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Nuclear Versus Coal plus CCS: a Comparison of Two Competitive Base-Load Climate Control Options

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Abstract In this paper, we analyze the relative importance and mutual behavior of two competing base-load electricity generation options that each are capable of contributing significantly to the abatement of global CO_2 emissions: nuclear energy and coal-based power production complemented with CO_2 capture and storage (CCS). We also investigate how, in scenarios developed with an integrated assessment model that simulates the economics of a climate-constrained world, the prospects for nuclear energy would change if exogenous limitations on the spread of nuclear technology were relaxed. Using the climate change economics model World Induced Technical Change Hybrid, we find that until 2050 the growth rates of nuclear electricity generation capacity would become comparable to historical rates observed during the 1980s. Given that nuclear energy continues to face serious challenges and contention, we inspect how extensive the improvements of coal-based power equipped with CCS technology would need to be if our economic optimization model is to significantly scale down the construction of new nuclear power plants.

Keywords Economic competition · Electricity sector · Nuclear power · Coal power · CCS · Renewables · Climate policy

JEL Classification D8 · D9 · H0 · O3 · O4 · Q4 · Q5

1 Introduction

The development of nuclear power has experienced significant hindrance from concerns over three main categories of issues that are intrinsically related to its use: reactor accidents, radioactive waste, and nuclear proliferation. Arguments regarding economic competition and public opinion and more recently terrorist activity add to the obstacles faced by the civil use of nuclear energy for electricity generation. These fundamental drawbacks of nuclear energy have been the principal cause for this power production option not to have expanded as widely as predicted decades ago by many energy specialists, while when launched in the 1960s it was portrayed as a promising energy alternative and foreseen by some to potentially fulfill much of mankind's future energy needs. Nonetheless, in recent years, the debate over the role of nuclear power has revived, particularly as a result of high current fuel prices and likely future threats emanating from global climate change. Even after the recent financial crisis, we are likely to see an increase in the construction of nuclear power plants worldwide over the years to come. Before the start of this crisis in the fall of 2008, particularly countries in Asia (among which China, India, Japan, and South Korea) were reported to have large nuclear capacity expansion plans for the short to medium term [9]. Today countries with

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ambitious and increasingly concrete nuclear energy plans can also and especially be found in the Middle East.

During the past decade, climate change has gained broad public attention; today it appears high on most countries' political agendas. Policymakers, notably those involved in negotiating a post-2012 climate agreement, rely increasingly on quantitative estimates of the implications of climate change. Similarly, they are informed more and more quantitatively about the possible implications of climate policy for national, regional, and global technology diffusion and economic development. The economic analysis of climate policy has therefore become a fertile and rapidly growing research area. It forms the basis of the surveys carried out by Working Group III of the Intergovernmental Panel on Climate Change (IPCC). In this branch of research, energy–environment–economy (EEE) models occupy a leading role, since they are capable of generating figures on the technological, climatic, and economic variables at stake. Determining the values of these variables and their mutual interferences requires the large-scale integrated assessment approach offered by EEE models.

Different modeling techniques can be employed to prevent a restricted number of technologies from either dominating the entire climate mitigation portfolio or hardly contributing to it at all. Some of these involve means of slightly changing various types of input assumptions, a practice known colloquially as "penny switching." They can also involve the introduction of limitations on technology penetration rates or the use of supply cost curves. Indeed, such constraints are frequently an essential element of EEE models. Given the distinctive nature of nuclear power, however, the use of such restrictive assumptions to capture the potential consequences of its drawbacks warrants particular attention. The uncertainties governing quantitative estimates of the economic and social costs associated, for instance, with waste management and nuclear proliferation are such that ex-ante hypotheses regarding the deployment potential of nuclear power are often based on the modelers' perception of the technology's attractiveness rather than on un-ambivalent objective analysis. The approach of straight-jacketing technology diffusion through the application of deployment constraints can be questioned for at least four reasons.

