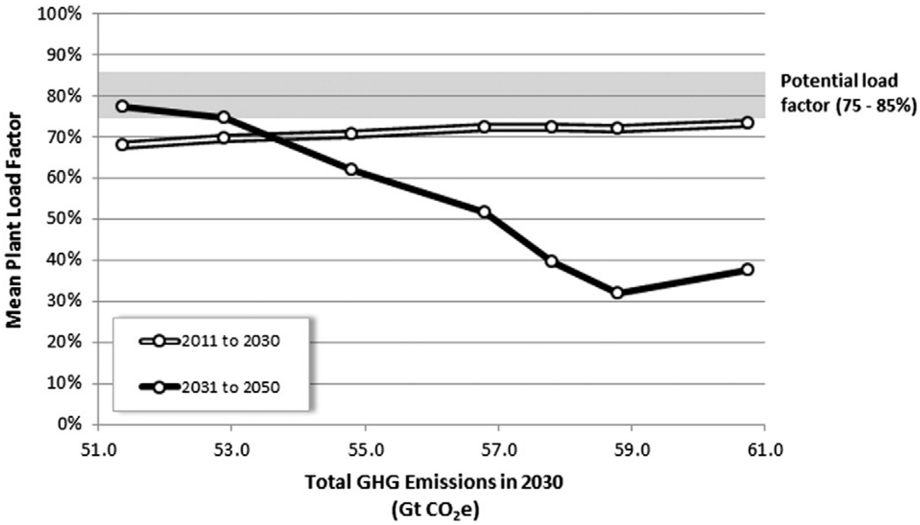

Fig. 3. Mean plant load factors in 2011–2030 and 2031–2050 compared with the range for the potential load factor (gray shaded area). Note that the potential load factor is shown as a range since it depends on the time period and the mix of different coal plant types in the energy system (see supplementary material).

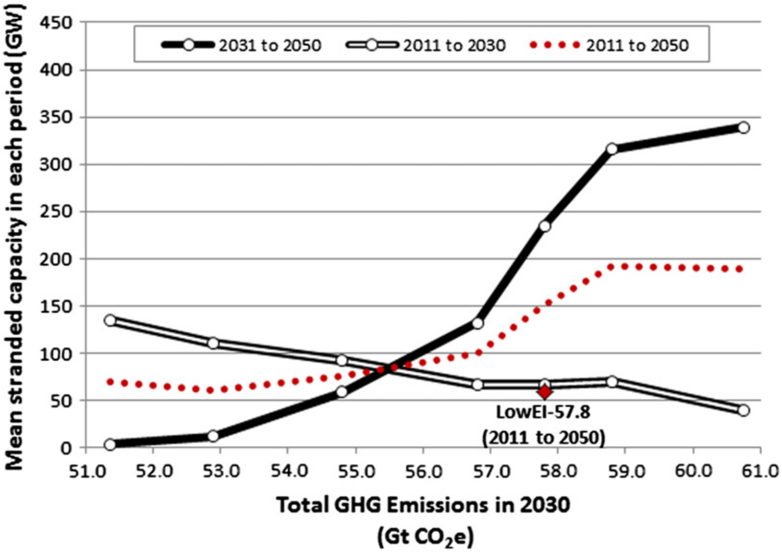

Fig. 4. Mean stranded capacity of conventional coal power plants over the 40-year period from 2011 to 2050. Black lines indicate mean stranded capacity for 2011–2030 and 2031–2050 and the red dotted line indicates the value for the entire 40-year period. The red diamond represents the stranded capacity for LowEI-57.8 over the 40-year period.

4.2. Cost of stranded capacity

The undiscounted cumulative stranded investments[12] associated with stranded capacity in each of the scenarios are summarized in Fig. 5. The stranded investments illustrate the same general trend indicated by the stranded capacity estimates. Specifically, there is a tradeoff in the stranded investment associated with each time period depending on the stringency of near-term policy and total investment does not increase dramatically until the 2030 emission target exceeds ~55 Gt CO_2e.[13] However, the relative

[12] The stranded investment is calculated in each period by multiplying the stranded capacity (GW) by the annualized capital cost ($/GW/year) and the period length (years) and, thus, assumes that the capacity is stranded for the entire period. The annualized capital cost is based on a 30-year plant lifetime and real interest rate of 5% (i.e., capital recovery factor of 6.5%). Capital costs are listed in the supplementary material and all calculations assume that the oldest plants are stranded first (i.e., stranded capacity in the 2031–2040 period is assumed to first come from plants built in 2011–2020 period and then from plants built in later periods). All costs are in 2005 U.S. dollars.

[13] In fact, the net present value (NPV) of stranded investment, using a 5% discount rate, remains essentially flat until ~55 Gt CO_2e because stranded investment gets progressively shifted to later time periods as policy becomes less stringent. However, beyond 55 Gt CO_2e, the NPV trend is similar to the undiscounted trend with stranded investment increasing as policy in 2030 becomes less stringent.

