The 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 analyze the interactions and trade-offs 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 inter-temporal 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. Inter-temporal flexibility of the carbon budget approach enables higher near-term emissions due to 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 | nuclear policy | energy economy model | mitigation scenarios

Introduction

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.

Due to the fact that 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 sulphur, nitrogen oxides, etc. [1, 2, 3, 4]. Even in the absence of climate policies, the Nuclear Energy Agency "red book" [5] expects world-wide nuclear power capacity to increase by 37-110%; and the International Energy Agency [6] expects a 79% increase by 2035 in global nuclear electricity generation in their "New Policies Scenarios," (and of 136% for the "450ppm Scenario"). 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 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 450ppm of CO_2 equivalent concentration [8]. 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 inter alia 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 strong long-term stabilization scenario to the case of full flexibility in nuclear power expansion and found a relatively small increase in mitigation costs. Ref. [11, 12] present additional scenario studies on nuclear power.

Currently, however, the future of nuclear power has become much more uncertain since 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 as well as 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 trade-off 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

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long-term emissions caps? Finally, what are robust energy sector strategies to fill the electricity generation gap due to decommissioning?

Dimensions of nuclear power and climate policies

In this section we introduce both 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 due to economic barriers set by high standards for refurbishment. Building of new capacity might be hindered by either outright bans or by requiring safety standards that increase investments costs. We distinguish four nuclear policy scenarios:

Renaissance Existing plants are utilized 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 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 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 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. The SI Material 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 300GtC for the period 2005 to 2100 representing a relatively aggressive climate mitigation policy consistent with the long-term target of limiting global warming to 2°C.

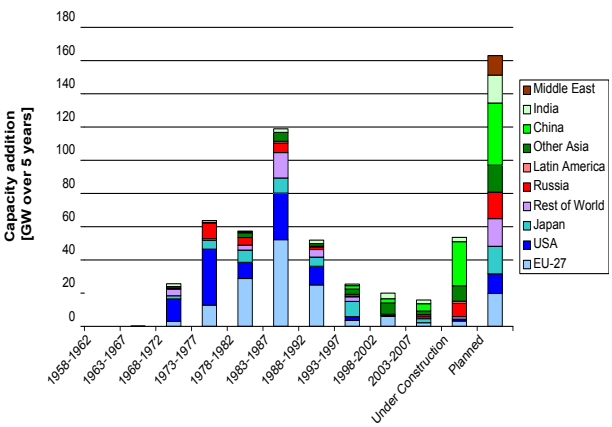

Fig. 1. Vintages of existing nuclear power installed in the past and capacities under construction and planned. The figure does not contain plants decommissioned before 2011, but does include plants shut-down after March 2011. The figure does not account for recent revisions of expansion plans. "Rest of World" includes Canada, South Africa, Switzerland, Ukraine, Turkey. Other Asia includes Taiwan and South Korea. Source: [16].

The techno-economics of nuclear power

Existing capacities Fig. depicts the vintage structure of nuclear power generation capacity in operation in early 2011. The oldest plants are 45 years old, while the five-year period with the highest installation rate was 1982 to 1987, reaching nearly 120GW. Vintages put in place before 1992 are mostly located in 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 last ten years tending sharply upward. Most recent estimates for overnight construction costs are in the range of 3000-6000US$/kW [2, 17, 18], with somewhat lower costs in non-OECD countries (IEA 2010). Ref. [19] found a highly skewed distribution function for observed investment costs in the US, with median costs of 2200US$/kW and a 90% quantile of 8200US$/kW (typically plants with long construction times). Ref. [20, 21] analyze changing investment costs and find a negative learning effect. A study of existing nuclear power plants in Germany [22] that were being considered for technical lifetime extensions beyond 35 years estimated costs for refurbishment between 35 and 110US$/kW and reactor year.

The present study assumes overnight investment costs for a light water reactor of 3000US$/kW, which is at the low end of the ranges given above, but based on the expectation of capacity growth mainly in non-OECD countries. The technical lifetime of nuclear power plants is set at 60 years. After 40 years additional refurbishment costs of 100US$/kW and reactor year are required. The costs of regular decommissioning are included in the O&M costs.

Uranium resources Conventional identified resources of uranium are differentiated into recovery cost categories. The assessment by the Nuclear Energy Agency [5] comprises 6.3Mt of uranium, which equals approximately one hundred times current reactor requirements. The estimates of World Energy Council [23] and German Geological Survey [24] mainly rely on the numbers of NEA 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 23MtU are ultimately available with increasing extraction costs. Moreover, we account for nuclear fuel derived from dismantling military devices. It is assumed that the US receives 22 kilo tons p.a. Uranium at zero costs 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 [25].

