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Summary
This paper investigates whether an inefficient allocation of abatement, due to constraints on the use of currently available low carbon mitigation options, can promote innovation in new technologies and eventually generate welfare gains. We focus on the case of nuclear power phase out, when accounting for endogenous technical change in energy efficiency and in low carbon technologies. The analysis uses the Integrated Assessment Model WITCH, which features multiple externalities due to both climate and innovation market failures. Our results show that phasing out nuclear power stimulates additional R&D investments and deployment of infant technologies with large learning potential. The innovation benefits which this would generate and that would not otherwise be captured due to intertemporal and international externalities almost completely offset the economic costs of phasing out nuclear power. The technological change benefit depends on the stringency of the climate policy and is distributed unevenly across countries.

Keywords: Technological change, Climate policy, Nuclear phase-out

JEL Classification: H40, O33, Q40, Q55

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Abstract

This paper investigates whether an inefficient allocation of abatement, due to constraints on the use of currently available low carbon mitigation options, can promote innovation in new technologies and eventually generate welfare gains. We focus on the case of nuclear power phase out, when accounting for endogenous technical change in energy efficiency and in low carbon technologies. The analysis uses the Integrated Assessment Model WITCH, which features multiple externalities due to both climate and innovation market failures. Our results show that phasing out nuclear power stimulates additional R&D investments and deployment of infant technologies with large learning potential. The innovation benefits which this would generate and that would not otherwise be captured due to intertemporal and international externalities almost completely offsets the economic costs of phasing out nuclear power. The technological change benefit depends on the stringency of the climate policy and is distributed unevenly across countries.

1. Introduction

When GHG emissions are the only externality, a uniform carbon tax or a global cap and trade scheme with full when, where, and what flexibility would achieve the most efficient abatement allocation across polluting sources, regions, and technologies. In the context of climate change, this basic principle has been substantiated by a number of modeling comparison exercises, showing that a wider technology portfolio minimizes abatement costs. For policy, this means that no technology should get a special treatment, as the efficient allocation of mitigation effort would be ensured by the economic signal of carbon pricing.

Technology externalities can make the case for differentiated climate policies across sectors and technologies. When learning effects and international spillovers are not accounted for by the regulator, the optimal policy needs to differ from the first-best one (Goulder and Schneider 1999, Goulder and Mathai 2000, Gerlagh et al. 2009). Second-best policies exceed the Pigovian tax because a tighter emission requirement is a way of compensating for the lack of technology policy (Golombek and Hoel 2006, De Cian and

Tavoni 2012). In a cost-effective setting, multiple externalities affect the cost-minimizing abatement allocation, and welfare gains might arise from a differentiation in marginal abatement costs (Rosendahl 2004, Bramoullé and Olson 2005, Otto et al. 2008). In particular, technology externalities provide an incentive to differentiate their pollution tax to technologies with relatively high technology externalities associated to them. Bramoullé and Olson (2005) show that a policy that equalizes the instantaneous marginal costs of abatement between technologies is not optimal under learning by doing. Technology policies that affect the technological trajectory towards sectors with high learning and high spillovers potential might lower the costs of achieving a climate change targets.

This paper investigates whether second-best allocation of abatement across technologies is inefficient and to what extent welfare gains arise if technologies feature learning potential and international externalities. In particular, we examine the technology and welfare implications of an inefficient abatement allocation due to the phase out of nuclear energy after 2010. The analysis uses the Integrated Assessment Model (IAM) WITCH. The model provides a compact, but rich characterization of the energy system and its technology dynamics, both in terms of learning and innovation. Different technologies are characterized on the basis of their stage of development. Infant technologies, represented in the model as breakthrough substitutes of conventional options, feature much higher learning and innovation externalities potentials, while conventional technologies are assumed not have learning. These elements are fully integrated into a macroeconomic model of economic growth. Therefore, welfare implications can be analyzed in a consistent way. The remainder of the paper is organized as follows. Section 2 introduces a standard abatement model with technology externalities. Section 3 describes the motivation and the experiment design. Section 4 presents the integrated assessment model. Section 5 illustrates the results. Section 6 concludes.

2. Abatement allocation with two technologies

A simple static example can be used to illustrate the case for differentiated policy incentives across technologies. Consider a two-technology model where the two technologies, $C_i \; i = 1{,}2$, can be used to achieve a given level of abatement. Let us assume that technology 1 has a constant marginal costs, $C_1\;(a_1)$, while technology 2 features intertemporal as well as international externalities generated by experience, $\bar{Z} = Z_1 + Z_2$, and knowledge, $\bar{H} = H_1 + H_2$, $C_2\;(a_2, \bar{Z}, \bar{H})$. *Intertemporal externalities* occur because learning by doing is external to the maximizing region. Learning benefits *($\bar{Z}$)* occur as a side effect of capacity accumulation in technologies, but they are not taken into account in the optimization process (Arrow, 1962). *International externalities* occur because regions investing in R&D cannot fully protect their inventive activity. Patents are temporary and do not allow to appropriate the full benefits of R&D (Romer, 1986). Therefore, R&D investments in each given region *i* contribute to the creation of a stock of knowledge that has an external effect on regional abatement costs, $\bar{H}$. Since increased abatement today lowers costs at all future dates, the optimal allocation of abatement across technologies depends on the marginal effect abatement today has on the entire time path of abatement costs. What should be actually equalized are the adjusted marginal abatement costs (Bramoullé and Olson, 2005), that is the marginal abatement costs of abatement less the cumulative cost reduction due to learning by doing and knowledge spillovers:

