Economics of nuclear power and climate change mitigation policies

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The events of March 2011 at the nuclear power complex in Fukushima, Japan, raised questions about the safe operation of nuclear power plants, with early retirement of existing nuclear power plants being debated in the policy arena and considered by regulators. Also, the future of building new nuclear power plants is highly uncertain. Should nuclear power policies become more restrictive, one potential option for climate change mitigation will be less available. However, a systematic analysis of nuclear power policies, including early retirement, has been missing in the climate change mitigation literature. We apply an energy economy model framework to derive scenarios and analyze the interactions and tradeoffs between these two policy fields. Our results indicate that early retirement of nuclear power plants leads to discounted cumulative global GDP losses of 0.07% by 2020. If, in addition, new nuclear investments are excluded, total losses will double. The effect of climate policies imposed by an intertemporal carbon budget on incremental costs of policies restricting nuclear power use is small. However, climate policies have much larger impacts than policies restricting the use of nuclear power. The carbon budget leads to cumulative discounted near term reductions of global GDP of 0.64% until 2020. Intertemporal flexibility of the carbon budget approach enables higher near-term emissions as a result of increased power generation from natural gas to fill the emerging gap in electricity supply, while still remaining within the overall carbon budget. Demand reductions and efficiency improvements are the second major response strategy.

climate policy | energy economy model | mitigation scenarios | nuclear policy

The dramatic events at the Fukushima Daiichi nuclear complex triggered after the combined earthquake/tsunami event on March 11, 2011, revived the debate about the future of nuclear power generation. The Fukushima event put safety issues of civilian use of nuclear power back on the policy agenda, along with problems and risks of treating waste, proliferation, economic performance, and resource availability.

Because nuclear power results in no direct CO_2 emissions, some see it to be a promising technology option for climate change mitigation. Nuclear power is also promoted as a technology with low emissions of other air pollutants such as sulfur and nitrogen oxides (1–4). Even in the absence of climate policies, the Nuclear Energy Agency "Red Book" (5) expects worldwide nuclear power capacity to increase by 37% to 110%, and the International Energy Agency (6) expects a 79% increase by 2035 in global nuclear electricity generation in their New Policies Scenario [and an increase of 136% for the "450-ppm Scenario" (6)]. The US Energy Information Administration expects global electricity from nuclear power plants to increase only 39% by 2030 without climate change mitigation policies (7).

The 22nd round of the Stanford Energy Modeling Forum (8) published scenarios from a large number of integrated assessment models on development of the global energy sector over the 21st century for a reference case, as well as for greenhouse gas stabilization scenarios to 550 and 450 ppm of CO_2 equivalent concentration. In the reference scenarios, nuclear power generation increases 34% to 180% by 2035. In the stabilization scenarios, all models show heavier deployment of nuclear power than in the reference scenario. Two other model comparison exercises focused, among other things, on the economic value of future nuclear power expansion for addressing climate change stabilization (9, 10). For different sets of models, both compared limited deployment of nuclear power in a strong long-term stabilization scenario vs. the case of full flexibility in nuclear power expansion and found a relatively small increase in mitigation costs. Remme and Blesl (11) and Vaillancourt et al. (12) present additional scenario studies on nuclear power.

Currently, however, the future of nuclear power has become much more uncertain, as national policy makers are reviewing their nuclear programs (13). Whereas the United States and France have continued to express confidence in their own nuclear plans, and Saudi Arabia and Poland announced plans to start a nuclear power industry, China, India, and Japan have announced a thorough review of their plans. A public vote in Italy reconfirmed an earlier decision to refrain from nuclear power. Switzerland's governing federal council decided to phase out nuclear power; existing plants may continue operation subject to safety constraints. The German parliament voted for an accelerated decommissioning of existing plants and also to preclude the addition of any new capacity. Moreover, as of spring 2012, all Japanese nuclear power capacity is out of operation, and local policy makers announced that safety concerns may prevent many plants from ever restarting.