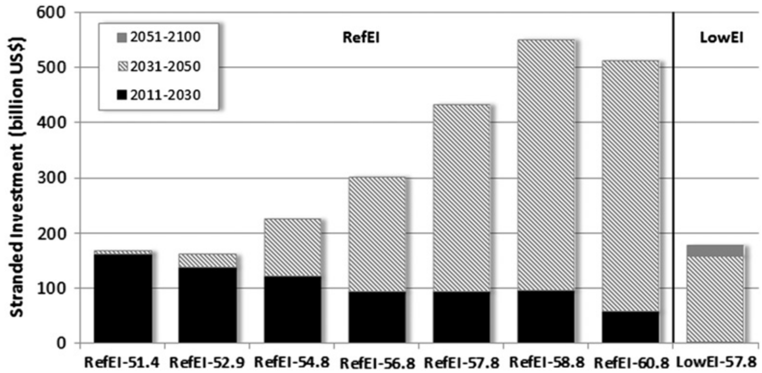

Fig. 5. Global stranded investment associated with stranded conventional coal capacity from 2011 to 2100.

increase in investment is much larger than the relative increase in stranded capacity in most scenarios. For example, the RefEI-54.8 scenario has ~10% more stranded capacity than the RefEI-51.4 scenario, but a roughly 35% larger stranded investment. The reason for the disproportionate increase in investment is the fact that more new coal capacity is installed in the 2021–2030 period as the 2030 emission target increases and the majority of this new capacity is supercritical coal, which is more efficient but also more expensive. As a result, the mean per-GW stranded investment after 2030 increases with less stringent policy. This finding also suggests that a strategy to reduce near-term emissions by replacing old coal power plants with new more efficient and expensive plants in the next two decades would ultimately increase the stranded investment in scenarios with a 2 °C long-term target.

As the stringency of climate policy declines in the RefEI scenarios, the global stranded investment associated with stranded conventional coal capacity more than triples from $165 to $550 billion over the 2011–2050 period. This is equivalent to 5–17% of the projected investment in fossil-based electricity generation over this period (~$3 trillion) and 1–4% of the projected investment in all electricity generation (~$15 trillion). However, in the scenario with the largest stranded investment (RefEI-60.8), over 75% of the investment occurs in only two regions, South Asia (SAS), which includes India, and Centrally Planned Asia (CPA), which includes China, and in the 20-year period from 2031 to 2050 (Fig. 6). Thus, the cost implications of stranded capacity can be much larger at the regional level. For example, the stranded investments in CPA and SAS during the 2031–2050 period are equivalent to 76% and 55%, respectively, of the projected investment in fossil-based electricity generation and 10% and 11%, respectively, of the projected investment in all electricity generation in each region over the same period. However, in the scenario with the most stringent near-term policy (RefEI-51.4), no stranded capacity is projected in SAS and CPA. Instead, stranded investments are largest in North America (NAM), the Former Soviet Union (FSU), and Western Europe (WEU). Thus, reducing the stringency of near-term policy shifts the burden of stranded coal capacity from developed regions to developing regions. As a result, despite the existing near-term commitments to new coal capacity in SAS and CPA, these regions will have less stranded capacity in the long-term under more stringent near-term policy.

5. Strategies to reduce stranded capacity

Given the significant stranded conventional coal capacity associated with weak near-term policy, this section explores four strategies for reducing stranded capacity and its associated costs. The first strategy is to focus on energy intensity improvements that can help to reduce electricity demand and, thus, also the construction of new coal-based power plant capacity. The second strategy is to extend the lifetimes of existing coal power plants so that fewer plants must be retired in the near-term and, thus, less new capacity is required over the next 20 years. It is hypothesized that reducing the capacity of new builds in the 2011–2030 period, either through reduced electricity demand or extending plant lifetimes, will translate to less stranded capacity in the 2031–2050 period. The third strategy is to grandfather existing power plants (i.e., provide emission exemptions), which would eliminate stranded capacity by allowing the plants to continue to operate without penalty. However, this strategy will also increase GHG emissions from the electricity sector and may have significant implications for achieving the long-term target. The fourth strategy is to retrofit conventional coal power plants with CCS to reduce their CO_2 emissions and, thus, mitigate additional costs associated with carbon prices under stringent climate policy.

5.1. Energy intensity improvements

The RefEI scenarios indicate that the magnitude and cost of stranded capacity increase when the stringency of near-term climate policy declines. However, these scenarios assume reference energy intensity improvements, which correspond with a continuation of historical rates of energy intensity improvement (~1.3%/year). It is also interesting to examine whether concerted efforts to improve energy efficiency and reduce energy intensity, as in LowEI-57.8, can help to reduce the stranded capacity of conventional coal power plants under less stringent near-term policy.