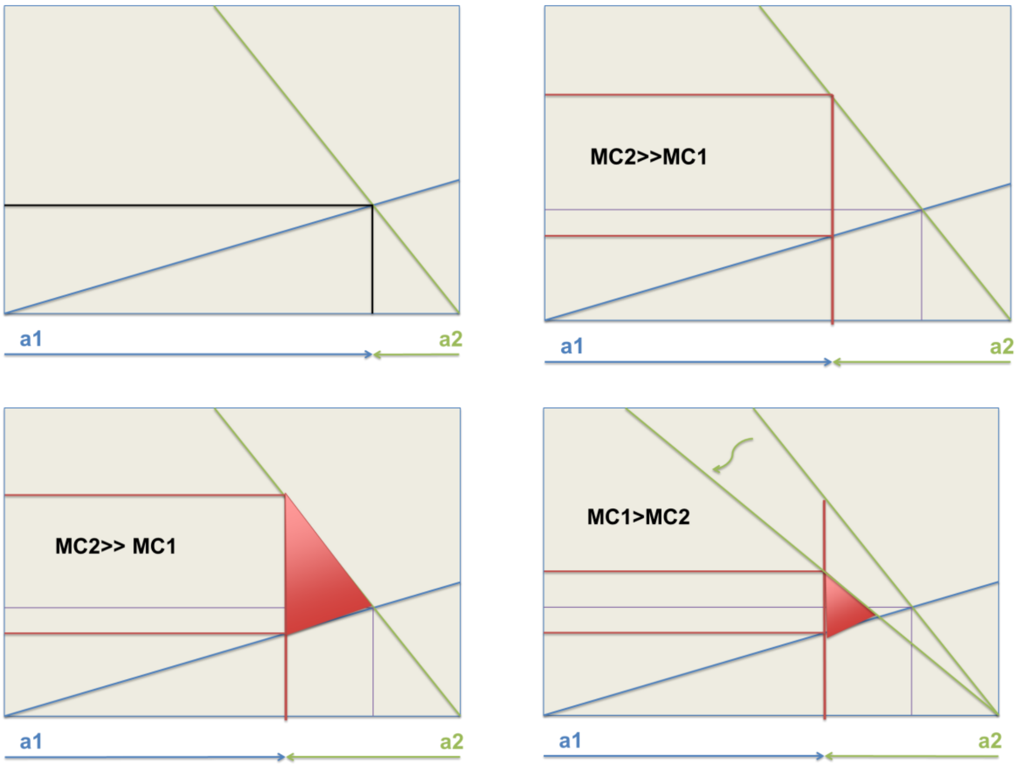
$$c_{2a}(a_2,\bar{Z},\bar{H}) - \int_t^T e^{t-s}[c_{2Z}(a_2,\bar{Z},\bar{H}) + c_{2H}(a_2,\bar{Z},\bar{H})ds] = c_{1a}(a_1)$$

where

$$c_{2\bar{Z}}(a_2,\bar{Z},\bar{H}) < 0;\ c_{2\bar{H}}(a_2,\bar{Z},\bar{H}) < 0; c_{ia}(a_2,\bar{Z},\bar{H}) > 0$$

This has two implications. Excluding technology options *with* high externalities leads to higher penalties than excluding technologies *without* externalities because it also foregoes the associated externalities. Given two alternative abatement technologies such as technology 1 and 2, inducing more abatement in the option with higher learning potentials and externalities can lead to Pareto improvements. This is illustrated by a simple static example in Figure 1.

Fig. 1 A simple example with two abatement technology and learning externalities



The top-left panel shows the cost-effective abatement allocation between technology 1 and 2, *a1*, *a2*. Consider now a cap on the amount of abatement that can be achieved with the cheapest technology, *a1*. As shown in the top-right panel of Figure 1, marginal abatement costs would no longer be equalized and the marginal abatement cost of option 2 would exceed that of option 1, as too much abatement is left to the less efficient technology 2. This leads to a welfare loss represented by the red area in the bottom-left panel. This would be the end of the story if there were no link between abatement and technology costs. If the costs of the most expensive technology instead depend on abatement and R&D (not shown in the chart), then a situation like the one depicted in the bottom-right panel could emerge. The greater abatement allocated to technology 2 induces learning that reduces the technology cost, leading to a lower net welfare loss, represented by the smaller red area.

This simple example provides a rationale for subsidizing learning technologies (e.g. renewables, see Badcock and Lenzen, 2010). Constraining the use of mature technologies (e.g. nuclear) is equivalent to a subsidy to all remaining mitigation options, including technologies subject to learning (which can be either dirty or clean). In the next sections we set forth to quantify these benefits using an IAM.