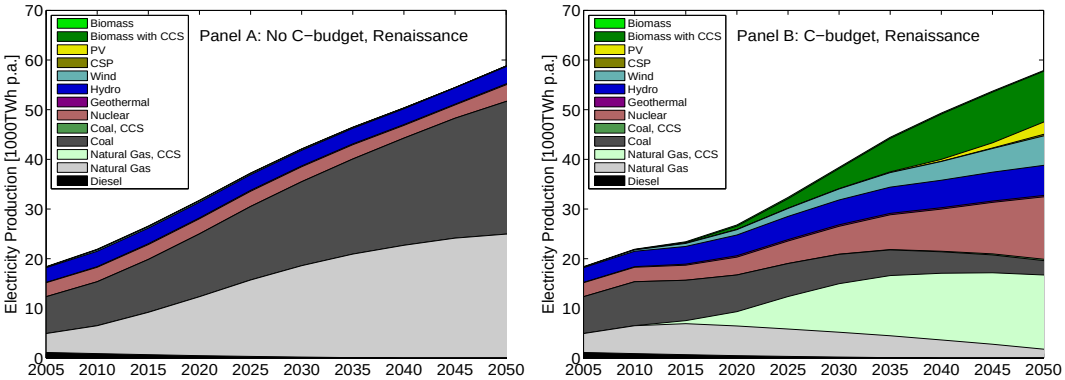

Fig. 2. Global electricity generation mix 2005-2050 for the nuclear renaissance cases. Panel A without and Panel B with carbon budget imposed.

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 to this baseline. SI Material Sec. 2 contains more information.

Over the 21st century total primary energy consumption grows by about 133%, from 513EJ 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 mid-century 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 due to resource constraints. The reliance on fossil fuels increases CO_2 emissions from 8GtC in 2005 to 21GtC in 2100.

In the reference case global nuclear power generation remains roughly constant until 2050; see Fig. 2(A). The constant aggregate, however, contains a global shift of nuclear power generation from OECD countries towards 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 peaks due to the resource constraint on uranium use.

Nuclear phase-out and the 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, thus, decreases usage of fossil fuels compared to the no policy case in 2020: coal by 40%, gas by 18% and oil by 13%; see SI Material 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 due to climate policies is the addition of CCS to natural gas power plants. The net short-fall in gas and coal power generation in 2020 is 3000TWh and 5300TWh compared with the no-policy case, respectively. This short-fall of fossil-fueled electricity supply is partially compensated (3300TWh) by low-carbon technologies, of which nuclear power accounts for 540TWh. The remainder is provided by hydropower, bio-energy with CCS, wind, and geo-thermal. 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 the generation of nuclear power is 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 due to integration and adjustment costs. In the longer-term (after 2040) fossil 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 350MtC/year in 2050. The effect is most significant in Asian regions where most nuclear power plants are expected to be built. On the other hand, if the carbon budget is imposed, there is nearly no inter-temporal reallocation of optimally using up the CO_2 emissions budget over time.

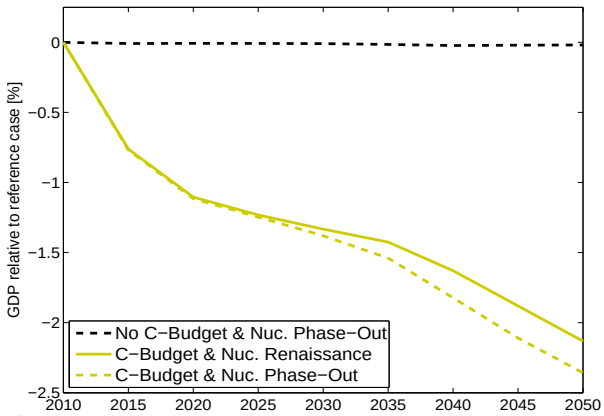

Fig. 3. Differences of GDP 2010-2050 relative to the reference case without carbon budget and nuclear renaissance.