Improved energy efficiency reduces energy demand and, thus, less electricity generation and fewer coal power plants are required in the period from 2011 to 2030 relative to RefEI-57.8,

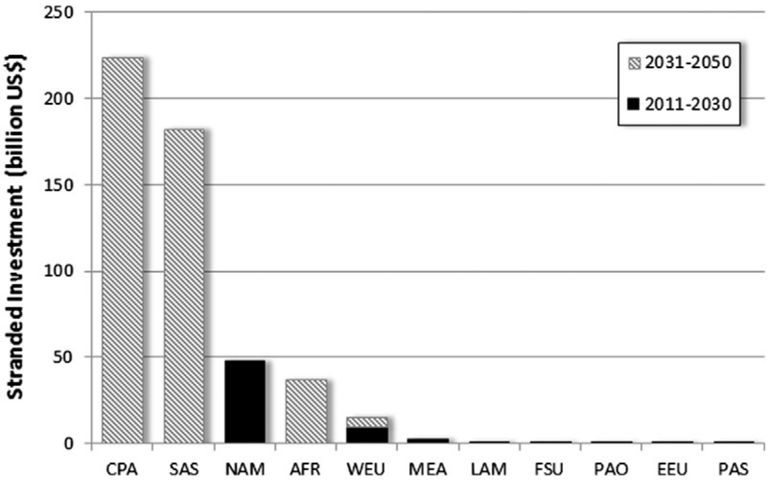

Fig. 6. Stranded investment associated with stranded conventional coal assets by region from 2011 to 2050 for the RefEI-60.8 scenario. CPA (Centrally Planned Asia and China), SAS (South Asia), NAM (North America), AFR (Sub-saharan Africa), WEU (Western Europe), MEA (Middle East and North Africa), LAM (Latin America), FSU (Former Soviet Union), PAO (Pacific OECD), EEU (Eastern Europe), PAS (Pacific Asia). See supplementary material for list of countries in each region.

which has the same 2030 emission target (Fig. 1).[14] Furthermore, the reduction in energy intensity decreases the pressure to reduce carbon intensity, resulting in a more gradual phase-out of fossil-based generation. The combination of less new capacity through 2030 and reduced urgency to decrease carbon intensity translates to much less stranded capacity than expected given the emission level in 2030 (Fig. 4). In fact, stranded capacity is smaller than all other scenarios over the entire 40-year period. These findings are reflected in the stranded investment, which suggests that improved energy efficiency can reduce the cost of stranded capacity by more than 65% relative to RefEI-60.8 (Fig. 5). Even relative to the scenario with the most stringent near-term policy (RefEI-51.4), the stranded investment is only 6% larger in the LowEI scenario, which suggests that demand-side energy efficiency improvements offer a good strategy for electric utilities and energy-service providers to hedge against future climate policies, as they reduce potential stranded investments. This finding adds to the list of benefits associated with reducing energy intensity that have been identified in the literature [4,24].

5.2. Extending plant lifetime

MESSAGE accounts for the age (i.e., vintage) of long-lived infrastructure when making investment decisions regarding the timing of the replacement or phase-out of existing energy technologies (see Section 2). The default setup assumes that conventional coal power plants have a maximum lifetime of 30 years, but the model also allows for the premature retirement of unused capacity. In reality, many coal plants operate for much longer periods, even exceeding 50 years. In this section, we examine two additional scenarios in which the lifetimes of all conventional coal plants are extended for either 40 or 50 years.[15] These scenarios are conducted for only the least stringent policy scenario (RefEI-60.8).

In each lifetime extension scenario, all plants are extended for the specified operating lifetime. However, we assume that the capital investments are financed over a 30-year period so that these investments are paid off after 30 years. Thus, in these scenarios, plant lifetime can be extended to the maximum lifetime, but a plant can be retired after 30 years without financial penalty.[16] The aim is to minimize stranded capacity by using extended lifetimes in the near-term to reduce the need to build new capacity while allowing for short lifetimes in the mid-term to reduce stranded capacity.

As expected, the results indicate that extending the lifetime of conventional coal plants reduces the need to install new capacity in the near-term since older plants continue to operate longer (Fig. 7a). It is also interesting that, with a 2 °C long-term target, no new conventional coal capacity without CCS is built after 2030 even with the least stringent near-term climate policy. The reduction in new

[14] The RefEI and LowEI scenarios all exhibit an increase in the share of total final energy supplied by electricity over time since many sectors become increasingly electrified under climate policy. However, the phenomenon of increased electrification is slowed in the LowEI scenario since there is less pressure to reduce carbon intensity and, thus, move to cleaner energy, given the smaller total energy demand. Thus, the total electricity demand is smaller in LowEI-57.8 than RefEI-57.8.

[15] Note that a change in technology lifetime impacts the vintage structure in not only future time periods, but also historic time periods since MESSAGE tracks capacity installments pre-1985. Although the total installed capacity in the *historic* time periods is relatively fixed for each technology based on the load factor and the calibrated electricity generation, the new installed capacity depends on the vintage structure of the pre-existing capacity, which changes with lifetime. Thus, the new installed capacity in historic time periods is different in each of the lifetime extension scenarios, which leads to different vintage structures into the future. Essentially, the extension scenarios examine the implications of MESSAGE assuming a 40 or 50-year standard lifetime for conventional coal plants instead of 30 years.