3. Motivation and experiment design

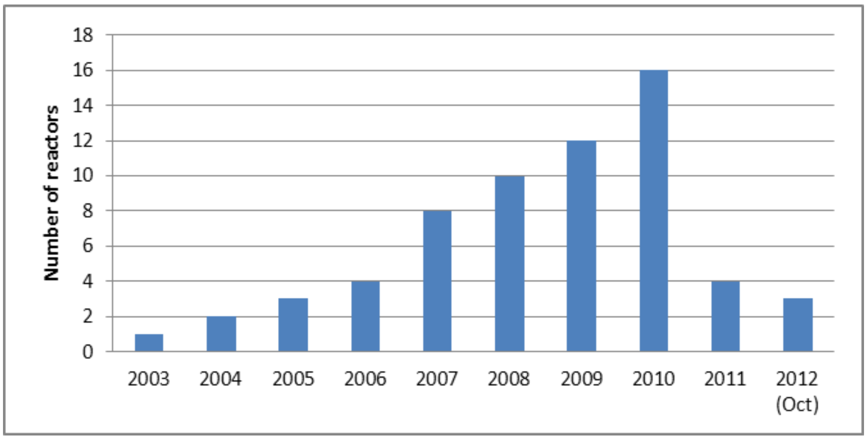
After the disaster occurred at the Fukushima Daiichi nuclear power plant (March 2011), a debate mainly focused on the safety of this energy technology has risen in many countries of the world, especially in Western Europe, leading in some cases to a re-thinking of the nuclear option. In Germany, which at that date featured seventeen reactors, the government ordered the immediate shutdown of the eldest eight, with a progressive phasing out of the remainders to be completed within 2022. It is evident how political that decision was, as just the previous year a law aimed at extending the operational life of the more modern nuclear plants until 2038 had been approved. Indeed, it must be said that this choice did not have major impacts on the 2011 electricity import/export balance (Loreck, 2012) nor on GHG emissions (Umweltbundesamt, 2012), which actually decreased with respect to 2010, even if long-term impacts on electricity price are difficult to forecast (Pahle et al., 2012). The Swiss government pronounced immediately after the accident, announcing a complete phase out of nuclear according to the pre-determined schedule (i.e. between 2019 and 2034) and blocking the projects concerning the construction of three new plants. An analogous scenario has been taking shape in Belgium, whose government has fixed the shutdown of the national seven plants between 2015 and 2025. In Italy, a similar post-Chernobyl situation took place. In late 80s, the government decided the abandonment of nuclear energy, shutting down the four existing plants and blocking the construction of additional two. The decision reflected the public aversion emerged in a national referendum held in 1987, one year after the disaster in the former Soviet Union. In late 2000s, the government decided to re-start a nuclear program, planning to meet 25% of the internal electricity demand with such a source within twenty years, but again a post-incident referendum determined a stop to this policy. The recently released 2020 energy national program excludes nuclear as a deployable option. Obviously the most considerable consequences were felt in Japan, where the disaster heavily impacted on the population, and the effects on the nuclear energy policies have been accordingly substantial. Immediately after the incident, which directly caused the loss of four reactors, all the other fifty were shut down for safety checks, planning a gradual re-start of the safer ones in the following months. Before the accident, 30% of Japan electricity demand was covered by nuclear, with plans of up-scaling up to 50% by 2030. After the accident, the government released a new energy plan which scheduled a gradual phasing out of the operating plants by 2040.

It must be said that many countries have not modified their plans of continuation or development of their nuclear programs. Among them, we can mention China, Russia, Republic of Korea (which inaugurated two reactors in 2012) and India. United States too have confirmed nuclear as a strategic energy source for the nation, even if very few projects have concretely been moving forward.

Setting aside single countries' intentions, it must be noted that out of the 437 nuclear reactors operating worldwide as of October 2012, 349 are more than twenty years old. Therefore, despite the development programs (64 reactors are under construction, 160 are planned), it is possible to forecast a short- to medium-term reduction in electric output from nuclear plants due to the decommissioning of old plants not fully replaced by new ones.

However, if the Fukushima-Daiichi incident boosted the debate on nuclear energy, and in particular on the safety issues, it is true that other criticisms rose in recent years even before that fact, mainly focusing on the nuclear waste disposal or treatment and on cost and time uncertainties, which, especially in the new European plants, have been showing considerable increases in this sense with respect to the planned ones (Hass, 2012). As a result, although it is difficult to draw definitive trends throughout the century, after a decade in which construction starts of new plants had progressively increased, in the last two years the number of construction starts showed a considerable drop (see Figure 2).

Fig. 2 Construction starts of new reactors sorted by years



Against this background, evaluating scenarios of phasing out nuclear power becomes a policy relevant exercise. Relevant questions concern implications on the technology mix, induced innovation and technology development, and welfare. To the extent to which nuclear power is a CO_2-free option and therefore its value increases in mitigation scenarios (Tavoni et al., 2012), phasing out nuclear power would induce a second-best allocation of abatement. The extent to which this second-best abatement allocation generates efficiency losses and positive technology externalities is an empirical question that we address using the Integrated Assessment Model WITCH (see Section 4 and 5). This investigation represents a novel contribution to the literature because, to our knowledge, the innovation implications of the nuclear phase out has never been addressed in the literature. In fact, if the nuclear phase out is a typical scenario considered in all comparison exercises, while the analysis of additional nuclear power policies is much rarer, see Bauer et al. (2012), models normally focus on the rearrangement of the electricity mix and on the climatic and economic impacts of this technology constraint, but secondary effects on new technologies and innovation are never examined in detail[1].