First, adding constraints to optimization models results in economic penalties that depend on the extent to which the space of feasible solutions is reduced. The tendency of nuclear power to dominate over alternative technologies, even when carbon dioxide is priced at relatively low levels, suggests that ad hoc restrictions on this specific technology might have a significant bearing on the economic costs of climate protection. Second, imposing growth constraints on particular technologies in order to avoid an outcome that one judges unlikely or unacceptable may be considered at odds with the underlying methodology of economic optimization. Third, however, reasonable it may be to remain reserved about the prospects of a given technology, as with nuclear energy in our case, the imposition of an external constraint on the speed with which this technology can be deployed in the future may be inconsistent with historical records. This practice therefore often renders the calculated scenarios rather subjective. Fourth, while the approaches of cost minimization, profit maximization, or welfare optimization all have solid foundations in economic theory and comply with standard empirically observed phenomena, there is often little economic rationale for the existence of a central agent or socially optimizing institution, especially at the global level, that in our case would be in the position to impose a universal restriction (or stimulus) on the expansion of a certain energy technology. At best, one could argue that through international agreements, social processes, and public organizations, the nature of deployable technologies could be requested to satisfy certain minimum (preferably enforceable) quality, safety, environmental, or usability qualifications.

The potential contribution of nuclear power to the mitigation effort required for global climate stabilization varies appreciably across different studies and depends among others on the type of climate policy architecture implemented in the near future (see, e.g., Weisser et al. [20]). In some cases, nuclear power is expected to play a negligible role in carbon mitigation scenarios. For example, in a recent modeling comparison exercise that includes simulations by the MIT Integrated Global System Model, stabilization scenarios are reported with a use of nuclear energy not much different from the no-climate-policy case and limited at roughly today's values [5]. The ex-ante opinion of the authors is that, mostly for security and safety reasons, nuclear power ought to be constrained in the portfolio of CO_2 abatement options. Their assumption may be legitimate—indeed, for these reasons, nuclear power has not been eligible for emissions avoidance under all mechanisms created in the context of the Kyoto Protocol. We argue, however, that the audience reading and interpreting scenario modeling results should be informed about the economic and technological consequences that stem from such an assumption.[1]

Unfortunately, reports on climate economics modeling often lack transparency in this respect. In comprehensive studies such as produced by Working Group III of the IPCC, e.g., in its Fourth Assessment Report, nuclear power is found to play some mitigation role, but significantly less than other technologies like CO_2 capture and storage (CCS) or renewables (see Fig. SPM 9 in [10]). Little insight is provided in how this result relates to a series of relevant modeling assumptions including with regards to the nuclear penetration rate.

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[1] More recently, some modeling assumptions fed into the MIT scenarios were revised: Nuclear power is now projected to increase more rapidly than in previous studies (see [13]).

This article is meant to shed light on this issue. We use the World Induced Technical Change Hybrid (WITCH) model to investigate how in a climate-constrained world the prospects for nuclear energy would change if imposed restrictions on technological growth are relaxed (for details on the WITCH model, see, e.g., Bosetti et al. [1]). Given that nuclear energy continues to remain unpopular in several countries, largely for reasons related to its inalienable risks, we also evaluate the improvements of its main base-load electricity production competitor—coal-fired power plants complemented with CCS technology—needed to significantly scale down the prospects for nuclear power on purely (non-constrained) economic grounds. Bosetti et al. [2] evaluate with WITCH the optimal portfolio of investments in energy technology deployment and energy R&D, from an economic viewpoint, for a range of climate stabilization scenarios. This paper extends their work by explicitly focusing on the role of nuclear electricity vis-à-vis other non-carbon power generation technologies.

Despite a rapidly growing body of literature that investigates a broad scope of climate mitigation options, little energy system or general equilibrium analysis has concentrated on the specific role of nuclear power in global climate stabilization scenarios. Chakravorty et al. [4] provide a partial equilibrium analysis that accounts for the exhaustibility of uranium ore reserves. A refined back-of-the-envelope calculation of the possible contribution of nuclear energy to mitigating global climate change can be found in van der Zwaan [18]. Rogner et al. [14] calculate country-dependent levelized life-cycle electricity costs for nuclear energy. Vaillancourt et al. [17] use the detailed energy systems model TIMES to explore a range of nuclear deployment scenarios, under various sets of assumptions on technology parameters and exogenous constraints for nuclear power development to reflect, for instance, social perceptions. The analysis presented in this paper is a contribution to this under-explored subject matter. In attempting to address the aforementioned modeling issues and overcome some of the associated caveats, we use historical references to benchmark nuclear deployment in a carbon-constrained world, with a minimum reliance on ex-ante hypotheses. We also provide a detailed comparison of nuclear energy with its main competitive base-load low-carbon power generation alternative.