Policy debates about the future of nuclear power and climate change mitigation touch on the issues of existing and new nuclear power plants as well as the impact on CO_2 emissions and long-term climate change stabilization. The existing literature on the economics of climate change mitigation covers only some of the different dimensions of the nuclear power policy space. It focuses on the role of nuclear power in a carbon-constrained world and on constraints to future capacity extensions. The issue of decommissioning existing plants as an additional dimension of the policy space has thus far not been addressed. The present study aims at closing this gap by providing a systematic tradeoff analysis that covers the fundamental dimensions of climate and nuclear power policies. We address three questions. First, what are the economic implications of decommissioning existing nuclear power plants? Second, what are the additional consequences of combining decommissioning with restrictions on future investments in new nuclear generating capacity and long-term emissions caps? Finally, what are robust energy sector strategies to fill the electricity generation gap caused by decommissioning?

SUSTAINABILITY SCIENCE

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Dimensions of Nuclear Power and Climate Policies

In this section, we introduce the nuclear power scenarios and the climate policy used in the analysis. We divide the former into four different cases, differentiating between two main dimensions of nuclear power policies: (*i*) the treatment of existing capacities and (*ii*) investments into new capacities.

Nuclear policies may result in the switch-off of existing capacities for safety reasons or because of economic barriers set by high standards for refurbishment. Building of new capacity might be hindered by outright bans or by requiring safety standards that increase investments costs. We distinguish four nuclear policy scenarios as follows:

Renaissance. Existing plants are used until the end of their lifetime, and refurbishment could extend the lifetime. In addition, nuclear power capacities are expanded. The implicit assumption underlying this policy package is that nuclear power is safe, as commonly assumed in global assessments and projections.

Phase Out. In a phase-out scenario, existing plants operate until the end of their lifetime, but no new capacity is installed. In this scenario, the property rights of operators of existing plants are respected, but the confidence in safety improvements in new reactor designs is assumed to be insufficient for allowing capacity extensions.

New Start. In a new-start scenario, existing plants are decommissioned, but investments in new capacity are possible. This scenario assumes that old plants are considered unsafe, while policymakers are confident about the technological progress embodied in new reactor designs. The implicit assumption is that the technology option for the future is valued higher than the existing operational rights that are subject to safety risks.

Full Exit. In a full-exit scenario, existing plants are decommissioned and no additional investments will take place. This scenario puts an immediate end to nuclear power, reflecting a skeptical position regarding safety or public acceptability.

The decommissioning dimension is analyzed by varying gradually the constraint on the operation of existing nuclear power capacity to shed light into this largely unexplored policy dimension. The dimension of building new plants is analyzed by either allowing investments in new nuclear power plants or restricting them to zero. *SI Appendix*, Fig. S9, contains a sensitivity analysis in which we gradually increase the investment costs of nuclear power plants.

Climate policies in the present framework are implemented via an intertemporal global budget on energy sector CO_2 emissions (14, 15). The budget applied in the present study limits the cumulative CO_2 emissions from the global energy sector to 300 GtC for the period of 2005 to 2100, representing a relatively aggressive climate mitigation policy consistent with the long-term target of limiting global warming to 2 °C.

Techno-Economics of Nuclear Power

Existing Capacities. Fig. 1 depicts the vintage structure of nuclear power generation capacity in operation in early 2011. The oldest plants are 45 y old, and the 5-y period with the highest installation rate was 1982 to 1987, reaching nearly 120 GW. Vintages put in place before 1992 are mostly located in Organization for Economic Cooperation and Development (OECD) countries. Only during the 1990s did other countries start to adopt nuclear power at a notable scale. Nuclear power plants currently planned or under construction are mainly in non-OECD countries.

Investment Costs. Capital costs make up a large share of total nuclear electricity generation costs, and additional safety measures tend to increase these costs. Investment costs also change over time depending on economic, technical, and political conditions, with estimates in the past 10 y tending sharply upward. Most recent estimates for overnight construction costs are in the range of \$3,000 to \$6,000/kW (2, 16, 17), with somewhat lower costs in non-OECD countries (IEA 2010; ref. 16). Koomey and Hultman (18) found a highly skewed distribution function for observed investment costs in the United States, with median costs of \$2,200/kW and a 90% quantile of \$8,200/kW (typically plants with long construction times). Grubler et al. (19) and Lako et al. (20) analyze changing investment costs and find a negative learning effect. A study of existing nuclear power plants in Germany (21) that were being considered for technical lifetime extensions beyond 35 y estimated costs for refurbishment between \$35 and \$110/kW and reactor year.