Regarding the theoretical considerations, the nuclear phase out case offers a case study that mimics very closely the simple example given in Section 2. The WITCH model, which is used for the numerical analysis and described in Section 3, characterizes power generation from different technology options, including nuclear power, renewables, and breakthrough technologies with endogenous costs. In the jargon of the analytical model of Section 2, nuclear power represents an example of technology 1, with lower but constant investment costs. Wind power and the breakthrough technology are alternatives with characteristics similar to technology 2, as costs decline with abatement and R&D in the case of the breakthrough technology. The breakthrough technology is not meant to represent a specific technology choice, but it could be associated with nuclear fusion or with advanced generation, waste-free nuclear fission.

These two technology options generate positive technology externalities. Therefore, the nuclear phase out offers a case study for analyzing in a quantitative way the qualitative conclusion formulated at the end of Section 2, namely that constraining the use of mature technologies (e.g. nuclear) is equivalent to a subsidy and that subsiding early-stage technologies can create welfare gains. In Section 5 we explore whether this conclusion holds across policy regimes and regions.

Incidentally, there is no doubt at all that nuclear power can be considered a mature technology, having been deployed starting from the 50s and definitively consolidated during the 70s and 80s. As such, it is characterized by low learning rates and potentials, and specifically lower than the other technologies with which it would compete (Kahouli-Brahmi, 2008).

The experiment is designed as described in Table 1. Four technology scenarios have been taken into account. In the "With All Technologies" case, no constraint is set on the energy options portfolio, which thus is fully optimized. In the other three cases, instead, nuclear power is subject to phase out, which means no construction of new nuclear power plants

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[1] It is not within the scopes of this paper, instead, to deeply investigate what could be the technology solutions to replace nuclear. It suffices to say that there is an on-going debate on this issue. In fact, nuclear plants guarantee full-load electricity supply throughout the year without emitting carbon dioxide, which makes them a more valuable option in a climate mitigation perspective. Renewable energies are basically carbon-free as well, and some studies depict a 100% renewable scenario for the electric system (Steinke, 2013) or even for the whole energy sector (Delucchi and Jacobson, 2011a and 2011b). However, the well-known intermittency problems make their use as base or intermediate load plants very difficult, if not impossible, without a proper backup capacity, which in a way only reformulates the problem (Trainer, 2012). On the other hand, any alternative option involving fossil fuels would necessarily entail the coupling of a CCS system in order to limit the impact in terms of carbon dioxide (Tavoni and van der Zwaan, 2009).

beyond those already under construction or planned (thus excluding proposed ones), with no lifetime extensions. In the “With Nuclear Phase Out” case no other constraints are imposed, and in particular R&D investments and the deployment of technologies characterized by LbD freely adjust according to the new technology framework. In “With Nuclear Phase Out w/o innovation benefits” R&D investments are instead fixed to the “With All Technologies” case, even if investments in innovative energy technology are not constrained. Finally, in “With Nuclear Phase Out w/o technology benefits” both R&D investments and investments in learning technologies are fixed to the reference case in order to completely remove any benefit deriving from the redirection of investments from mature nuclear power to renewables and breakthrough.

All these scenarios have been run under three different policy cases, i.e. Baseline, where no constraint is imposed to GHG emissions, 450ppme and 550ppme, where a pre-determined emission path is fixed, in order to achieve a GHG concentration in 2100 equal to the corresponding value, as will be better described in Section 5.

Table 1 Scenario matrix

Policy cases	***Technology assumptions***			
Baseline//450ppme//550ppme	**With All Technologies**	**With Nuclear Phase Out**	**With Nuclear Phase Out w/o innovation benefits**	**With Nuclear Phase Out w/o technology benefits**
	All technology investments are chosen optimally	No new nuclear power plants beyond those under construction/ planned.	No new nuclear power plants beyond those under construction/ planned.	No new nuclear power plants beyond those under construction/ planned.
		R&D investments and the deployment of technologies characterized by LbD freely adjust.	R&D investments are fixed to ‘all technologies’ levels. The deployment of technologies characterized by LbD freely adjusts.	R&D investments and the deployment of technologies characterized by LbD are fixed to ‘all technologies’ levels.

4. Innovation and technology dynamics in the WITCH model

The numerical analysis is performed with the WITCH model[2], an energy-economy model that features multiple externalities. A full description of the model can be found in Bosetti et al. (2006) and Bosetti et al. (2009). A more recent description of R&D and learning dynamics are presented in De Cian et al. (2012). Here we briefly discuss how the externalities are represented in the model.

WITCH is a dynamic, optimal growth model with a focus on the energy sector and on GHG mitigation options. It consists of thirteen aggregated regions, denoted with *n*. Model regions behave independently with respect to all major economic decision variables, including investments and fossil fuel use, by playing a non-cooperative game. Technological change in energy efficiency and specific clean technologies is endogenous and reacts to price and policy signals. Technological innovation and diffusion processes are also subject to international and intertemporal spillovers. This implies that the Nash equilibrium, which is the model solution, does not internalize the technology externalities.