[16] Throughout this paper, the cost of stranded capacity is equated with the stranded capital investment. We do not consider the opportunity cost associated with the additional revenue that could be earned by keeping a plant operating. This is not an issue when the financing period matches the plant lifetime (e.g., 30-year scenario), but there would be an opportunity cost in the 40 and 50-year scenarios where the financing period is less than the potential operating lifetime.

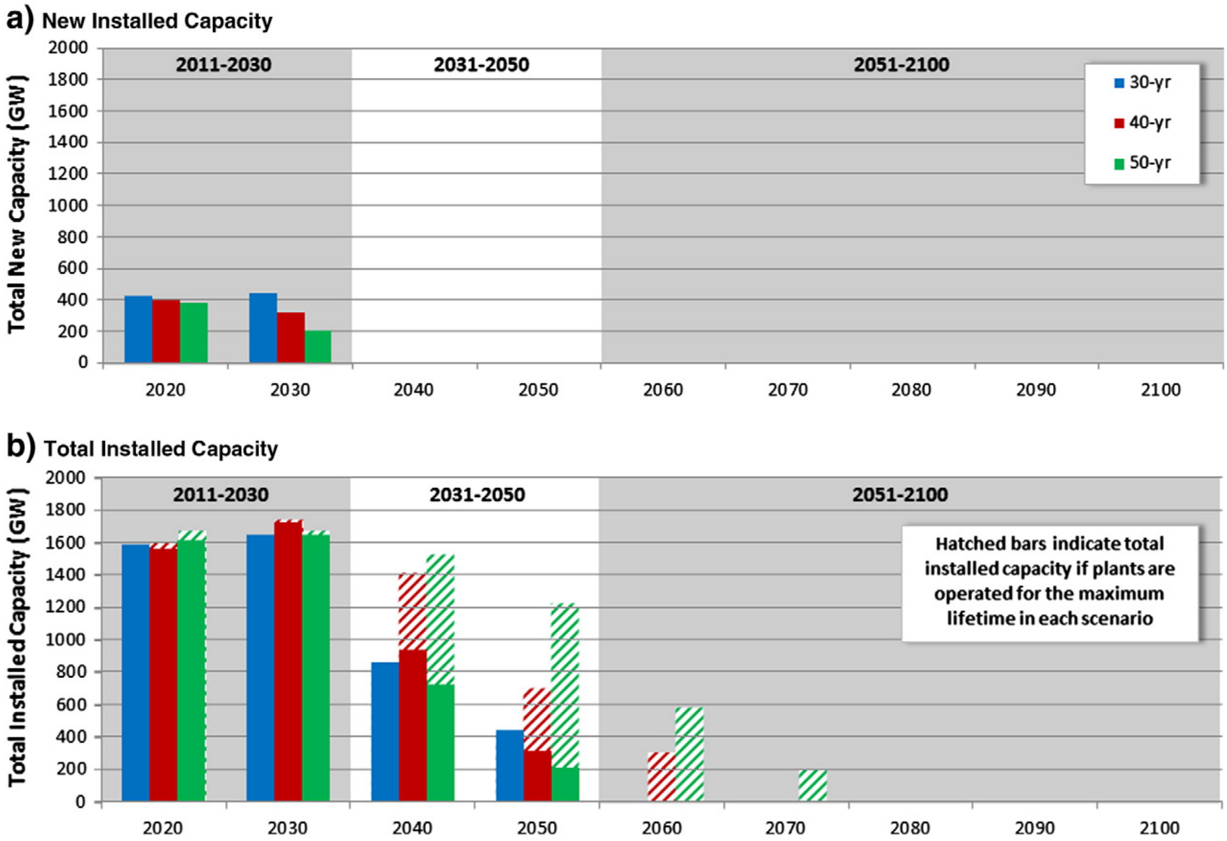

Fig. 7. a) Total new capacity and b) total installed capacity of conventional coal power plants without CCS for each plant lifetime scenario. Solid bars indicate capacities when plant lifetime can be extended, but can also be limited to 30 years without penalty. Hatched bars indicate the additional capacity if all plants are operated for the maximum lifetime specified in each scenario (e.g., with grandfathering).

capacity in the 2011–2030 period translates to less total installed capacity in the following two decades, assuming that the new capacity built after 2010 is not extended beyond 30 years (Fig. 7b). Thus, the combination of extending the lifetime of coal plants existing in 2010 and limiting the lifetime of plants built after 2010 is expected to reduce stranded capacity.

The undiscounted cumulative stranded investment in each scenario supports the hypothesis that extending the lifetimes of existing plants can help to avoid stranded capacity (Fig. 8). In the

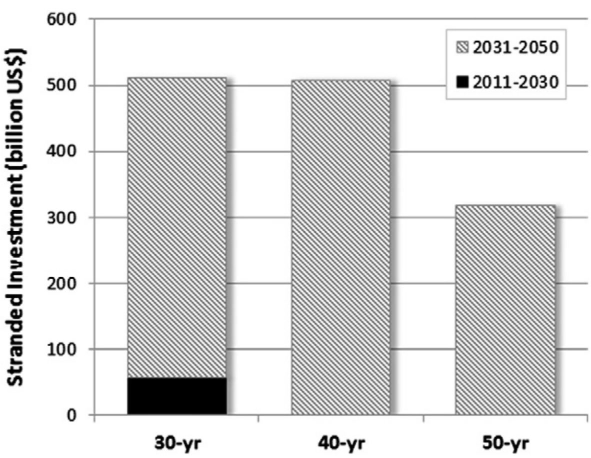

Fig. 8. Stranded investment in 2011–2030 and 2031–2050 for each plant lifetime scenario.

