Climatic Change (2014) 123:637–650
DOI 10.1007/s10584-013-0870-9

Innovation benefits from nuclear phase-out: can they compensate the costs?

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Received: 22 November 2012 / Accepted: 10 August 2013 / Published online: 30 August 2013

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 have a positive impact on welfare. We focus on the case of a nuclear power phase-out and endogenous technical change in energy efficiency and alternative low carbon technologies. The research is inspired by the re-thinking about nuclear power deployment which took place in some countries, especially in Western Europe, after the Fukushima accident in March 2011. The analysis uses an Integrated Assessment Model, WITCH, which features multiple externalities related to greenhouse gas emissions and innovation market failures. Our results show that phasing out nuclear power stimulates R&D investments and deployment of technologies with large learning potential. The resulting technology benefits that would not otherwise occur due to intertemporal and international externalities almost completely offset the economic costs of foregoing nuclear power. The extent of technology benefits 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

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The research leading to these results has received funding from the Italian Ministry of Education, University and Research and the Italian Ministry of Environment, Land and Sea under the GEMINA project.

This article is part of the Special Issue on “The EMF27 Study on Global Technology and Climate Policy Strategies” edited by John Weyant, Elmar Kriegler, Geoffrey Blanford, Volker Krey, Jae Edmonds, Keywan Riahi, Richard Richels, and Massimo Tavoni.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-013-0870-9) contains supplementary material, which is available to authorized users.

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that no technology should get a special treatment, as the efficient allocation of mitigation effort would be ensured by the economic signal created by 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 intervention that would be optimal in the absence of technology externalities (Goulder and Schneider 1999; Goulder and Mathai 2000; Gerlagh et al. 2009). In this context, policy stringency –as expressed by the carbon price – would exceed the Pigouvian level as a way to compensate 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 increase pollution taxes on technologies with relatively high technology externalities. 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 target.

This paper investigates whether a sub-optimal allocation of abatement across technologies induced by restrictions in the technology portfolio is inefficient and to what extent welfare gains can arise if technologies feature high 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, which has become a policy relevant reality in many countries following the Fukushima accident. The analysis uses an 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 than conventional technologies. These elements are endogenously integrated into a macroeconomic model of economic growth where energy is a production factor together with capital and labor. In this setting, welfare implications can be analyzed in a coherent 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 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 the cost of technology 1 depends only on abatement, a_1, and thus has a marginal cost, C_1 (a_1), which does not vary across time. Technology 2 features intertemporal as well as international externalities generated by experience, $\overline{Z}$, and knowledge, $\overline{H}$, C_2 (a_2, $\overline{Z}$, $\overline{H}$), where $\overline{Z}$ and $\overline{H}$ refer to the global stock of capacity installed and knowledge, respectively. *Intertemporal externalities* occur because learning-by-doing is external to the maximization objective in the region. Learning benefits ($\overline{Z}$) 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 appropriating 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, $\overline{H}$. 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:

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

where[1]

$$c_{2\overline{Z}}\left(a_2,\overline{Z},\overline{H}\right)<0;\ c_{2\overline{H}}\left(a_2,\overline{Z},\overline{H}\right)<0; c_{ia}\left(a_2,\overline{Z},\overline{H}\right)>0 \tag{2}$$

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.

Figure 1 illustrates the welfare loss due to the inefficient allocation of abatement across technologies and how technology externalities can partly offset them. The top-left panel shows the cost-effective abatement allocation between technologies 1 and 2, a_1, a_2. 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 Fig. 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. A situation like the one depicted in the bottom-right panel could emerge if the costs of the most expensive technology depend on abatement and R&D (not shown in the chart). 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). The main objective of this paper is to provide some numerical assessment of these effects using an IAM.

3 Motivation and experiment design

The disaster at the Fukushima Daiichi nuclear power plant (March 2011) sparked a debate mainly focused on the safety of this energy technology in many countries of the world, especially in Western Europe, leading in some cases to a re-thinking of the nuclear option.

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[1] In the notation of the equations, the second subscript indicates the variable with respect to which the cost function is differentiated, $c_{2a}=\frac{\partial C_2}{\partial a}, c_{2z}=\frac{\partial C_2}{\partial Z}, C_{2H}=\frac{\partial C_2}{\partial H}$.