In Section 2 of this article, we describe the main features of the climate change integrated assessment model WITCH that we use for our analysis. Section 3 presents our scenario results, based on tests with regard to the slackening of diffusion limitations for new nuclear electricity generation capacity. Section 4 reports the techno-economic advancements for CCS technology needed to downsize the deployment of nuclear energy on competitive grounds. Section 5 presents a discussion of our findings and draws our main conclusions.

2 The WITCH Model

The WITCH model, developed by the climate change team at FEEM, has been extensively used for the investigation of climate-related research subjects.[2] It belongs to the collection of integrated assessment models dedicated to enhancing our understanding of the economic implications of climate change mitigation policies. These models allow for determining economically efficient strategies to achieve a broad range of possible climate control targets. With respect to other models of a similar kind—now widely used for the numerical analysis of energy–climate–economy interactions, notably as part of ongoing work for the IPCC—WITCH has a series of features that place it in a position to capture additional aspects of the climate change conundrum.

WITCH has a neo-classical optimal growth structure. The long-term nature of climate change is accounted for via inter-temporal optimization of far-sighted economic agents who can incorporate future effects into current decision making. Strategies calculated by the solution of model runs are thus efficient over long periods of time, an important characteristic given that CO_2 has an atmospheric lifetime of hundreds of years and investments in the energy sector usually generate lock-ins that last for decades.[3] As a result, today's decisions lead to long-lasting responses and are important determinants of how the future looks like, the climatic and economic dynamics of which are modeled in WITCH. The simulation of the energy sector, the largest source of greenhouse gas emissions, is fully integrated in the aggregate production function, a "hard link" that ensures consistency of economic output with investments in conventional or innovative energy carriers and electricity production facilities. The power sector consists of seven options capable of generating electricity: These are based on, respectively, traditional coal (i.e., pulverized coal, PC, without CCS), advanced coal (an integrated gasification combined cycle (IGCC) with CCS), oil, natural gas, hydropower, nuclear energy, and renewables (in our case a combination of wind and solar energy).

WITCH possesses a game-theoretical setup that allows mimicking free-riding incentives that the 12 regions constituting the world are confronted with as a result of the consumption of public "goods" and production of public "bads." Global externalities due to emissions of CO_2 (reflected by a damage function and a global atmosphere–climate module), extraction limits of exhaustible resources

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[2] For more details, see, e.g., Bosetti et al. [1] and the model's website at http://www.witchmodel.org.

[3] The half time of atmospheric CO_2 is roughly 100 years, and the lifetime of a power plant can surpass half a century.

such as fossil fuels, and a limited appropriability of knowledge behind innovation are also taken into account, so that regions choose their investment paths strategically with respect to the choices of other regions. The result is a hybrid model that provides quantitative insight in the design of climate protection policies and informs policy-makers regarding the economically efficient set of strategies fit to address global climate change, while it simultaneously deals with a set of inter-related environmental and economic (in)efficiencies.