40-year scenario, stranded investment is only reduced by about 1% relative to the 30-year scenario because, given myopic foresight in 2030, the model chooses to generate significantly more electricity from conventional coal in 2030 than in the 30 or 50-year scenarios. Then, when climate policy becomes more stringent after 2030, much of the conventional coal capacity is immediately stranded, leading to significant stranded investment in the 2031–2040 period. Because the difference in stranded investment is so small, it is difficult to state a definitive conclusion regarding the impact of the 40-year lifetime extension as it may fluctuate depending on the assumed historic vintage structure of plants.[17] However, in the 50-year scenario, the conclusion is more robust with a 38% reduction in stranded investment relative to the 30-year scenario. This scenario suggests that minimizing the installation of new conventional coal capacity in the next two decades by keeping existing plants operating is an effective strategy for reducing stranded capacity in the mid-term. Essentially, scenarios that seek to limit warming to 2 °C require that conventional coal capacity without CCS is rapidly phased out after 2030, meaning that most of the new capacity built in the 2011–2030 period will be stranded in the following two decades. Consequently, the construction of new coal capacity without CCS, even if more efficient, should be minimized.

5.3. Grandfathering

Another strategy to eliminate stranded capacity and its associated costs is to provide exemptions for existing plants through grandfathering, as done for example in the European emission trading scheme (ETS) [25]. This strategy would essentially allow existing plants to continue to run without emission penalties at their potential load factors for their design lifetimes. Although this approach would eliminate stranded capacity, it would also allow significant additional CO_2 emissions that may increase the likelihood of exceeding the 2 °C target, unless more costly mitigation options are adopted to compensate for the additional emissions.

In this section, we estimate the additional CO_2 emissions associated with each scenario in Table 1 that would result if all stranded capacity was instead operated for its entire lifetime and analyze the implications of these additional emissions for meeting the long-term climate objective.[18] For simplicity, we assume that the additional electricity generated from coal-fired power plants displaces low-carbon sources, such as wind and solar,[19] and that plant operators are given no notice of grandfathering so that they do not over-install capacity prior to the exemption deadline. The additional emissions are calculated based on the potential load factors and plant efficiencies for each plant type (see supplementary material) and using an emission factor of 94.6 tCO_2 per TJ of coal input [26].[20]

The impact of additional CO_2 emissions on achieving the 2 °C target depends primarily on the additional cumulative emissions over time, and, thus also, to a smaller degree, on the timing of these emissions. Fig. 9 indicates that the increase in global cumulative CO_2 emissions resulting from grandfathering in the scenarios with a 30-year plant lifetime ranges from 20 to 50 Gt CO_2 over the course of the century, with emissions increasing as near-term climate policy becomes less stringent. However, even in the scenario with the least stringent policy (RefEI-60.8), we find only a 3% increase in global cumulative CO_2 emissions above the full century cumulative emission target (1500 Gt CO_2). The timing of the additional emissions associated with grandfathering differs between scenarios with additional emissions shifting from the 2011–2030 period to the 2031–2050 period as near-term policy becomes less stringent. However, in all scenarios, the additional emissions associated with grandfathering are concentrated in the next 40 years (2011–2050).

The implication of additional emissions for the maximum likelihood of exceeding the 2 °C target over the century is calculated using MAGICC6 and the cumulative distribution function for equilibrium climate sensitivity from Rogelj et al. ([14,15,17] and supplementary material). Without grandfathering, the maximum likelihood of exceeding the 2 °C target increases from 48% to 50%, or two percentage points, as near-term climate policy becomes less stringent (i.e., from RefEI-51.4 to RefEI-60.8). With grandfathering, the maximum likelihood in each scenario increases by 0.3–1.3 percentage points relative to the same scenario without grandfathering when we assume a 30-year maximum plant lifetime. Consequently, with a 30-year plant lifetime, grandfathering as a strategy to minimize costs associated with stranded capacity seems to have a minimal impact on the likelihood of exceeding the 2 °C target.

However, if a limit is not placed on the length of the exemption period, grandfathering may incentivize plant operators to extend the lifetimes of their plants. In this case, conventional coal plants without CCS could operate as late as 2070 (hatched bars in Fig. 7b). As a result of this continued operation, Fig. 9 indicates that the increase in full century cumulative CO_2 emissions resulting from grandfathering increases by ~70 Gt CO_2 for each 10-year extension of plant life. If plant lifetime is extended to 50 years, cumulative emissions increase by ~180 Gt CO_2, which represents a 12% increase relative to the long-term cumulative emission target for meeting the 2 °C target (1500 Gt CO_2). Thus, the maximum likelihood of exceeding the 2 °C target can increase by as much as seven percentage points when the lifetimes of grandfathered plants are extended, or 3.5 times the increase in maximum likelihood resulting from reducing near-term policy stringency. Since the risk of failure to meet the target increases as plant lifetimes are extended, it is important that any grandfathering program specify strict limits on the period of time that plants are eligible to receive exemptions. Moreover, early notice of a grandfathering

[17] Currently, the *actual* vintage structure of coal plants is unknown by the model since the historic period is calibrated based on electricity generation and not new installed capacity.