The present study assumes overnight investment costs for a light water reactor of \$3,000/kW, which is at the low end of the ranges given earlier, but based on the expectation of capacity growth mainly in non-OECD countries. The technical lifetime of nuclear power plants is set at 60 y. After 40 y, additional refurbishment costs of \$100/kW and reactor year are required. The costs of regular decommissioning are included in the operation and maintenance costs.

Uranium Resources. Conventional identified resources of uranium are differentiated into recovery cost categories. The assessment by the Nuclear Energy Agency (5) comprises 6.3 Mt of uranium, which equals approximately 100 times the current reactor requirements. The estimates of the World Energy Council (22) and German Geological Survey (23) mainly rely on the numbers of the

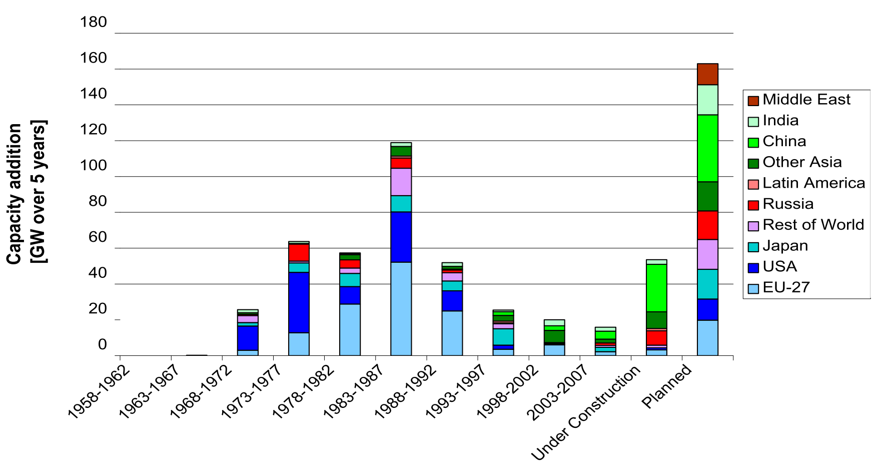

Fig. 1. Vintages of existing nuclear power installed in the past and capacities under construction and planned. The figure does not contain plants decommissioned before 2011, but does include plants shut down after March 2011. The figure does not account for recent revisions of expansion plans. "Rest of world" includes Canada, South Africa, Switzerland, Ukraine, and Turkey. "Other Asia" includes Taiwan and South Korea. Source: International Atomic Energy Agency Power Reactor Information System database (http://www.iaea.org/pris/).

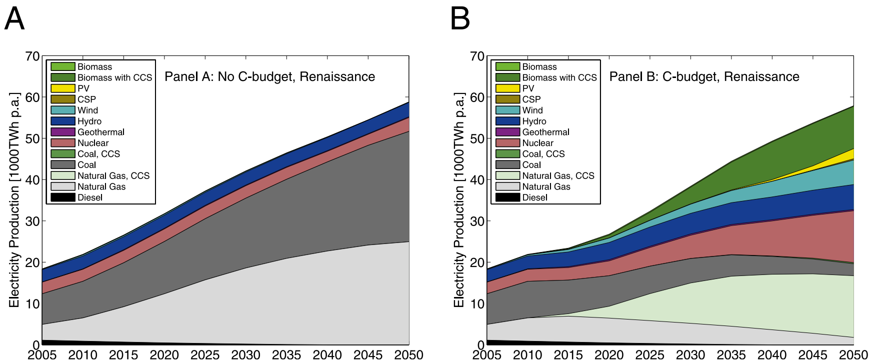

Fig. 2. Global electricity generation mix for 2005 to 2050 for the nuclear renaissance cases without (*A*) and with (*B*) with carbon budget imposed.

Nuclear Energy Agency but apply different interpretations for identified uranium resources. The more uncertain category of conventional undiscovered uranium resources are also assessed differently by the three institutions. For the present study, the assumption is that 23 MtU are ultimately available with increasing extraction costs. Moreover, we account for nuclear fuel derived from dismantling military devices. It is assumed that the United States receives 22 kilotons uranium per annum at zero cost until 2015 (5). Reprocessing and fast-breeding reactors are not considered here. Given the optimistic assessment of uranium resources, this assumption is economically reasonable in the near term (24).

Results

Nuclear Renaissance Without Carbon Budget. As a baseline, we use the scenario of a nuclear renaissance without imposition of the intertemporal carbon budget, as this represents the least intervention of public policy in the energy market. The policy scenarios will be compared with this baseline. *SI Appendix* contains more information.