Given that the focus of this paper is on the power sector (and given our assumption that hydropower is little expandable on a global basis), the three most prominent essentially carbon-free technologies are coal-based power plants equipped with CCS, nuclear power plants, and electricity generation based on renewables (that consist of a bundle of wind and solar energy). Table 1 provides our main techno-economic assumptions for these technologies. Nuclear energy and IGCC plants complemented with CCS technology are described by rather similar parameter values in some respects: relatively high investment costs and a high utilization factor as typical for base-load electricity production. Coal reserves are assumed to be abundant, with an equilibrium price not exceeding \$80/t throughout the century in a business-as-usual (BAU) coal-intensive scenario. Similarly, uranium is assumed to be sufficiently abundant at low prices to satisfy a significant revival of the nuclear industry during the twenty-first century [3]. The cost of uranium is modeled endogenously via resource extraction curves. Reserves are assumed to be particularly large at prices up to a level of approximately \$300/kg, at which point reprocessing spent fuel and the use of fast breeder reactors become competitive (hence preventing any further rise in the price of uranium and corresponding cost increase of nuclear energy). In order to be used as fissile material, uranium ore must undergo a process of conversion, enrichment, and fuel fabrication; we have set the corresponding cost at \$250/kg (see [12]). Nuclear waste storage and management fees are assumed to increase linearly with the quantity of spent fuel produced and are set at 0.1 ¢/kWh [12]. For CCS, CO_2 transport and storage costs are accounted for via regional supply curves calibrated on data available in Hendriks et al. [7]. The fraction of CO_2 captured is supposed to be 90%, and a zero geological CO_2 leakage rate is assumed. Wind and solar energy are characterized by relatively low investment costs, but also by a low load or utilization factor. They are the only technologies that we assume to be subject to significant technological change through learning-by-doing: Especially for solar power plants, it is expected that there is substantial scope for further improvements in competitiveness. We therefore assume that wind and solar power are subject to progress in such a way that each doubling of cumulative installed capacity leads to an investment cost reduction of 13%. This is a rather conservative value in comparison to learning rates observed in practice because we argue learning will not continue indefinitely [6, 8].

3 Scenario Results

In addition to a BAU scenario, under median assumptions on population growth and economic development and central values for a range of energy technology parameters and their evolution over time, we model two policy scenarios, consistent with the stabilization of atmospheric concentrations of CO_2 at 450 and 550 ppm. For all greenhouse gases combined, we assume that these concentrations roughly correspond to 550 and 650 ppm-e (CO_2-equivalent) stabilization scenarios, respectively. These two scenarios are thus compatible with a stabilization of the global average atmospheric temperature at an increase of 2.5°C and 3°C, respectively, if the climate sensitivity is lower than 3°C. Although the IPCC suggests a considerably more stringent target of 2°C, both scenarios imply very significant emission reductions. Global emissions are assumed to peak in 2015 for the 450-ppm case and in 2050 for the 550-ppm case, while cumulative mitigation throughout the century would amount to over 1,100 and 750 $GtCO_2$, respectively. Because of the convexity of the marginal abatement cost curve in our model, the additional effort needed to achieve the most stringent target would come at a considerably and disproportionally higher price. The scenarios are run up to 2150, but for our present purposes, it suffices to report results until 2050 only. The reference year for our optimization runs is 2005. While

Table 1 Techno-economic assumptions for the main low-carbon electricity generation alternatives in WITCH: coal+CCS, nuclear energy, and renewables

	Coal+CCS	Nuclear energy	Wind+solar
Investment cost (\$2,005/kW)	2,500	2,500	1,900
Utilization factor, %	85	85	25
Thermal efficiency, %	40[a]	35	–
CO_2 capture or avoidance share, %	90	100	100
Learning rate, %	–	–	13

[a] This value accounts for the energy penalty that results from the CO_2 capture process

under these climate control scenarios the development of all power generation options are affected, either negatively (as with the carbon-intensive options) or positively (the carbon-poor alternatives), with respect to the BAU run, we inspect for our purposes here three (clusters of) technologies only: nuclear power, coal with CCS, and renewables (wind and solar energy combined).