[18] The grandfathering scenarios are not new scenarios, but rather the additional CO_2 emissions are calculated based on the stranded capacities and efficiencies of conventional coal plants in each existing scenario.

[19] As a result, these calculations represent the maximum additional emissions from running the coal plants. If emitting sources, such as natural gas power plants, were displaced, the additional emissions could be significantly smaller. However, also note that we do not include additional non-CO_2 GHG emissions or the upstream emissions associated with the mining, transport, and distribution of coal.

[20] For plants with efficiencies ranging from 32 to 47%, the emission factor translates to 1065–725 gCO_2 per kWh.

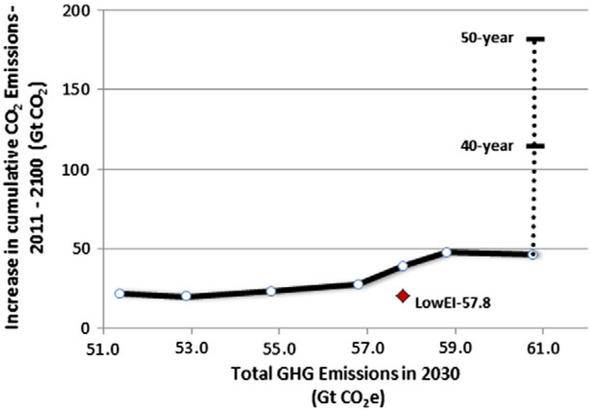

Fig. 9. Increase in global cumulative CO_2 emissions (2011–2100) resulting from grandfathering. The RefEI and LowEI scenarios with 30-year plant lifetimes are indicated by the thick black line and red diamond, respectively. The RefEI-60.8 scenarios with plant lifetime extensions are indicated along the black dotted line.

program could trigger large investments in new coal capacity as utilities may seek to lock-in exemptions before the deadline. Such a scenario is not examined in this study, but could lead to much greater risks of failure than the estimates provided.

5.4. CCS retrofits

A final strategy to reduce stranded coal capacity under stringent long-term climate policy is to retrofit existing capacity with carbon capture and storage (CCS), which entails capturing a portion of the CO_2 emissions at retrofitted plants before it is released to the atmosphere and then storing it in geologic reservoirs. This option could potentially improve the economics of operating conventional coal plants under stringent climate policy by reducing CO_2 emissions and, thus, the associated economic penalties. However, adding CCS to existing plants also requires significant additional capital investment and reduces plant efficiency so that it is unclear whether retrofitting capacity is preferable to prematurely retiring capacity. This section discusses two additional scenarios in which CCS retrofit technologies are available for all conventional coal power plants under the least stringent near-term climate policy (i.e., 60.8 Gt CO_2e in 2030).

In the first scenario, entitled “Unbound”, the market penetration *rate* of CCS retrofits is unconstrained, but the *maximum* market penetration is limited to 90% of conventional coal capacity.[21] This scenario explores the degree to which retrofits could reduce stranded coal capacity under optimistic conditions in which CCS can be deployed extremely rapidly. However, given that the model deploys no CCS through 2030, it is likely that significant technological and regulatory barriers will exist that will prevent a rapid deployment in the 2031–2050 period. The second scenario, entitled “Bound”, represents a more conservative view of the deployment of CCS retrofits, in which the market penetration of retrofits is constrained. Specifically, a maximum of 12 GW (i.e., twenty-four 500 MW plants) of each coal plant type can be retrofit in each region during the 2031–2040 period.[22] In both scenarios, CCS retrofits require an additional capital investment of \$1000/kW to \$1200/kW (depending on the time and region), impose a 25% energy penalty, and capture 90% of emitted CO_2. In addition, the lifetime of each retrofit is assumed to be 20 years since retrofits are added to existing plant capacity at least one time period (i.e., decade) after the plants are constructed.

In both the “Bound” and “Unbound” scenarios, installation of CCS retrofits on supercritical coal capacity built in the 2021–2030 period is maximized (i.e., it is only limited by constraints on market penetration), while retrofits on subcritical capacity is nearly maximized. In the “Bound” scenario, retrofits are installed on 44 GW of conventional coal capacity globally in the 2031–2040 period, or ~10% of the new coal capacity without CCS installed in the previous period (Fig. 10). In the “Unbound” scenario, there is a ten-fold increase in the deployment of retrofits relative to the “Bound” scenario to 418 GW globally, or 83% of the new conventional coal capacity installed in the 2021–2030 period. Assuming an average nameplate capacity of 500 MW, the “Unbound” scenario entails installing retrofits on more than 800 plants over the course of a single decade, or about 84 plants per year globally. In contrast, the “Bound” scenario entails installing retrofits on approximately 9 coal plants per year globally. The “No Retrofit” scenario is identical to RefEI-60.8 and represents a scenario in which no retrofits are installed.