Over the 21st century, total primary energy consumption grows by approximately 133%, from 513 EJ in 2010. Fossil fuels will dominate the global energy sector until 2050. The electricity sector grows by 258% from 2010 to 2050. For electricity generation, gas and coal are increasing, as shown in Fig. 2*A*. Oil is mainly used to fuel the growing demand for transportation fuels. After midcentury, the energy mix—especially for electricity generation—becomes more diversified. Coal and gas fade out of the electricity mix (52% in 2100) as carbon-free technologies gain share. However, total coal use will continue to grow as a source for liquid transportation fuels that substitute for oil supplies peaking as a result of resource constraints. The reliance on fossil fuels increases CO_2 emissions from 8 GtC in 2005 to 21 GtC in 2100.

In the reference case, global nuclear power generation remains approximately constant until 2050 (Fig. 2*A*). The constant aggregate, however, contains a global shift of nuclear power generation from OECD countries toward Asian countries. These countries increase deployment considerably in the second half of the 21st century, which leads to the total growth. In the reference scenario, nuclear power will achieve the highest share in the power mix at 17.2% in 2075. In this year, nuclear power peaks as a result of the resource constraint on uranium use.

Nuclear Phase-Out and Carbon Budget. The imposition of a carbon budget and the phase-out of nuclear power production are considered as severe policy interventions. The imposition of the carbon budget puts a price on carbon emissions and thereby decreases use of fossil fuels compared with the no-policy case in 2020: coal by 40%, gas by 18%, and oil by 13% (*SI Appendix*, Fig. S5). The electricity generation mix for the nuclear renaissance case with carbon budget is shown in Fig. 2*B*. A major shift in electricity generation caused by climate policies is the addition of carbon capture and sequestration (CCS) to natural gas power plants. The net shortfalls in gas and coal power generation in 2020 are 3,000 TWh and 5,300 TWh compared with the no-policy case, respectively. This shortfall of fossil-fueled electricity supply is partially compensated (3,300 TWh) by low-carbon technologies, of which nuclear power accounts for 540 TWh. The remainder is provided by hydropower, bioenergy with CCS, wind, and geothermal power. Solar electricity production does not play a significant role in the short run.

The phase-out of nuclear power does not change these figures until 2020 independent of the imposition of stringent climate policies. Only in the following years is the generation of nuclear power significantly higher in the case with carbon budget and a nuclear renaissance. The impact of nuclear phase-out on fossil fuel use is therefore also very small in the near-term.

Wind deployment is an important option to supply low-carbon electricity in the near term, but phasing out of nuclear power does not give an additional boost to wind power deployment because the high growth rates already become costly as result of integration and adjustment costs. In the longer term (after 2040), fossil fuel generation is substituted by heavy deployment of solar energy sources to meet the carbon budget, but, in the short term, solar technologies do not play a significant role in supplying electricity. If, in addition, nuclear power is phased out, solar power technologies become much more prominent after 2030.

One key consequence arising from the phase-out of nuclear power is that CO_2 emissions in the absence of a carbon budget increase significantly, especially after 2025, and eventually reach an additional 350 MtC/y in 2050. The effect is most significant in Asian regions where most nuclear power plants are expected to

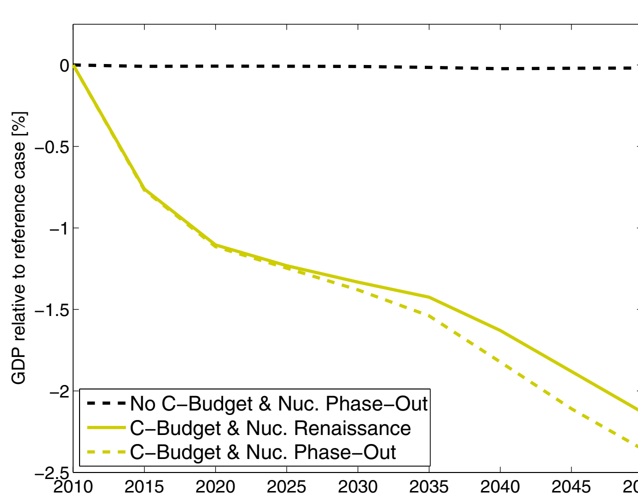

Fig. 3. Differences of GDP 2010 to 2050 relative to the reference case without carbon budget and nuclear renaissance.

be built. On the contrary, if the carbon budget is imposed, there is nearly no intertemporal reallocation of optimally using the CO_2 emissions budget over time.