The *technology externality* is modeled via international and intertemporal spillovers of knowledge and experience across countries and over time. The *innovation externality* takes the form of international spillovers of knowledge embodied in the energy sector. In each given model region, *n*, the stock knowledge for technology *i*, H_i, evolves over time with domestic investments I_H and a global stock of knowledge, $\overline{H}_i$:

$$H_i(n,t+1) = H_i(n,t)(1-\delta_i) + I\_H(n,t)_i^{\alpha} H_i^{\beta}(n,t)\overline{H}_i^{\gamma}(n,t) \qquad (1)$$

where investments in R&D are combined with cumulated stock of existing national knowledge, H_i, to account for standing on shoulder effects (intertemporal externalities), and foreign knowledge, $\overline{H}_i$, to account for international externalities:

$$\overline{H}_i(n,t) = \frac{H_i(n,t)}{\sum_{j\in OECD} H_i(j,t)}\left(\sum_{j\in OECD} H_i(j,t) - H_i(n,t)\right) \qquad (2)$$

The knowledge frontier is represented by the total stock of knowledge available in top innovator countries, the OECD, and it is taken as an externality by each optimizing region.

The two stages of innovation and diffusion are combined in a two-factor learning curve specification for investment costs. Investment costs of some technologies (see Table 2) are an endogenous function of the knowledge stock (Learning-By-Researching) and installed capacity (Learning-By-Doing). Learning-By-Researching (first term in eq. [3]) occurs before the technology penetrates the market, while Learning-By-Doing (second term in eq. [3]) operates when technology deployment starts:

$$\frac{C_i(n,t)}{C_i(n,0)} = \left(\frac{H_i(n,t-2)}{H_i(n,0)}\right)^{-\theta_{i,1}} \left(\frac{\overline{Z}_i(n,t)}{\overline{Z}_i(n,0)}\right)^{-\theta_{i,2}} \qquad (3)$$

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[2] See www.witchmodel.org for model description and related papers.

$$\bar{Z}_i = \sum_n \sum_0^t Z_i(n,t) \quad (4)$$

The available technologies *i* include energy efficiency improvements, fossil-fuel-based technologies in power sector, fossil-fuel-based technologies in final use sectors, carbon-free technologies in power sector, carbon-free technologies in final use sectors, breakthrough technologies.[3] Table 2 summarizes the characterization of externalities for the various technologies represented in the WITCH model.

Table 2 Technology and innovation externalities represented in the WITCH model

		Fossil-fuel based technologies	*Fossil-fuel based technologies with CCS*	*Nuclear power*	*Renewable energy (Wind)*	*Breakthrough technologies*
Innovation externalities	*Hi*	NA	NA	NA	NA	YES
	$\theta_{i,1}$	NA	NA	NA	0	YES
Technology externalities	*Zi*	NA	NA	NA	YES	YES
	$\theta_{i,2}$	NA	NA	NA	YES	YES

Nuclear power can be replaced by fossil-based technologies with and without CCS, wind power, and a breakthrough technology. The two latter options, and in particular the breakthrough, are less mature than fossil-based technologies and therefore generate a greater amount of externalities. For more details on the representation of these technologies in terms of costs and potential, we refer the reader to the model website and papers contained therein.

Despite the endogenous characterization of knowledge formation and learning, the representation of technical change is still a simplification of actual dynamics. First of all,

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[3] Electricity can be generated using fossil fuel based technologies and carbon-free options. Fossil-fuel-based technologies include natural gas combined cycle (NGCC), oil- and pulverized coal-based power plants. Integrated gasification combined cycle power plants equipped with carbon capture and storage (CCS) are also modeled. Zero carbon technologies include hydroelectric and nuclear power plants, wind turbines and photovoltaic panels (Wind&Solar). The end-use sector uses traditional biomass, biofuels, coal, gas, and oil. Oil and gas together account for more than 70% of energy consumption in the non-electric sector. Instead, the use of coal and traditional biomass is limited to some developing regions and decreases over time. First generation biofuels consumption is currently low in all regions of the world and the overall penetration remains modest over time given the conservative assumptions on their large scale deployment.

the model is fully deterministic and it assumes that innovation or learning reduce technology costs when they reach a certain level. Second, we do not model technological change in less mature technologies, such as fossil-fuel based technologies and extraction technologies.

On the one hand, since this study neglects the endogenous innovation dynamics in the conventional sector, our results might overestimate the welfare gains associated with the nuclear phase out. This would actually be the case if nuclear phase out stimulated investments in technologies, such as natural gas, which have lower learning potentials. On the other hand, since we do not account for the learning potential and externalities in CCS technologies, our results might underestimate the welfare gains associated with the nuclear phase out.

5. Model solution and results

The model outcome is the solution of a non-cooperative game between native regions. In the baseline scenarios, model's regions choose investments in final goods and energy technologies in order to maximize utility under a set of technology constrains. In the policy scenarios, regions solve the same program, but under the additional constraint on regional GHG emissions. The regional emission caps are computed on the basis of a Contraction & Convergence scheme (Meyer, 2000). The global optimal GHG caps consistent with the long-term targets of 450 and 550ppme are determined by solving the model in a cooperative way. A unique global social planner maximizes global aggregate welfare under a radiative forcing constraint. Full when and where flexibility is allowed, and countries can buy and sell carbon permits on the international carbon market.