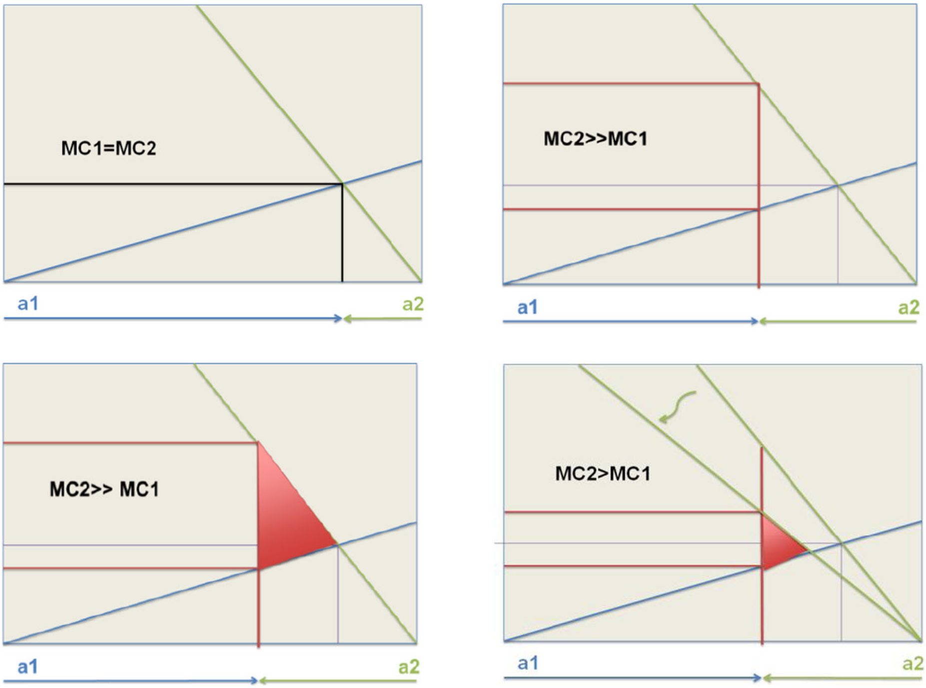

Fig. 1 A simple example with two abatement technology and learning externalities. Marginal technology costs (MC) on the vertical axis and abatement by technology 1 (a1) and 2 (a2) on the horizontal axis

In Germany the government ordered the immediate shutdown of the oldest eight of a total of seventeen reactors, with a progressive phase-out of the remaining ones to be completed within 2022. That decision was obviously political, as just the previous year a law aimed at extending the operational life of the more modern nuclear plants until 2038 had been approved. Immediately after the accident the Swiss government announced a complete nuclear phase-out according to a pre-determined schedule (i.e. between 2019 and 2034) and a stop to the projects concerning the construction of three new plants. An analogous reaction was observed in Belgium, whose government has fixed the shutdown of the seven national plants between 2015 and 2025. In Italy, a similar post-Chernobyl situation took place. In the late 80s, the government had decided to abandon nuclear energy, shutting down the three operating reactors and blocking the construction of four new ones. The decision reflected the results of a national referendum held in 1987, 1 year after the nuclear disaster in the former Soviet Union. In the late 2000s, the Italian government had decided to re-start a nuclear program but again a post-incident referendum[2] determined a stop to this policy.

The most severe consequences were felt in Japan, where the disaster heavily impacted on the population. Before Fukushima, 30 % of Japan's electricity demand was covered by nuclear, with plans of up-scaling up to 50 % by 2030. Immediately after the accident, which caused the substantial loss of four reactors, the remaining fifty were shut down for safety checks with plans for a gradual re-start of the safer ones in the following months or years

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[2] The referendum had been planned long before the Japanese accident, and was scheduled for June 2011, which turned out to be only 3 months after the accident.

(although only two plants are back in line as of June 2013), and afterwards the government released a new energy plan that scheduled a gradual phase-out by 2040. Nevertheless, the new government, installed in December 2012, has announced a new change of direction, which is supposed to lead to a substantial restoration of the original expansion programs.