The sensitivity of GDP in the three policy scenarios relative to the no-policy case is shown in Fig. 3. If no carbon budget is imposed, the nuclear phase-out has only a negligible effect. The imposition of the carbon budget implies a growing GDP loss that reaches 2.1% per year in 2050. The incremental costs of a nuclear phase-out are higher in the case with climate policy. The deviation starts in 2030 and reaches 0.2% in 2050. Hence, the nuclear phase-out has little impact on the macroeconomy in the near term. The imposition of the carbon budget, independent of nuclear phase-out, makes a difference even in the near term.

Effect of Decommissioning Existing Nuclear Capacities. The nuclear policy dimension of decommissioning existing nuclear power plants is gradually added to each of the four scenarios. The additional constraint is implemented by decommissioning certain vintages starting in 2010 that were supposed to operate until the end of the technical lifetime. The constraint is varied in strength by decommissioning only the oldest vintage, then the second oldest, and so on. In the strongest case, all existing capacities are decommissioned, which implies that 2,730 TWh of nuclear power generation would not be available after 2015.

Fig. 4 shows the differential effect of decommissioning on the global electricity sector for the cases with and without carbon budget and nuclear phase-out. All scenarios share three main features. First, the shortfall of electricity is most sensitive for varying the decommissioning of plants that entered operation between 1978 and 1993. This reflects the specific structure of the nuclear vintages presented in Fig. 1. Second, the shortfall of electricity production is only partially compensated by new capacity, which implies significant demand reductions. Finally, substitution with new capacity becomes more important as the stringency of the decommissioning constraint is increased. Natural gas generally plays the most important role in filling the emerging generation gap.

In addition to these three general observations, the two scenarios that allow the addition of new nuclear power plants show significant contributions in reducing the shortfall from decommissioning