Figure 1 shows the simulation by WITCH of the 5-year averages of annual capacity additions (excluding the replacement of ageing existing capacity) for nuclear power until 2050 under each of the three scenarios. The values of the annual additions as realized over the past two decades are also plotted, as well as the historic single-year maximum attained during this time frame. We see that in the BAU scenario nuclear power additions over the forthcoming decades reach a value of over 10 GW/year, while in recent years this annual new capacity did not amount to more than a few gigawatts per year at most. This result connects to the reality in several countries with rapid economic growth, like (but not exclusively) China and India, where increased interest exists for this power production option for reasons of competitive costs, energy security, and air pollution control. Figure 1 also shows that under a 550-ppm climate stabilization scenario, this new capacity deployment is significantly enhanced to a level of 15–20 GW/year and reaches a value of over 35 GW/year by the middle of the century under a 450-ppm scenario. In the 550-ppm scenario, annual additions of nuclear capacity reach the level observed in the 1980s, while in the 450-ppm scenario they obtain after several decades a value consistently similar to the 1-year high of 1985. The explanation for this rapid expansion of nuclear power is of course the fact that nuclear energy emits essentially no CO_2 and that the carbon price needed to achieve emission reductions coherent with the indicated climate targets is substantial and grows fast. For example, in the stringent 450-ppm scenario, the marginal cost of CO_2 abatement exceeds \$100/tCO_2 already in 2030 and grows markedly after that. This growth in the value of CO_2 naturally provides a large incentive for the deployment of CO_2-free technologies for power generation, a sector characterized by marginal abatement costs less steep than other parts of the economy such as the transportation sector.

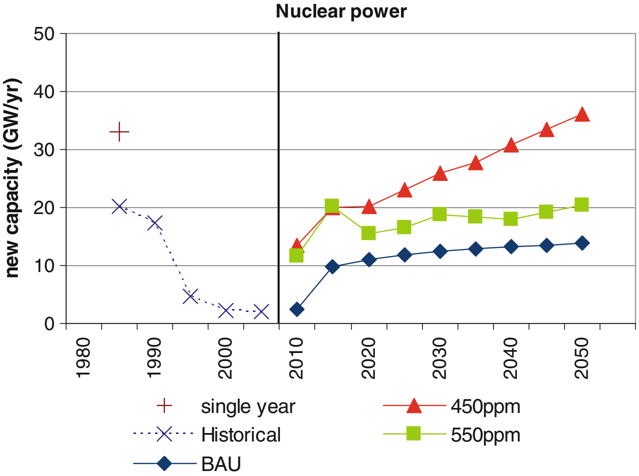

Fig. 1 WITCH simulations of future capacity additions of nuclear power (in gigawatts per year) in BAU, 450 and 550 ppm scenarios, as well as realized during 1985–2005. The "single-year" point shows the historic maximum realized

Total installed capacity for nuclear power in 2050 amounts to roughly 1,150 and 1,500 GW for the 550- and 450-ppm cases, respectively. These numbers are somewhat higher in comparison to estimates reported in, for example, Vaillancourt et al. [17], who determine a nuclear capacity of about 1,000 GW in a 450-ppm scenario and slightly lower numbers for 550 ppm and BAU cases. The International Energy Agency [9], which analyzes scenarios with somewhat different climate objectives, projects nuclear capacity in 2050 to lie between 860 and 1,150 GW.

Figure 2 shows the same results for the development of coal-based electricity generation equipped with and without CCS technology (note the larger vertical scale). CCS technology is obviously not economical without a price on CO_2, as demonstrated by the horizontal line for BAU, but experiences a widespread application under either a 450- or 550-ppm climate stabilization target. Under a 550-ppm scenario in less than two decades, as much as 30-GW/year additional coal-based power plants are (fully) equipped with CCS technology until at least the middle of the century (and in fact much beyond). Typically this level of annual additions equals the average number of new coal-based power plants (without CCS) built since the 1990s. Under a 450-ppm climate target, the use of CCS explodes initially, reaching a peak around 2020 of over 40 GW/year of additional capacity. This exceedingly high level (although still below the record level of non-CCS coal-based power plants taken in operation in 2005) vanishes over time, however, given that the low but non-zero CO_2 emission rate of coal plus CCS power (see Table 1) is penalized by progressively stringent climate obligations (instead of which totally carbon-free technologies are preferred).[4] Nonetheless, for both climate policies, the deployment of CCS becomes very significant and reaches a level as high as 550 GtCO_2 of cumulative storage by the end of the century, with a world average transport and storage cost by then of about \$25/tCO_2.