Many countries have not modified their plans of either continuation or development of their nuclear programs. Among them, we can mention Russia, India, China and the Republic of Korea. China and Korea both inaugurated two reactors since January 2012. The United States too have confirmed nuclear as a strategic energy source for the nation, even if very few projects are actually moving forward (the construction of two plants started in March 2013).[3]

As a consequence, the construction of new plants dropped considerably in the last 2 years, after a decade of steady increase (see Figure SM1). Moreover, out of the 434 nuclear reactors operating worldwide as of June 2013 (corresponding to a capacity of 371 GW), 350 are more than 20 years old. The decommissioning of old plants not fully replaced by new ones, especially in the USA and Western Europe, which feature the most numerous and eldest fleets (see more details in Table SM1), is likely to cause a short- to medium-term reduction in electric output from nuclear plants.[4]

In this context, evaluating the economic consequences of nuclear power phase-out is certainly a policy relevant exercise. Relevant questions concern the implications on the technology mix, technology development and deployment, and on welfare. Since nuclear power is a CO_2-free option and its value increases in mitigation scenarios (Tavoni et al. 2012), phasing out nuclear power would induce a sub-optimal allocation of abatement. We use the Integrated Assessment Model WITCH (see Section 4 and 5) to quantify the associated efficiency losses and positive technology. This investigation represents a novel contribution to the literature, as the innovation implications of the nuclear phase-out have not been addressed before. Prior comparison exercises have focused on the rearrangement of the electricity mix and on the climatic and economic impacts of nuclear constraints, but secondary effects on new technologies and innovation have not been examined in detail.[5]

The nuclear phase-out case offers a case study that mimics very closely the simple example given in Section 2. The WITCH model, described in Section 4, 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. Renewables (in particular wind and solar) 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, with advanced generation, waste-free and 100 %-safe breeder nuclear fission reactors, or with any hypothetic technology potentially able to generate power more than 6–7,000 h per year with no fuel costs and without emitting carbon dioxide.

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

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[3] For additional information on single countries' strategies (net of Japan's predicted policy change), see for instance Rogner (2013).

[4] See IAEA and WNA statistics.

[5] 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, see among others, Steinke et al. (2013), Delucchi and Jacobson (2011a, b), Trainer (2012), and Tavoni and van der Zwaan (2009).

technologies (e.g. nuclear) is equivalent to a subsidy and that subsiding early-stage technologies can theoretically create welfare gains.[6]

The experiment design is 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 beyond those already under construction or planned (thus excluding proposed ones), with no lifetime extensions (see Kriegler et al. 2013, for scenario details). 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 learning-by-doing (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 technologies 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, 550 ppme and 450 ppme, 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.

4 Innovation and technology dynamics in the WITCH model

The numerical analysis is performed with the WITCH model,[7] 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, which 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

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[6] Incidentally, large-scale fission nuclear power may well 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 low-carbon technologies with which it would compete (Kahouli-Brahmi 2008).

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

Table 1 Scenario matrix

Policy cases	Technology assumptions			
Baseline// 550 ppme// 450 ppme	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.

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, $\overline{H}_i$:

$$H_i(n,t+1) = H_i(n,t)(1-\delta_i) + I\_H(n,t)_i^{\alpha} H_i(n,t)^{\beta} \overline{H}_i(n,t)^{\gamma} \tag{3}$$

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:

$$\overline{H}_i(n,t) = \frac{H_i(n,t)}{\sum_{j\in OECD} H_i(j,t)} \left(\sum_{j\in OECD} H_i(j,t) - H_i(n,t)\right) \tag{4}$$

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 first term in Eq. (4) describes the countries' absorptive capacity whereas the second one captures the distance of each region from the technology frontier. The technology frontier is represented by the sum of the stock of knowledge across high-income countries (De Cian et al. 2012).