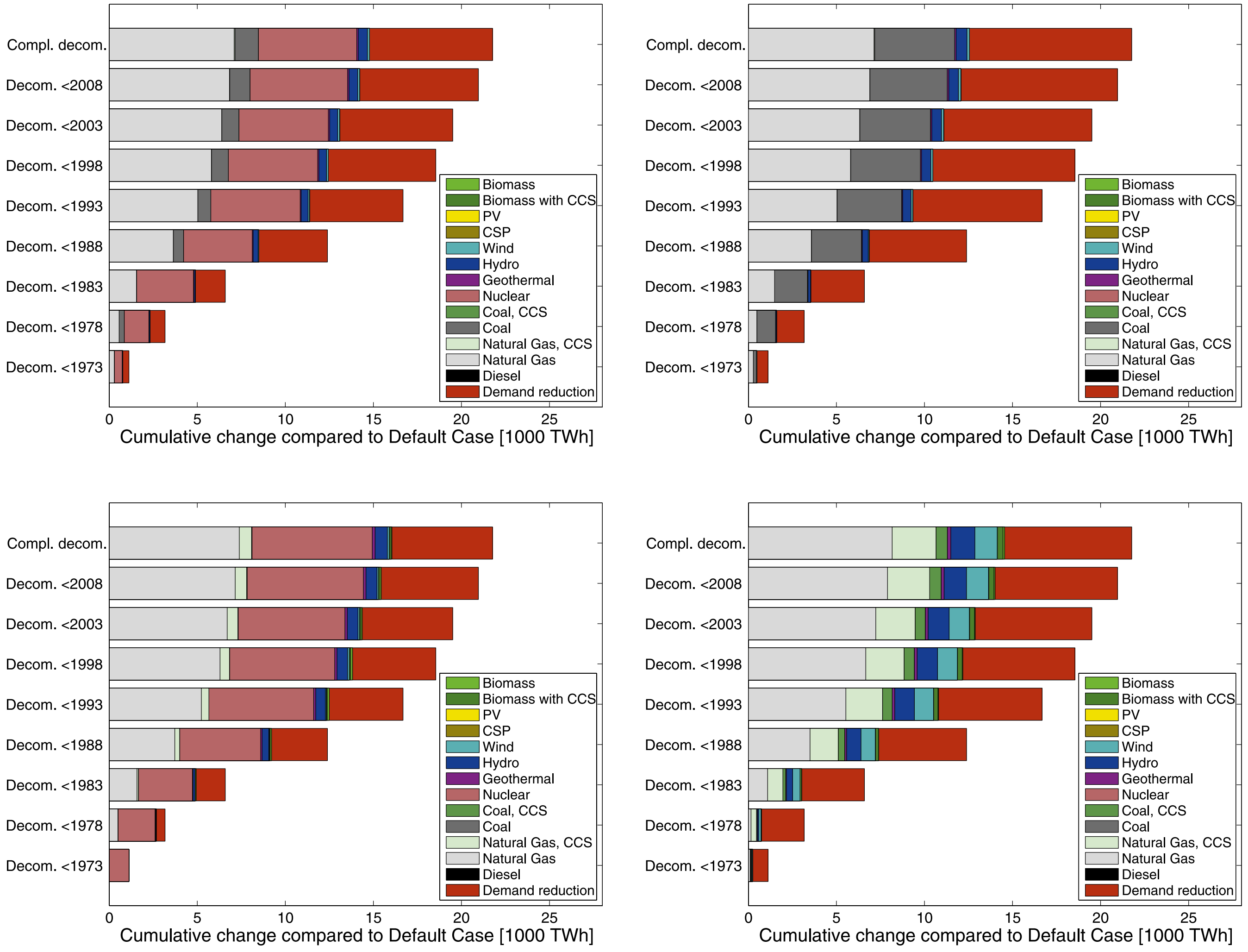

Fig. 4. Differential impact of decommissioning on the global electricity sector measured by changes of cumulative electricity generation from 2010 to 2020. The reference case is always without decommissioning. *Upper*: No carbon budget. *Lower*: Carbon budget imposed. *Left*: Scenarios in which investment in new nuclear power plants are feasible. *Right*: Cases without investments in new nuclear capacity. Within each of the four graphs, the bottom stacked bar shows the case of only the oldest vintage (i.e., everything built before 1973) being decommissioned. The next stacked bar above the bottom bar shows the result when the second-oldest vintage was also decommissioned, and so forth, up to the top bar, which represents the case of full decommissioning. The sum of the stacked bars represents the shortfall of cumulative electricity production over the period of 2010 to 2020. The components show how the shortfall is compensated by alternative technologies, including demand reduction.

old plants. Coal plays a notable role only in the absence of a carbon budget, with a larger contribution if new nuclear power plants are not allowed. If the carbon budget is implemented, the contribution of coal is substituted by a mix of natural gas with CCS, hydropower, and wind; coal with CCS is of only minor importance. Although renewable sources are essential for producing carbon-free electricity in the longer term, their contribution in filling the gap caused by decommissioning nuclear power plants is small. More details of electricity generation mixes are given in *SI Appendix*, Fig. S6.

The increased use of fossil-fuel electricity generation implies higher CO_2 emissions as a result of nuclear power decommissioning. If power sector CO_2 emissions are not compensated by reductions in other sectors, total emissions will increase. The effect on CO_2 emissions is shown in Fig. 5. The four cases show an inverted U-shape that nearly vanishes by 2050. The new effect of decommissioning is that it implies a temporal reallocation of the optimal emission trajectory if the carbon budget is imposed, with near-term CO_2 emissions increasing by 100 MtC/y, which is a rather small share of total power sector emissions. The reallocation of CO_2 emissions in the two cases with carbon budget are at maximum 2.2 GtC, which is less than 1% of the total budget of 300 GtC until 2100. The effect on CO_2 emissions is more significant if the carbon budget is not imposed.

Fig. 6 shows the costs for various policy scenarios measured by the net present value of GDP losses in relative terms compared with the scenario without policies for the period of 2010 to 2020. For scenarios without climate policy, the phase-out scenario leads to costs of 0.006%, whereas the new-start scenario implies policy costs of 0.07%. Combining the decommissioning and the investment abandoning leads to policy costs of 0.14%. This is nearly twice the sum of the isolated policies. In case of decommissioning, the refurbishment costs of old plants are no longer incurred.