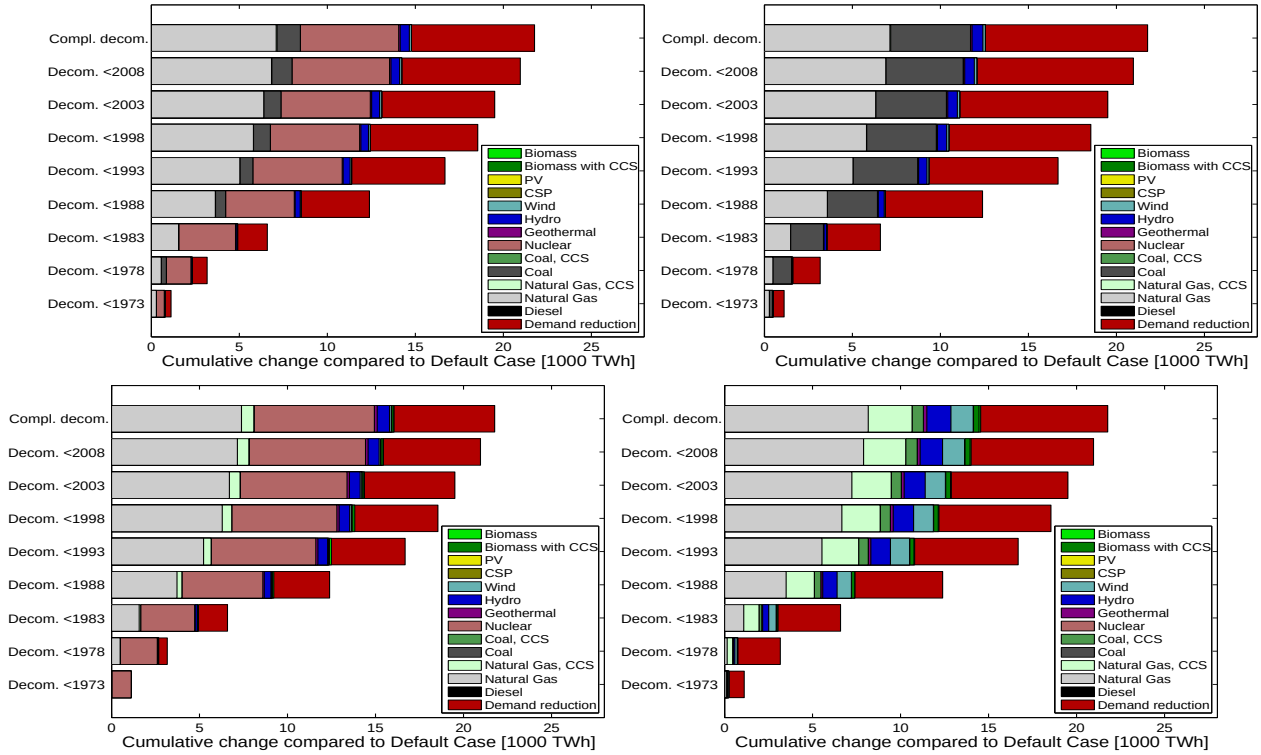

Fig. 4. Differential impact of decommissioning on the global electricity sector measured by changes of cumulative electricity generation 2010-20. The reference case is always without decommissioning. Upper row of graphs: no carbon budget; bottom row: with carbon budget imposed. Graphs on the left show scenarios in which the investment in new nuclear power plants are feasible, whereas the right hand figures show 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 stacked bar above shows result when the second-oldest vintage 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 2010-20. The components show how the short-fall is compensated by alternative technologies, including demand reduction.

The sensitivity of GDP in the three policy scenarios relative to the no-policy case is shown in Fig. 2. 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% p.a. 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 macro-economy in the near term. The imposition of the carbon budget, independent of nuclear phase-out, makes a difference even in the near term.

The 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 life-time. 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 2730 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. . Second, the short-fall 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.

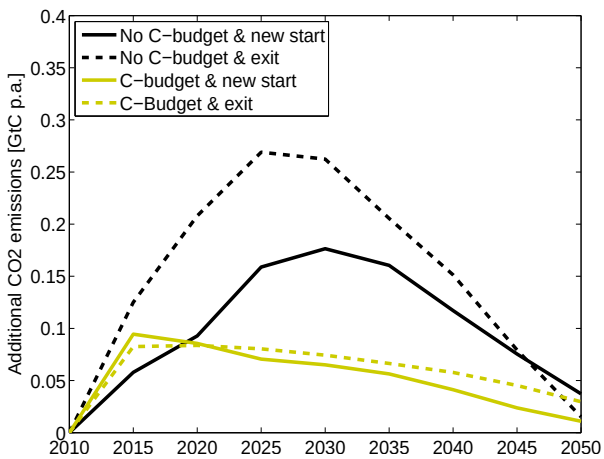

Fig. 5. The impact of decommissioning nuclear power plants on energy related CO_2 emissions. The graph shows the impact of complete decommissioning over time by depicting the differences to the case without decommissioning for four scenarios.