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. [5]) occurs before the technology penetrates the market, while learning-by-doing (second term in Eq. [5]) operates when technology deployment starts:

$$\frac{C_i(n,t)}{C_i(n,0)} = \left(\frac{H_i(n,t-2)}{H_i(n,0)}\right)^{-\theta_{i,1}} \left(\frac{\overline{Z}_i(n,t)}{\overline{Z}_i(n,0)}\right)^{-\theta_{i,2}} \tag{5}$$

$$\overline{Z}_i = \sum_n \sum_0^t Z_i(n,t) \tag{6}$$

Table 2 Learning-by-Researching (LbR) and Learning-by-Doing (LbD) externalities represented in the WITCH model, learning rates, and installation costs in 2005 (US$2005/kW). The percentage in brackets indicates the corresponding cost reduction related to doubling the capital stock

		Fossil-fuel based technologies	Fossil-fuel based technologies with CCS	Nuclear power	Renewable energies (Wind and solar)	Breakthrough technologies
Innovation externalities	LbR (*Hi*)	NA	NA	NA	NA	YES
	$\theta_{i,1}$				0	0.20 (13 %)
Technology externalities	LbD (*Zi*)	NA	NA	NA	YES	YES
	$\theta_{i,2}$				Wind Onshore 0.15 (10 %) Wind Offshore 0.20 (13 %) Solar-PV 0.28 (17.5 %) Solar-CSP 0.15 (10 %)	0.15 (10 %)
C_i $(n,0)$ [US$2005/kW]				3807	Wind Onshore 1467 Wind Offshore 3061 Solar-PV 4650 Solar-CSP 6123	16000

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. Table 2 summarizes the characterization of externalities for the various technologies represented in the WITCH model.

Nuclear power can be replaced by fossil-based technologies with and without CCS, renewables (wind and solar), 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. The main economic assumptions (investment costs in 2005 and learning rates) are summarized in Table 2.[8] In the learning rate columns, the first number indicates the actual value of $\theta_{i,1}$ and $\theta_{i,2}$ (see Eq. [5]), while the percentage in brackets indicates the corresponding cost reduction related to doubling the capital stock.

Economic and technology assumptions are the same across regions. Besides the reported installation cost, nuclear features costs related to uranium supply, operation and maintenance (O&M), and waste management; renewables only to O&M, and breakthrough none of them (the only cost component is the initial installation cost). An economic penalty, modeled as a cost function exponentially increasing in the renewable share in the electricity mix (Hoogwijk et al. 2007), constrains renewable penetration. Electricity generation must also satisfy a flexibility constraint: the generation from intermittent renewables must be balanced

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[8] Concerning the offshore investment cost, the reported value is an average for the different offshore categories, where costs vary as a function of sea depth and distance from shore of the installation. The breakthrough investment cost is naturally somewhat arbitrary, fixed roughly ten times higher than traditional technologies' average one.

by other flexible technologies such as hydropower and gas (Sullivan et al. 2013). 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, 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 more 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. Results can be expected to be sensitive to the technology assumptions and in particular to the learning rates. De Cian and Tavoni (2012) explored at length the role of technology parameters and their effect on welfare effects under different climate policy scenarios. They show that, although the size of the effect is parameter-dependent, the qualitative pattern of the results would only change under the extreme assumption of no learning-by-doing and learning-by-researching effects at all.

5 Model solution and results

The model outcome is the solution of a non-cooperative game among 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 constraints. In the policy scenarios, regions solve the same program, but under the additional constraint on regional GHG emissions, consistent with the long-term targets of 550 and 450 ppme. We allow for full when and where flexibility, and countries can buy and sell carbon permits on the international carbon market. These two GHG concentrations have been selected as likely scenarios to yield a temperature increase in 2100 with respect to the pre-industrial level equal to 2.5 °C and 2 °C, respectively (Kriegler et al. 2013).

It is important to stress that, when optimizing their own welfare in a competitive environment, regions do not internalize innovation and technology externalities. The presence of positive externalities which are not fully internalized leads to the under-provision of the public goods knowledge and deployment of technologies with high learning. To the extent the model solution does not internalize these benefits, it represents a second-best, though optimal outcome. When market failures such as technology externalities 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 this technology, and in 2100 nuclear would generate 12 %, 30 % and 34 % of the global electricity production, in the baseline and in the two considered policy cases, 550 ppme and 450 ppme, respectively. 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-medium term, until 2040), more renewables and more clean power R&D (breakthrough). The breakthrough starts to replace nuclear power as well as fossil-based technologies in 2035. 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 (550 ppme) and 10 years (450 ppme) compared to the baseline (see Figure SM2). In 2100 the breakthrough technology achieves a penetration in the electricity mix similar to nuclear, namely 26 %, 31 % and 34 % in the BAU, 550 ppme, and 450 ppme, respectively. With nuclear phase-out renewables show a slight drop in 2100 in the BAU (from 6 % to 5 %), but they increase in the two policy cases, from 21 % to 22 % in the 550 ppme case, and from 20 % to 22 % in the 450 ppme case.