It is important to stress that, when optimizing their own welfare, regions do not internalize innovation and technology externalities, e.g. international spillovers of knowledge and the learning effects occur outside the decision process, after solving for the optimal choice of investments. The presence of positive externalities which are not fully internalized leads to the under-provision of the public goods knowledge and deployment of learning technologies. To the extent the model solution does not internalize these benefits, it represents a second-best outcome. In a second best context, where market failures cannot be easily removed, an additional distortion or failure can help to improve the economic equilibrium when a policy is implemented (Lipsey and Lancaster, 1956).

Nuclear power is a carbon-free source of power. If social and environmental concerns did not limit the extent to which countries rely on this source for electricity generation, the WITCH model would foresee a continued use of the technology, and in 2100 nuclear would generate between 10% and 50% of the global electricity production, in the baseline and in the most stringent policy case considered (450ppme). Should this technology be excluded from the portfolio of feasible options, then countries would revise their energy mix by modifying their investment strategy.

In a baseline scenario this means more investments in coal and gas (but only in the short term, i.e. until 2025-2030), more renewables and more clean power R&D (breakthrough). The breakthrough starts to replace nuclear power as well as fossil-based technologies in

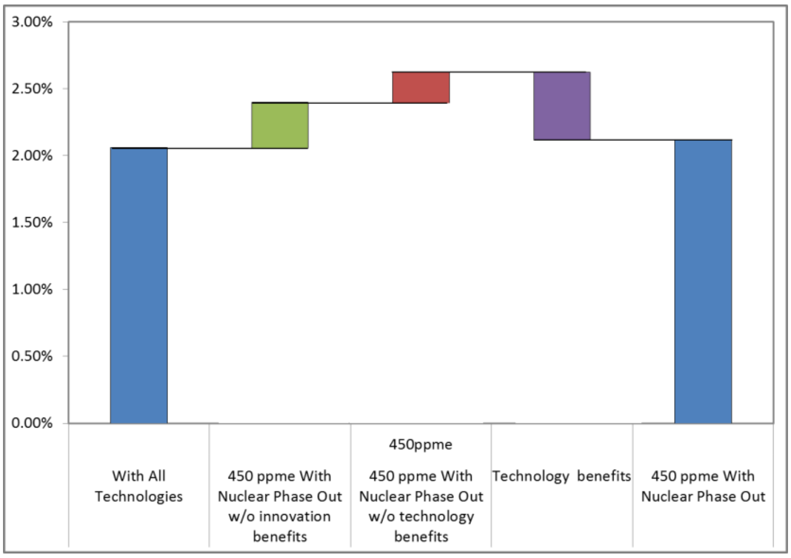
2030. In a policy scenario nuclear phase out translates into more investments in fossil technologies in combination with CCS (coal and gas), renewables and clean power R&D (breakthrough), which is anticipated by five (550ppme) and ten years (450ppme) with respect to the baseline. The breakthrough starts to replace nuclear power as well as fossil-based technologies in 2020 (450ppme) and 2025 (550ppme). Under all the policy regimes considered, the phase out of nuclear power induces investments in early stage technologies and innovation that feature higher learning potential and international externalities compared to the alternatives that are displaced. As a consequence, the economic penalty, measured as increase in policy costs, is partly compensated by the welfare improvements due to the penetration of technologies with externalities.

Figure 3 decomposes the penalty of phasing out nuclear into the gross component (gross of technology and innovation benefits) and the technology and innovation benefits. The two blue bars show the discounted world consumption loss at 450ppme in 2100 with a full technology portfolio (left) and with a constrained one, i.e. with nuclear phase out (right). Phasing out nuclear increases the aggregate discounted cost of the stabilization policy only slightly, from 2.06 to 2.12% (blue bars). Technology benefits reduce the macroeconomic loss by 0.5% (violet bar). Policy costs would increase to 2.62%, should the technology benefits be excluded. That is, the technology benefits due to implicit subsidy to learning technologies caused by the nuclear phase out is able to almost completely offset the cost of losing an important mitigation option, which otherwise would be substantial (by 27% in the 450ppme and 42% in the 550ppme).[4] A similar result holds in the 550ppme and in the BAU scenarios, where technology benefits reduce the macroeconomic loss by 0.35% and 0.14%, respectively.

Figure 4 traces the positive relationship between technology benefits and an indicator of policy stringency, namely cumulative abatement to 2100. Technology benefits are defined as the percentage point difference between the percentage change in discounted GDP/consumption in the 450/550ppme With Nuclear Phase Out w/o technology benefits compared to relative BAU (policy costs) and the same policy cost indicator computed in the 450/550ppme With Nuclear Phase Out. In the BAU we computed the percentage change in discounted GDP/consumption compared to the case With All Technologies. The technology benefit is defined as the percentage point difference between the percentage change in GDP/consumption in the BAU With Nuclear Phase Out w/o technology benefits and the BAU With Nuclear Phase Out. Technology benefits increase with policy stringency in absolute value. When measured relative to the total costs of the policy without nuclear they show diminishing returns, the benefits actually decrease when the policy becomes more stringent, from 38% of total costs in the 550ppme case to 29% in the 450ppme case. This is due to a saturation effect of the productivity of the innovation effort. As expected, the technology benefit is also positively correlated with cumulative investments in R&D, renewable energy and breakthrough.