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 short-fall from decommissioning old plants. Coal only plays a notable role

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 only of minor importance. Although renewables are essential for producing carbon-free electricity in the longer term, their contribution in filling the gap due to decommissioning nuclear power plants is small. More details of electricity generation mixes are given in the SI Material Fig. S6.

The increased use of fossil-fuel electricity generation implies higher CO_2 emissions due to nuclear power decommissioning. If power sector CO_2 emissions are not compensated by reductions in other sectors, total emissions will increase. The effect on total CO_2 emissions is shown in Fig. 4. 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 C-budget is imposed, with near-term CO_2 emissions increasing by 100MtC/year, which is a rather small share of total power sector emissions. The reallocation of CO_2 emissions in the two cases with C-budget are at maximum 2.2GtC, which is less than 1% of the total budget of 300GtC until 2100. The effect on CO_2 emissions is more significant, if the C-budget is not imposed.

Fig. 4 shows the costs for various policy scenarios measured by the net present value of GDP losses in relative terms compared to the scenario without policies for the period 2010-20. For scenarios without climate policy the Phase Out scenario leads to costs of 0.006%, wheras the New Start scenario implies policy costs of 0.07%. Combining the decommissioning and the investment abandoning leads to policy costs 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 only by 0.11% to 0.75%, if the restrictive nuclear policies of Full Exit are also imposed. The costs of the combined policies are, hence, smaller than the sum of the isolated effects of the carbon budget and the Full Exit policy that would be 0.78% (indicated by the move of the patch and the dashed lines). 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 Material Fig. S8 contains a more detailed analysis of the policy costs. In the SI Material Fig.@ S10 and S11 we analyze 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; see Fig. S7 in SI Material. 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 due to the inter-temporal 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.

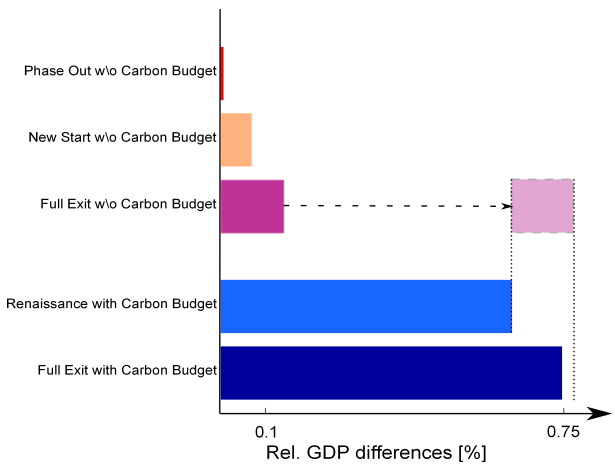

Fig. 6. Policy costs of nuclear power and climate policy scenarios. The graph depicts cumulative discounted policy costs 2010-20 compared with the reference scenario without additional policies in relative terms applying a 5% discount rate. The dashed arrow moving the patch for the scenario with Full Exit and without climate policy is added to the graph to illustrate the analysis of policy synergies that is explained in the text.

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 only of 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 short-fall 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, either 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 seem not to be a prominent solution approach to fill the short-fall, if nuclear power plants are decommissioned. In all scenarios with decommissioning, about one-third of the total short-fall 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 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 short-fall 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 their is not 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 towards 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 large scale has been proven in the past. For example, the US built 122GW of natural gas power capacity in the two years of 2002-03, which exceeds today's US nuclear power capacity (105GW) [26]. The US natural gas power capacity is 422GW that were operating on average only 26% of the year 2009 [28]. This low utilization rate suggests a huge idle capacities to overcome an electricity supply short-fall. Another issue is that presently large amounts of gas associated with crude oil production are flared. For example, Russia flares associated petroleum gas (168 - 315TWh [27, 28]) that could be used to replace large part of their nuclear power generation (164TWh in 2009 [28]). 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, since 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 employ the long-term global multi-regional model ReMIND-R [29, 30], an inter-temporal general equilibrium model that hard-links a top-down macro-economic growth model with a bottom-up energy system model [31]. The model finds an inter-temporal 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 build-up and resource extraction is subject to adjustment costs, thus reflecting the inertia increasing the scale and to changing the 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 set-up and parameterization can be found in SI Material Sec. 1.