Under all 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 2 decomposes the penalty of phasing out nuclear into the gross component (gross of technology and innovation benefits) and the technology and innovation benefits.[9] The two blue bars show the discounted world consumption loss at 450 ppme in 2100 with a full technology portfolio (left) and with a constrained one, i.e. with nuclear phase-out (right). Phasing out nuclear slightly increases the aggregate discounted cost of the stabilization policy, from 2.74 % to 2.78 % (blue bars), because technology benefits reduce the macroeconomic loss by 0.39 % (violet bar). Should the technology benefits be excluded, policy costs would increase to 3.17 %. The technology benefits due to the implicit subsidy to learning technologies caused by the nuclear phase-out are able to almost completely offset the cost of losing an important mitigation option, which otherwise would be substantial (+15 % in the 450 ppme and +19 % in the 550 ppme).[10] A similar result holds in the 550 ppme and in the BAU scenarios. In the former technology benefits reduce the macroeconomic loss by 0.27 %, perfectly offsetting the additional costs related to nuclear phase-out (policy cost is 1.43 % both with and without nuclear power), while in the latter benefits account for 0.02 %, making nuclear phase-out even slightly more convenient than the default case (+0.01 %).

Figure 3 traces the relationship between technology benefits and an indicator of policy stringency, namely cumulative abatement to 2100. Absolute technology benefits (left panel) are defined as the percentage point difference between the policy cost of the 550/450 ppme With Nuclear Phase-out w/o technology benefits compared to the relative BAU (policy costs) and the same policy cost indicator computed in the 550/450 ppme With Nuclear Phase-out. In the BAU we computed the percentage change in discounted GDP/consumption compared to the case With All Technologies. Relative technology benefits (right panel) are defined as the ratio of technology benefits to policy cost in the case With Nuclear Phase-out w/o technology benefits.[11] When measured relative to the total costs of the policy without nuclear they show diminishing returns, as the benefits actually decrease when the policy becomes more stringent, from 19 % of total costs in the 550 ppme case to 14 % in the 450 ppme case. The relative impact

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[9] The expression “technology benefits” refers to the innovation benefits related to R&D and to the technological benefits associated with the deployment of infant technologies characterized by LbD related to experience.

[10] Policy costs measured in terms of GDP are larger, but we focus on consumption as a better indicator of welfare. In the 450 ppme scenario, the GDP loss without nuclear power would be 3.71 % and it would increase to 4.47 %, should technology benefits be excluded.

[11] For example, in the 450 ppme case reported in Figure 3 relative technology benefits would be equal to 0.39/(3.17–2.74)=91 %.