Fig. 10 illustrates that as constraints on the deployment of CCS retrofits decline, retrofits are increasingly installed on existing conventional coal capacity, which suggests that retrofitting is a cost-effective strategy for mitigating CO_2 emissions. Moreover, Fig. 11a indicates that the deployment of retrofits at large scale can substantially improve the utilization of conventional coal-fired power plants in the

[21] Even if CCS retrofits could be adopted quickly, several factors would restrict the eligibility of many plants for retrofitting, including additional space requirements for retrofit equipment and proximity to suitable CO_2 storage sites [27].

[22] There are three conventional coal technologies and 11 regions so, even in the conservative scenario, if all regions were to maximize their implementation of retrofits, almost 400 GW could be installed globally in the 2031–2040 period alone. However, since coal-based electricity is concentrated in only a few regions (Fig. 6) and generated by a limited set of technologies in each region, deployment is much more limited in this scenario.

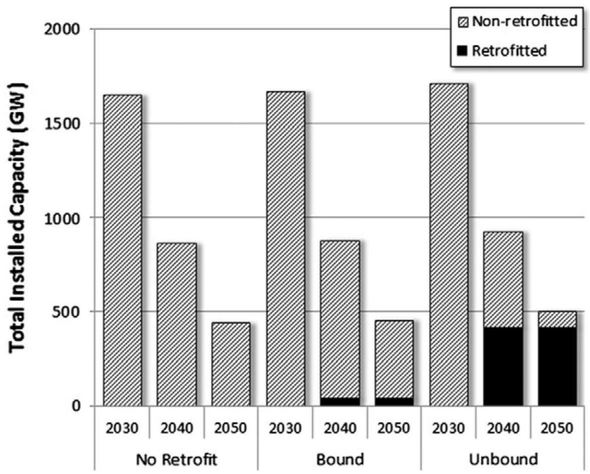

Fig. 10. Total installed capacity of retrofitted and non-retrofitted conventional coal power plants in the three retrofit scenarios. The "No Retrofit" scenario is equivalent to RefEI-60.8.

2031-2050 period and, thus, reduce stranded capacity. In fact, stranded investment can decline by as much as 70% if deployment is largely unconstrained, as in the "Unbound" scenario (Fig. 11b). However, the reduction in stranded investment is small when deployment of CCS retrofits is constrained, as in the "Bound" scenario, which suggests that the effectiveness of retrofits for reducing stranded capacity depends on how quickly the technology can be deployed in the 2031-2040 period. Thus, if this strategy is to be effective, it is crucial that research, development, and demonstration (RD&D) projects are conducted over the next two decades to ensure that CCS retrofits and all associated infrastructure, including CO_2 transport and injection, can be deployed rapidly post-2030.

6. Conclusions

The scenarios examined in this study all indicate that limiting warming to 2 °C over the course of the century will require the complete phase-out of coal-based electricity generation without CCS by 2050. However, the timing and rate of this phase-out depend on the stringency of near-term climate policy. As near-term policy becomes less stringent, the phase-out of conventional coal capacity is delayed, resulting in larger capacity commitments in 2030 and, thus, the need for a more aggressive phase-out of capacity during the 2031–2050 period.

The increase in the rate of phase-out amplifies the risk of stranded capacity, which is supported by the finding that stranded capacity and its associated cost increase as near-term policy becomes less stringent. However, we find that stranded investment does not increase significantly when the near-term GHG emission target is below about 55 Gt CO_2e, which suggests that near-term climate policy can be weakened moderately without much impact on stranded coal capacity. In scenarios with the least stringent near-term policies (i.e., with targets of 59–61 Gt CO_2e), stranded investment more than triples relative to the scenarios with the most stringent policies (i.e., with targets of 51–53 Gt CO_2e). As a result, it is important to identify and

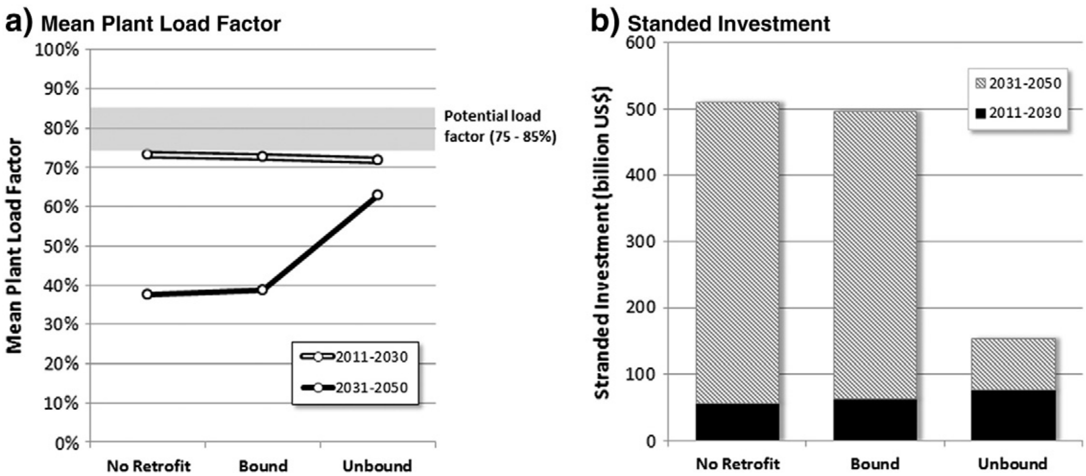

Fig. 11. A comparison of a) mean load factor and b) stranded investment in each of the three retrofit scenarios.