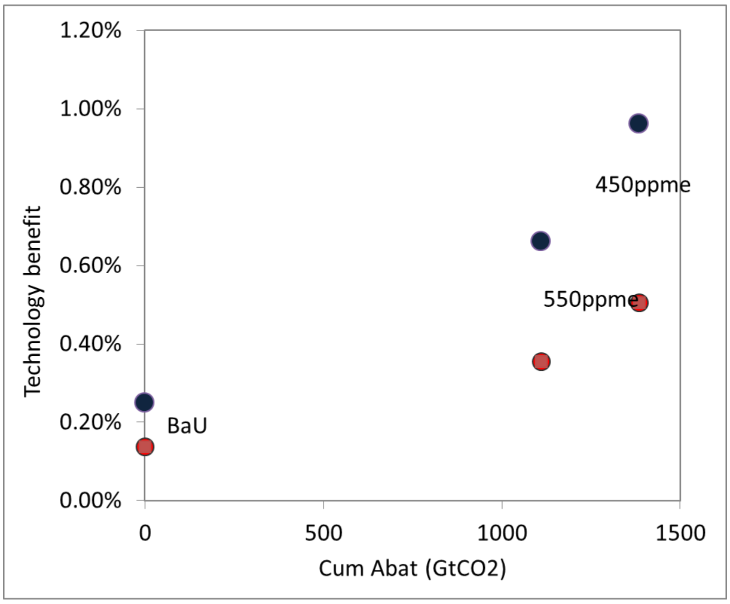
[4] Policy costs measured in terms of GDP are larger, but we focus on consumption as a better indicator of welfare. The GDP losses without nuclear power would be 3.23% and it would increase to 4.19%, should technology benefits be excluded.

Fig. 3 Decomposing the technology penalty from technology benefits (450ppme): consumption net present losses compared to Baseline (5% discounting).



Technology benefits are defined as the percentage point difference between the percentage change in discounted consumption in the 450ppme With Nuclear Phase Out w/o technology benefits compared to relative BAU (policy costs) and the same policy cost indicator computed in the 450ppme With Nuclear Phase Out.

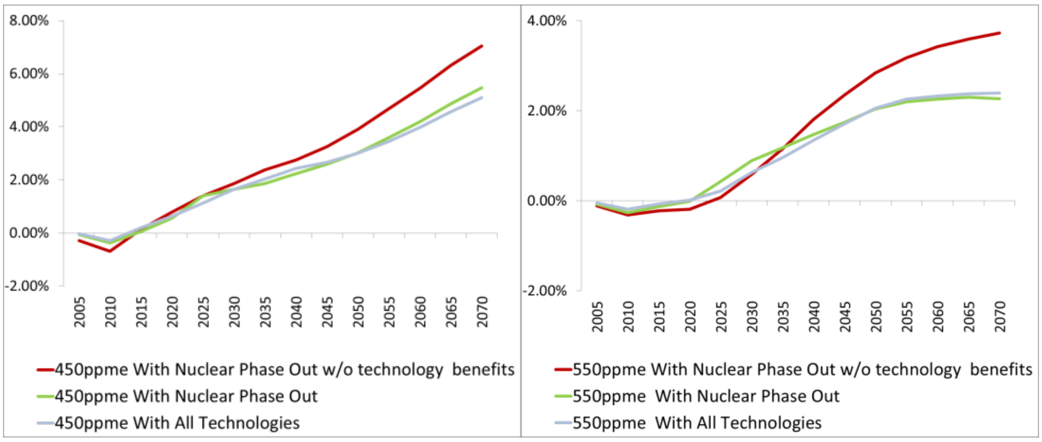
Fig. 4 Technology benefits and policy stringency measures in consumption NPV losses (red dots) and GDP NPV losses (blue dots).



Technology benefits are defined as the percentage point difference between the percentage change in discounted GDP/consumption in the 450/550ppme With Nuclear Phase Out w/o technology benefits compared to relative BAU (policy costs) and the same policy cost indicator computed in the 450/550ppme With Nuclear Phase Out. In the BAU we computed the percentage change in discounted GDP/consumption compared to the case With All Technologies. The technology benefit is defined as the percentage point difference between the percentage change in GDP/consumption in the BAU With Nuclear Phase Out w/o technology benefits and the BAU With Nuclear Phase Out.