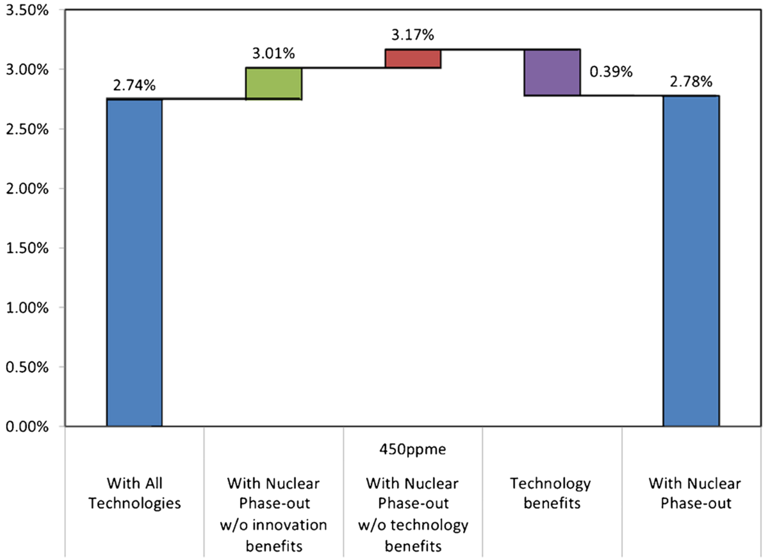

Fig. 2 Decomposing the technology penalty from technology benefits (450 ppme): consumption net present losses compared to the baseline (5 % discounting). Technology benefits are defined as the percentage point difference between the percentage change in discounted consumption in the 450 ppme With Nuclear Phase-out w/o technology benefits compared to the relative BAU (policy costs) and the same policy cost indicator computed in the 450 ppme With Nuclear Phase-out

in terms of compensation of the additional policy costs due to nuclear phase-out decreases accordingly (right panel in Fig. 3). 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.

The evaluation of the discounted technology benefits depends on the chosen discount factor, the former increasing as the latter decreases.

Discounted policy costs are a neat indicator for comparing scenarios, but they do not inform about the intertemporal dynamics. Figure SM3 illustrates the temporal distribution of technology benefits. Phasing out nuclear power has a small transitory penalty with respect to

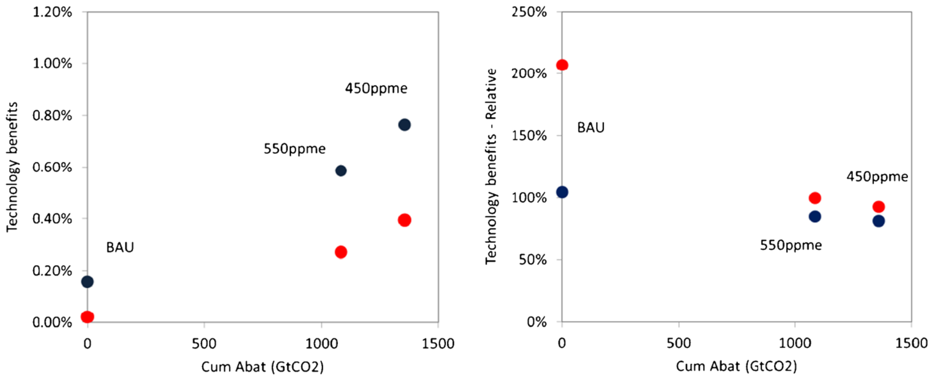

Fig. 3 Technology benefits and policy stringency using NPV consumption (*red*) and GDP (*blue*) changes (*left panel*) and relative compensation of the additional nuclear phase-out costs (*right panel*)