As extensively described in the literature, it is unlikely that one or a couple of CO_2 abatement options alone can

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[4] A higher CO_2 capture rate or the use of CCS in conjunction with biomass would allow CCS to remain competitive in a stringent climate scenario beyond 2050.

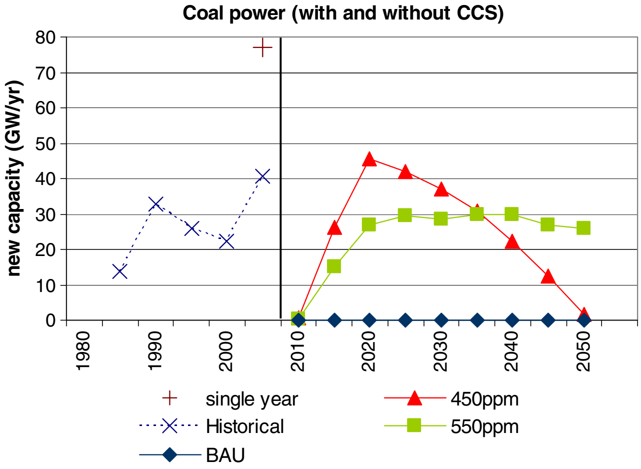

Fig. 2 WITCH simulations of future capacity additions of coal-based power plus CCS (in gigawatts per year) under BAU, 450 and 550 ppm scenarios, as well as realized without CCS during 1985–2005. The "single-year" point shows the historic maximum realized

address any reasonable level of climate control [10]. Indeed, Fig. 3 confirms that renewables such as wind energy and solar power are strong favorites as necessary additional mitigation options (notably in regions with large wind and solar radiation potentials). Even under BAU conditions, wind and solar power continue their surge and easily more than double over the forthcoming decades in terms of annual power additions from the present value of about 5 GW/year. When global climate policy is adhered to, renewables will grow much faster: Their additions may even exponentially increase to values over 30 GW/year by 2050 in the case of a 450-ppm climate objective. Such stringent climate policy would rapidly render renewable energy at a similar footing as the traditional options currently in use, as a result of its increased competitiveness following policy-induced learning-by-doing effects. For the moment, however, renewables are still characterized by a relatively low deployment rate in absolute terms, due to their high early investment costs and low capacity factors, especially for solar energy.

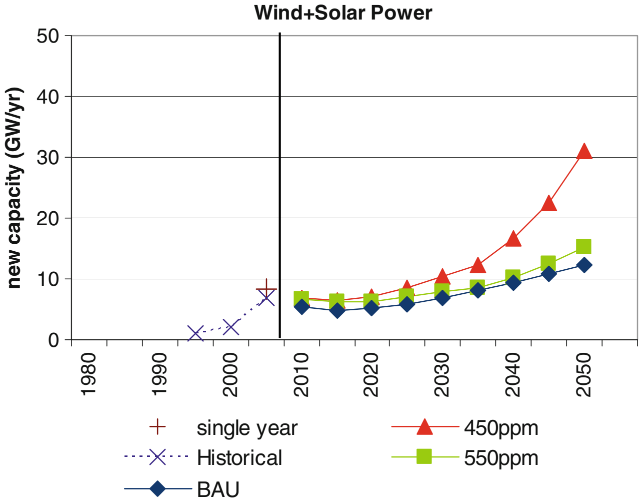

Fig. 3 WITCH simulations of future capacity additions of renewables (wind plus solar, in gigawatts per year) under BAU, 450 and 550 ppm scenarios, and realized since 1995. The "single-year" point shows the historic maximum realized

Our overall observation is that each of these three types of power technologies—nuclear energy, coal plus CCS, and renewables—is needed for serious climate change control, in addition to extensive efficiency and savings efforts. In order to reach CO_2 emission reduction targets that avoid increasing the atmospheric CO_2 concentration to more than 450 or 550 ppm, at least two of these three options are needed at a globally very large scale and most probably all three (and more). We also see that, when the commonly applied growth constraints on nuclear power are relaxed, it is expanded rapidly but with rates not exceeding much the levels experienced in the past. Indeed, we find that the nuclear energy growth rates generated by WITCH are generally consistent with those observed during the 1970s and 1980s, i.e., when nuclear power was in its heydays and experienced a more favorable attitude than it did over the past two decades. Compatible results can be found in Bosetti et al. [2].