examine strategies that can help electric utilities and energy-service providers reduce stranded capacity, particularly in less stringent policy environments.

In this paper, we analyze four strategies for reducing stranded capacity and its costs: 1) improving energy intensity, 2) extending the lifetime of existing coal-fired power plants, 3) providing emission exemptions for existing power plants (i.e., grandfathering) and 4) retrofitting existing power plants with CCS. Based on the analysis, four primary conclusions are identified.

1 Reducing energy demand through energy intensity improvements is an effective strategy for avoiding stranded coal capacity

By reducing electricity demand, improvements in energy intensity both reduce construction of new coal-based electricity generation over the next two decades and the urgency with which coal plants without CCS need to be phased out after 2030. As a result, stranded capacity is significantly reduced even when comparing a scenario with low energy intensity and less stringent near-term policy with a scenario with reference energy intensity and more stringent policy. This finding suggests that reducing energy intensity is a good strategy for electric utilities and energy-service providers to hedge against uncertainty in future climate policy, as it reduces the potential cost of stranded capacity in all policy environments.

2 Keeping existing conventional coal capacity operating is preferable to building new capacity

In all scenarios with a 2 °C target, most of the conventional coal capacity built in the 2011–2030 period becomes stranded in the following two decades unless CCS retrofits are widely deployed. Consequently, strategies that minimize the construction of new coal capacity will result in less stranded capacity. As mentioned previously, reducing electricity demand is one strategy for avoiding new coal capacity, but our analysis of plant lifetime extensions also indicates that keeping existing plants operating is another effective strategy. By reducing new coal capacity, not only is the magnitude of stranded capacity reduced, but also the mean per-GW stranded investment since existing plants tend to have smaller capital costs than new, more efficient coal plants.

3 Although grandfathering eliminates stranded capacity, it increases the risk of failing to achieve the long-term climate objective

Providing emission exemptions for plants built before stringent policy is imposed (i.e., grandfathering) would eliminate the cost penalties associated with operating coal-fired plants in an environment with high carbon prices and, thus, incentivize the continued operation of these plants. Although, it has the advantage of eliminating stranded capacity and its associated costs, it would also lead to additional GHG emissions and would increase the maximum likelihood of exceeding the 2 °C target by 0.5–7 percentage points unless more costly mitigation options are adopted to compensate for the additional emissions. The probability of exceeding the target increases as plant lifetimes are extended so it is important that any grandfathering program limits the period of time that plants are eligible to receive exemptions. Moreover, early notice of a grandfathering program could trigger large investments in new coal capacity as utilities may seek to lock-in exemptions before the deadline. Such a scenario is not examined in this study, but could lead to much greater risks of failure than the estimates provided.

4 Retrofitting conventional coal plants with CCS is an effective strategy for reducing stranded capacity only if retrofits and the associated CCS infrastructure can be deployed rapidly

In the scenarios that allow CCS retrofits on existing conventional coal capacity, all retrofits are installed in the period immediately following the switch to more stringent policy (2031–2040). Thus, the effectiveness of this strategy for reducing stranded coal capacity depends on how much capacity can be retrofit in a single decade. Given the fact that these scenarios project no CCS up to 2030, it is uncertain whether CCS retrofits will be able to ramp up quickly enough and at sufficient scale to significantly mitigate stranded capacity. To reduce the uncertainty, it is crucial that CCS RD&D projects are started immediately and regulatory and legal frameworks that will facilitate rapid CCS deployment are established before 2030. Given the importance of rapid CCS deployment rates for mitigating stranded coal capacity, further research is needed to better quantify potential deployment rates and to identify policy mechanisms for facilitating CCS deployment.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.techfore.2014.02.028.

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Nils Johnson is a research scholar in the Energy Program at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria.

Volker Krey is the deputy program leader of the Energy Program at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. His scientific interests focus on the integrated assessment of climate change and the energy challenges.

David L. McCollum is a research scholar in the Energy Program at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria.

Shilpa Rao is a research assistant in the Energy Program at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria.

Keywan Riahi is leading the Energy Program at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. In addition, he holds a part-time position as Visiting Professor at the Graz University of Technology, Austria.

Joeri Rogelj is a postdoctoral researcher at the Institute for Atmospheric and Climate Science at ETH Zurich, Zurich, Switzerland. He is also affiliated with the Energy Program at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.