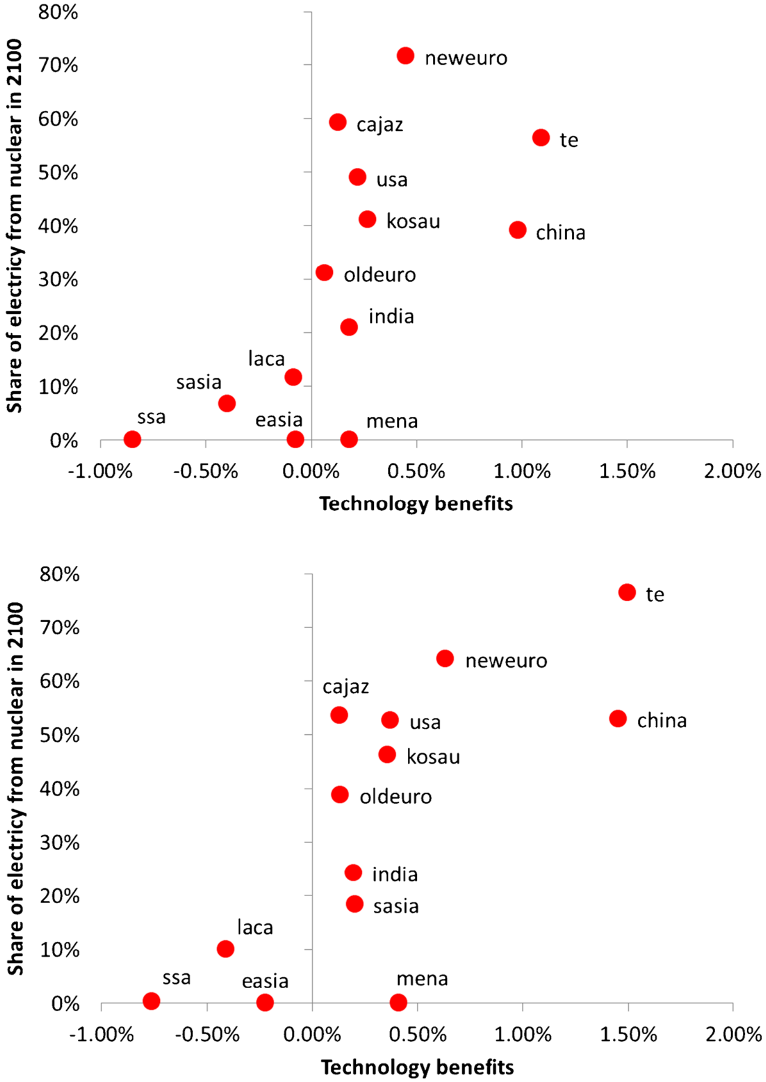

Fig. 4 Regional distribution of technology benefits in the 550 ppme (*upper panel*) and 450 ppme (*lower panel*)

the With All Technologies scenario but after 2050 (550 ppme) or 2035 (450 ppme), technology benefits are large enough to offset the efficiency loss. Innovation and technology externalities in fact result in an initial penalty, due to the massive investments required to develop infant technologies which remove resources for consumption, while in the long-run the positive effects prevail. In 2100 benefits reach 3 % in the 450 ppme case, as opposed to 2 % in the less stringent policy and to almost 1 % in the BAU.

It is instructive to analyze the regional distribution of the technology benefits of phasing out nuclear, see Fig. 4. We find greater technology benefits in the regions that in the future would rely more on nuclear power, especially in the more stringent case of a 450 ppme stabilization (lower panel). The regional distribution of the technology benefits also reflects other effects, namely the trading position of each region on the carbon and oil market and the interaction with the international prices of carbon permits and oil, the former being much more significant. Consider Sub-Saharan Africa (ssa), Latin America (laca), East Asia (easia) and, in the 450 ppme scenario, South Asia (sasia). These regions deploy no or few nuclear power plants already in the full technology portfolio scenario and thus they would not be directly affected by the nuclear phase-out. Yet, the technology externalities induced by the nuclear phase-out in other regions can induce a welfare loss compared to the case with no technology benefits in these regions, which are net carbon credit exporters, through the international carbon market (in which they have selling positions, since we have assumed a convergence to an equal per capita allocation scheme). Technology benefits, in fact, reduce the international carbon price. At the end of the century this reduction is 13 % in the 550 ppme case and 10 % in the 450 ppme case. Symmetrically, the Middle East and North Africa region (mena), being a permit importer, shows net benefits even though it is expected not to develop nuclear power at all.

The temporal evolution of technology benefits in the different regions is shown in the supplementary material, Figure SM4.

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 nuclear power. The rapid decline in the costs of competitive low carbon technologies over recent years, most notably renewables, has led some policymakers to speculate that the decarbonization of the electricity sector is possible without nuclear power, and hopefully at moderate costs. In Europe, the view that innovation in new low carbon alternatives can bring economic opportunities is summarized by the following remark made by Angela Merkel "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."

In this paper we have quantified the implications of a global nuclear phase-out on renewable deployment and innovation in low carbon technologies under a business-as-usual and two different climate stabilization targets using an integrated assessment model with induced technical change and multiple externalities.

Our results show that phasing out nuclear power stimulates investments in R&D and deployment of new technologies with large learning potentials, causing positive externalities which create economic benefits. Because of market failures related to intertemporal and international externalities, the cost-efficient solution is characterized by under-provision of innovation and under-deployment of technologies with high learning potential.

Technology benefits can be substantial and can compensate the costs of foregoing nuclear power, though technology benefits take time to materialize. Nuclear phase-out can cause temporary penalties, but over time the benefits associated with technology externality prevail.

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. Finally, in many countries renewable are already subsidized, thus reducing the scope for further incentives. 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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