4 Implications and Alternatives

All scenarios depicted in Fig. 1 foresee an expansion of the total capacity of nuclear energy over the coming half-century. In the 450-ppm case, for example, the available nuclear power in 2050 is increased by about a factor of three with respect to the currently installed global capacity of 370 GW. What does this imply for nuclear energy? The simulated growth paths for nuclear energy respond, along with other non-carbon energy resources, to the challenge of mitigating global climate change while simultaneously generating benefits in terms of air pollution reduction and energy security enhancement. Such an expansion would also spur innovation in the nuclear industry and generate incentives to develop and deploy new reactors of, e.g., generation III and eventually generation IV types. These can profit from technological improvements with respect to reactors presently in operation (see, e.g., [19]).In economic terms, an expansion of the nuclear sector could produce economies of scale, with corresponding cost reductions. Troublesome, however, is that an expansion of nuclear power would exacerbate the already serious concerns regarding its use at current levels, that is, in terms of the "classical" intricacies associated with this power generation option: reactor accidents, radioactive waste, and nuclear proliferation.

More reactors in operation worldwide enhance in principle the probability that with one of them a serious incident or accident occurs, especially when considering that an important share of the additions of nuclear capacity will probably take place in countries with still limited reactor operation experience and yet to be perfected safety standards. It has been pointed out, however, that while the chance for accidents remains unequal to zero, the likelihood for such events has reduced significantly over the past decades and should engender less concern today than it did in the 1980s [15]. Also, both through more advanced reactor designs and improved operation standards, risks for serious accidents are likely to continue to decrease in the future.

While radioactive waste production occurs at basically every stage of the nuclear fuel cycle, in solid, liquid, or gaseous state, spent fuel is most problematic, since it generates heat during many years after de-loading from the reactor core and remains highly radioactive for thousands of years. Radioactive contamination of the environment from spent fuel storage can be minimized through several layers of physical containment, probably at some stage including reversible geological deposition deep underground. While progress on deep geological disposal has been made in, e.g., Finland, France, and Sweden, many governments delay decisions on this subject and instead adopt strategies of intermediate aboveground bunker or dry cask storage like in the Netherlands and the USA. The main issue concerning underground storage remains uncertainty about the integrity of spent fuel canisters: It is questioned whether the isolation offered by geological formations will be sufficient over a period of thousands of years. The fear is that canisters, as a result of corrosion, will leak and consequently contaminate groundwater in the far future. Several channels exist through which this problem could be mitigated, in particular by organizing the disposal of waste regionally through Internationally Monitored Waste Repositories. As long as international solutions for the storage of waste continue to be delayed, however, or other solutions are not brought forward to tackle the intrinsic waste problematic of nuclear energy, its role in future power supply remains significantly handicapped. A possible expansion of nuclear energy worldwide would continue to give substantial reason for concern [18, 19].

Nuclear power generation inherently involves the risk that nuclear industry-related technologies and materials are diverted for non-civil purposes. Among nuclear energy's main proliferation threats are the use of uranium enrichment facilities and the production of fissile materials like plutonium (see notably [11]). Countries operating enrichment technology or organized terrorist groups possessing highly enriched uranium (HEU) may relatively easily construct a basic fission explosive device and use it for military or terrorist purposes. Several plutonium isotopes contained in reactor-grade spent fuel, accounting for 1–2% of its volume, are fissile and can serve to fabricate a nuclear weapon. Especially when spent fuel from the civil nuclear industry is reprocessed, this problem becomes apparent: Plutonium contained in spent fuel is reasonably safe against diversion for weapons use because of the highly radioactive waste materials in which it is embedded, but its separation during reprocessing makes it vulnerable for direct military or terrorist use, even while it is of lower quality than weapon-grade plutonium. The global control of sensitive technologies, the monitoring of nuclear activities and safeguarding, and the deletion of fissile materials, like HEU and plutonium, are central to any solution of the nuclear proliferation problem. In order to avoid fissile materials being diverted for non-civil purposes, dedicated technical efforts and effective international institutions are required. Their improvement is important irrespective of the future share of nuclear energy in total power production but will become more poignant when nuclear energy experiences a renaissance.