If the carbon budget is imposed in a renaissance scenario, the policy costs are 0.64%. These costs increase by 0.11% to 0.75% if the restrictive nuclear policies of full exit are also imposed. The costs of the combined policies are therefore smaller than the sum of the isolated effects of the carbon budget and the full-exit policy, which would be 0.78% (indicated by the move of the patch and the dashed lines, Fig. 6). Hence, the simultaneous imposition of the two nuclear power policy types implies an escalation of costs, whereas the cost increase dampens if the climate policy is added. *SI Appendix*, Fig. S8, contains a more detailed analysis of the

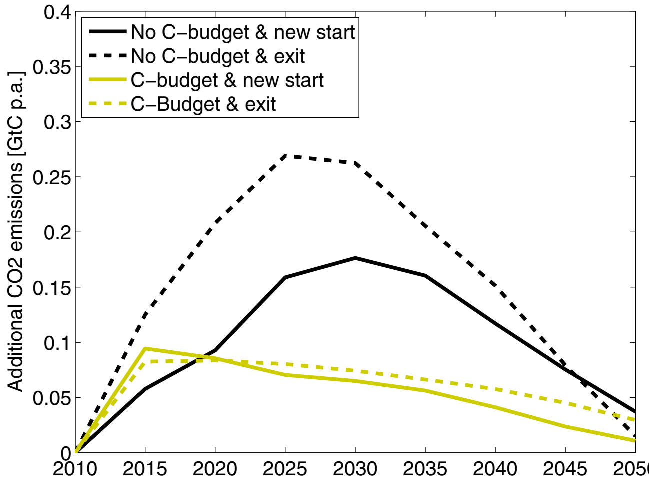

Fig. 5. The impact of decommissioning nuclear power plants on energy related CO_2 emissions. The graph shows the impact of complete decommissioning over time by depicting the differences vs. the case without decommissioning for four scenarios.

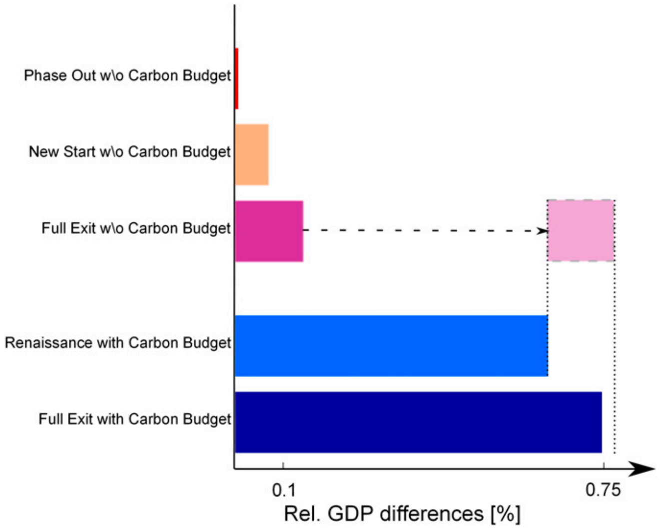

Fig. 6. Policy costs of nuclear power and climate policy scenarios. The graph depicts cumulative discounted policy costs from 2010 to 2020 compared with the reference scenario without additional policies in relative terms, applying a 5% discount rate. The dashed arrow moving the patch for the scenario with full exit and without climate policy is added to the graph to illustrate the analysis of policy synergies that is explained in the text.

policy costs. *SI Appendix*, Figs. S10 and S11, shows an analysis of the changes from relaxing the carbon budget.

The reason for this dampening is that climate policies have a dominant effect on fossil fuel markets. The impact of nuclear power plant decommissioning has to be related to the impact of climate policies on the markets for fossil fuels and carbon emission permits. The price of natural gas is decreased by the climate policy because demand is reduced (*SI Appendix*, Fig. S7). The additional gas demand from the decommissioning of nuclear power is therefore compensated by cheaper natural gas than in the case without climate policy. The negative effect from the increasing demand for emission permits does not overcompensate the natural gas market effect as a result of the intertemporal reallocation of the emission pathway. Hence, the economic costs of nuclear power plant decommissioning are not further escalated if it is combined with climate policies.

Conclusion

We present an assessment of the economics of nuclear and climate policies including decommissioning of existing nuclear power plants. Our analysis indicates that the economic and energy-related impacts of strong climate policies are more significant than the impact of restrictive nuclear power policies, both in the short term and in the longer term. The need to reduce emissions interferes with fossil energy markets and leads to significant reductions in the use of coal, oil, and gas. Additional nuclear power is of only moderate importance for achieving strong emission reductions.