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1. Ahearne JF (2011) Prospects for nuclear power. Energy Economics 33:572-80.
2. Ansolabehere SD, Deutsch J, Driscoll M, Gray PE, Holdren JP, Joskow, PL, et al. (2003): The future of nuclear power. Cambridge: MIT Press.
3. Toth FL, Rogner HH (2006) Oil and nuclear: past, present and future. Energy Economics 28:1-25.
4. van der Zwaan BCC (2008) Prospects for nuclear energy in Europe. International Journal for Global Energy Issues 30(1-4):102-21.
5. Nuclear Energy Agency NEA (2010) Uranium 2009. Resources, Production, and Demand. Nuclear Energy Agency and Organization of Economic Co-operation and Development. Paris, France.
6. International Energy Agency IEA (2010) World Energy Outlook 2010. Paris, France.
7. Energy Information Administration EIA (2009) International energy outlook 2009. Washington DC.
8. Clarke L, Edmonds JA, Krey V, Richels R, Rose S, Tavoni M (2009) International Climate Policy Architectures: Overview of the EMF 22 International Scenarios. Energy Economics 31:S64-S81.
9. Edenhofer O, et al. (2009) The economics of decarbonization. Report of the Recipe project. Potsdam-Institute for Climate Impact Research, Potsdam, Germany.
10. Edenhofer, O., Knopf, B., et al. (2010) The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs. Energy Journal (Special Issue on the Economics of Low Stabilization), pp. 11-48.
11. Remme U, Blesl M (2008) A global perspective to achieve low-carbon society (LCS): scenario analysis with ETSAP-TIAM. Climate Policy 8:S60-S75.
12. Vaillancourt K, Labriet M, Loulou R, Waaub JP (2009) The role of nuclear energy in long-term climate scenarios: an analysis with the World-TIMES model. Energy Policy 36:2296-307.
13. International Energy Agency IEA (2011) Clean Energy Progress Report. IEA Input to the Clean Energy Ministerial. Paris, France.
14. Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, Knutti R, Frame DJ, Allen MR (2009) Greenhouse-gas emission targets for limiting global warming to 2C. Nature 458:1158-1163
15. WBGU (2009) Solving the Climate Dilemma: the budget approach Springer, Berlin, Germany.
16. International Atomic Energy Agency IAEA (2011) Power Reactor Information System (PRIS) database. Accessed April 2011.
17. International Energy Agency IEA (2010) Costs of electricity. Paris, France.
18. Committee on America's Energy Future (2009) America's Energy Future: Technology and Transformation. National Academies Press, Washington.
19. Koomey J, Hultman NE (2007) A reactor-level analysis of busbar costs of US nuclear plants. Energy Policy 35:5630-42.
20. Grubler A (2010) The costs of the French nuclear scale-up: A case of negative learning by doing. Energy Policy 38:5274-88.
21. Lako P, van Heek A, Rothwell G (2010) Nuclear Power. In Junginger M, van Sark W, Faaij A (Eds.) Technological Learning in the Energy Sector, pp.176-92.
22. Schlesinger M, Lindenberger D, Lutz C (2010) Energieszenarien fr ein Energiekonzept der Bundesregierung. Project number 12/10 of the German Federal Ministry of Economics.
23. World Energy Council WEC (2010) 2010 Survey of energy resources. London, UK.
24. Bundesanstalt fr Geowissenschaften und Rohstoffe BGR (2010) Reserven, Ressourcen und Verfgbarkeit von Energierohstoffen. Hannover, Germany.
25. Bunn M, Holdren JP, Fetter S, van der Zwaan BCC (2005) The economics of reprocessing versus direct disposal of spent nuclear fuel. Nuclear Technology 150:209-30.
26. International Energy Agency IEA (2007) Electricity Information 2007. CD-ROM. Paris, France.
27. PFC Energy (2007) Using Russia's Associated Gas. Prepared for the "Global Gas Flaring Reduction Partnership" and World Bank. Accessed December 7, 2011. http://siteresources.worldbank.org/INTGGFR/Resources/pfc_energy_report.pdf
28. International Energy Agency IEA (2011) World Energy Outlook 2011. Paris, France.
29. Leimbach M, Bauer N, Baumstark L, Edenhofer O (2010) Mitigation Costs in a Globalized World: Climate Policy Analysis with ReMIND-R. Environmental Modeling and Assessment 15:155-73.
30. Leimbach M, Bauer N, Baumstark L, Lueken M, Edenhofer O (2010) International trade and technologcial change-insights from REMIND-R. The Energy Journal Special Issue, The Economics of Low Stabilization 31:161-188
31. Bauer N, Edenhofer O, Kypreos S (2008) Linking Energy System and Macroeconomic Growth Models. Journal of Computational Management Science 5 (1-2): 95-117.