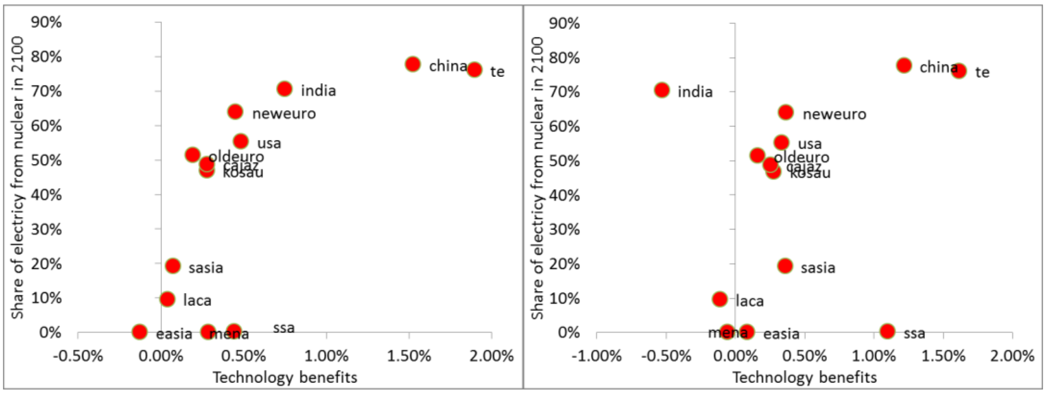
Discounted policy costs are a great indicator for comparing scenarios, but they do not inform about the intertemporal dynamics. Figure 5 illustrates the temporal distribution of innovation and learning benefits. It indicates that phasing out nuclear power would have only a transitory penalty in the case of a 550ppme policy. The panel on the right shows that after 2035 technology benefits are significantly large to offset the efficiency loss. A 450ppme stabilization policy case shows relatively larger benefits in the near term, until 2030, mostly due the innovation effect. The penalty of phasing out nuclear becomes positive in the longer term, after 2050. In the case of the more stringent policy, technology benefits counteract the efficiency loss, but only in the short-, medium-term. Over time, the efficiency effect prevails.

Fig. 5 Temporal distribution of technology benefits – 450ppme (left) and 550ppme (right). Consumption losses w.r.t. Baseline



It is instructive to analyze the regional distribution of the technology benefits of phasing out nuclear, see Figure 6. In the 450ppme case (left panel), we find greater technology benefits in the regions that would rely more on nuclear power, especially in the more stringent case of a 450ppme stabilization. Not coincidentally, these are also the regions that decided not to modify their plans of continuation or development of their nuclear programs in the aftermath of Fukushima, namely China, Russia, Republic of Korea, and India. However, the regional distribution of the technology benefits reflects also other effects, such as the trading position of each region on the carbon and on the oil markets and the interaction with the international prices of oil and carbon permits. These channels seem to have a stronger impact in the less stringent case of a 550ppme policy (right panel). Consider for example India. Although the share of nuclear power is expected to be significant, India will be a net seller of permits on the carbon market. Technology externalities can induce a loss compared to the case with no technology benefits in net carbon credit exporters, such as India and Latin America (LACA), because technology benefits reduce the carbon price when the stabilization target is not very stringent. In the 550ppme case, technology benefits reduce the carbon price at the end of the century by 17%.

Fig. 6 Regional distribution of technology benefits in the 450 (left panel) and 550ppme (right panel)



Technology benefits are defined as the percentage point difference between the percentage change in discounted GDP/consumption in the 450/550ppme With Nuclear Phase Out w/o technology benefits compared to relative BAU (policy costs) and the same policy cost indicator computed in the 450/550ppme With Nuclear Phase Out.

6. Conclusion

The nuclear disaster occurred at the Fukushima Daiichi nuclear power plant in March 2011 has led many countries to re-think the role of the nuclear power. The rapid decline in the costs of competitive low carbon technologies over the most recent years, most notably renewables, has led some policymakers to articulate that the decarbonization of the electricity sector is possible without nuclear power, and hopefully at moderate costs. In Europe, the idea that innovation in new low carbon alternatives can bring economic opportunities is summarized by Angela Merkel in the following remark "We believe we as a country can be a trailblazer for a new age of renewable energy sources….We can be the first major industrialized country that achieves the transition to renewable energy with all the opportunities - for exports, development, technology, jobs - it carries with it."

This paper has quantified the implications of a global nuclear phase out on renewable deployment and innovation in low carbon technologies both under a business as usual and two different climate stabilization targets, using an integrated assessment model which features induced technical change and multiple externalities.

Our results show that phasing out nuclear power would stimulate investments in R&D and deployment of infant technologies with large learning potentials. This could bring about economic benefits, given the under provision of innovation due to market failures related to both intertemporal and international externalities. Our numerical assessment has shown that technology benefits can be substantial and can almost compensate the costs of foregoing nuclear power as an energy and mitigation option. The timing of the benefits depends on the stringency of the policy. In a less stringent climate policy, they take time to materialize. Nuclear phase out would thus lead to a temporary penalty, over time offset by the positive technology externalities. In the most stringent climate cases, consistent with 2C policies, innovation and technology benefits counterbalance the efficiency loss but only in the medium-term, while in the long-term the efficiency loss prevails. Technology benefits would be distributed unevenly across countries. Assuming that all world regions phase out nuclear starting in 2010, benefits tend to be greater where nuclear power provides a larger share of electricity, though other channels such as international carbon trade and energy markets, also affect the regional distribution of technology benefits.

Our analysis is not without caveats. We have neglected technical change directed at conventional sectors, such as fossil fuels with and without CCS. Moreover, the economic penalty of a nuclear phase out is moderated by the assumption about availability of CCS at sufficiently large scale. Further analysis could explore to what extent the results presented in the paper hold in the case of temporary or fragmented phase out.

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