Restricting new investments in nuclear power mainly has impacts in the medium term. Decommissioning existing nuclear power capacities induces a shortfall of electricity production that is partially compensated by natural gas power. The new-start scenarios suggest that new nuclear power capacity can also be an important means to fill the remaining power production gap. If this alternative is also abandoned, coal—in the absence of a carbon budget—or a broad mix of other alternatives is applied if a carbon budget is in place. Renewable energy seems not to be a prominent solution approach to fill the shortfall if nuclear power plants are decommissioned. In all scenarios with decommissioning, approximately one third of the total shortfall is met by demand reductions.

The economic impact of combining climate and nuclear power policies reveals the interdependency of the policy dimensions. Combining restrictive policies regarding new and existing nuclear power capacities leads to an escalation of negative economic impacts. However, this escalation is not reinforced if strong climate policies are also added. The economic impact of imposing a stringent carbon budget on the economy is the first-order effect, and much larger than restrictive nuclear power policies. The reduced gas demand makes it easier to deal with restrictions on nuclear power deployment.

One important feature of the carbon budget is that it allows for flexible exhaustion over time. Restrictive nuclear power policies in the presence of the carbon budget can be alleviated by allowing for higher emissions from natural gas in the near term that are sufficient to fill a significant share of the supply shortfall from early retirement. The total amount of reallocation is, however, relatively small compared with the total carbon budget. Unfortunately, such policies are difficult to implement because they need to cover commitments over several decades. Policies that negotiate only short-term caps on carbon emissions are subject to miss the flexibility because there is no built-in mechanism that guarantees the consistency with the cumulative long-term emission target.

Another important point is the flexibility of natural gas markets. The present study assumes, for all scenarios, globally integrated gas markets. Current natural gas markets are, however, subject to a range of regulations, which put effective barriers on such flexible reactions. The prominence of natural gas in cases without climate policies and in cases with restrictive nuclear power policies indicates that a transformation toward integrated natural gas markets is a robust policy strategy. Also, the regional resolution is quite coarse. France, for instance, is part of the EU27 region. The high French nuclear share and limited European electricity market integration impose additional barriers that limit the speed and/or increase the costs of decommissioning existing nuclear power plants.

The flexibility to ramp up natural gas power plants at a large scale has been proven in the past. For example, the United States built 122 GW of natural gas power capacity in a 2-y span of 2002 to 2003, which exceeds today's US nuclear power capacity (105 GW) (25). The US natural gas power capacity is 422 GW, which was operating at an average of only 26% in the year 2009 (26). This low utilization rate suggests huge idle capacities to overcome an electricity supply shortfall. Another issue is that, presently, large amounts of gas associated with crude oil production are flared. For example, Russia flares associated petroleum gas [168–315 TWh (26, 27)] that could be used to replace a large part of their nuclear power generation [164 TWh in 2009 (26)]. To realize the flexibilities of markets and investments, clear policy signals are needed regarding climate mitigation, nuclear power, and the global integration of natural gas markets. The major caveat of the analysis presented here is that imperfections in the different markets and uncertain expectations by market participants regarding future policies are not analyzed. This critique, however, applies to the reference scenario as well, as full integration of fossil fuel markets is assumed. Improved analysis in the future will combine uncertainties about fossil fuel markets with uncertainties regarding policy signals.

Methodology

In this study, we use the long-term global multiregional model ReMIND-R (28, 29), an intertemporal general equilibrium model that hard-links a top-down macroeconomic growth model with a bottom-up energy system model (30). The model finds an intertemporal and international equilibrium solution for all markets (including capital, energy resource, and CO_2 permit markets) under perfect foresight until 2100 by applying the optimization-based Negishi approach. Energy conversion technologies are represented at the capacity level to account for inertia and path dependency. Acceleration of capacity buildup and resource extraction is subject to adjustment costs, thus reflecting the inertia increasing the scale, and to changing structural composition of the energy sector. Fluctuating renewables are subject to increasing integration costs as their generation share increases. Nuclear power and climate policies are implemented by setting restrictions and creation of new markets like those for CO_2 emission permits. More information about the model setup and parameterization is provided in the *SI Appendix*.

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