Suppose that for the reasons just given one finds an expansion of nuclear energy unacceptable, especially with annual additions over the coming 50 years that may run in the 15–20 GW/year, under a 550-ppm climate control scenario and that may increase to 35 GW/year in the 450-ppm scenario. What then would be the improvements that need to materialize for other non-carbon options in order to let them dominate or scale down the spread of nuclear power in the solution set of WITCH, that is, without the imposition of ex-ante growth constraints? In other words, can one crowd out nuclear power off the market by rendering other carbon-free electricity generation options economically more attractive and thereby more competitive? What sort of improvements need to be accomplished in order to avoid the widespread expansion of nuclear energy that many reject for the above listed set of "classical" arguments?

We address these questions by focusing on the combustion of coal for power production complemented with CCS, since we believe it is becoming one of the most direct competitors of nuclear power (much like nuclear energy and oil-based power were main competitors in the 1970s and 1980s until the last was essentially phased out as a result of broad deployment of the former; see [16]). Indeed, coal-based power generation plus CCS and nuclear energy are both base-load electricity production options. We focus on three potential areas of improvement for CCS technology by distinguishing three cases of assumptions:

- CCS+:
  the CO_2 emission capture rate is raised from 90% to 99%, making CCS an essentially zero-emission technology[5].

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[5] This could be achieved either by improving CO_2 capture technology or by co-firing coal with biomass.

- CCS++:
  In addition, transport and storage costs do not exceed \$12/tCO$_2$, i.e., the availability of suitable repositories is very large.
- CCS+++:
  In addition, CCS investment costs gradually decrease until a 50% reduction over the course of 20 years.

We abstain from associating probabilities to the achievability of these three CCS scenarios (but guess that the CCS+++ case may be very hard to materialize). Figure 4 revises Fig. 1 for the simulated nuclear energy expansion for these three CCS-favorable cases under the 450-ppm scenario. We see that each of these three cases generates a reduced reliance on nuclear power for climate control purposes. It can also be observed, however, that even in the most optimistic case for CCS technology, nuclear energy will still be needed at annual additions of about 20 GW/year. This level thus constitutes a sort of bottom-line requirement for nuclear power.

Figure 5 shows our results for the 550-ppm scenario under the same three cases of progress in the development of CCS technology. Like for the 450-ppm scenario, a reduced reliance on nuclear power for climate management materializes, with the same ranking between the three cases. Overall, however, the differences between the three cases are less pronounced, the explanation for which is the less ambitious climate control target. Under this scenario even in the most optimistic case for the amelioration of CCS, nuclear energy will still be needed at a minimum threshold level of annual additions of approximately 15 GW/year. In both Figs. 4 and 5, the evolution of nuclear energy over the coming half-century never drops below the BAU reference curve as shown in Fig. 1.

What do these results imply for the amounts of electricity generated by nuclear energy and coal-based power equipped with CCS, via existing capacity plus the installed additions depicted in the previous figures? Figure 6 summarizes, for the 450- and 550-ppm scenarios, respectively, the global electricity produced in 2050 for these two power production alternatives. It also shows how these total levels of electricity production change if the three cases of technological advancement are achieved for CCS.

Nuclear power contributes sizably more than coal plus CCS, by about 40%, only under the 450-ppm scenario and when none of the potential CCS improvements is attained, as shown by the histogram in the left plot of Fig. 6. Under optimistic assumptions for CCS technology innovation, either in the 450- or 550-ppm scenario, coal combustion plus CCS becomes significantly more important for power production than nuclear energy, by a factor of about two in the ideal case that all CCS improvements are realized. If only the capture rate for CCS can be improved, the level of electricity generated by these two options almost equalizes. Note that the total electricity generated by nuclear energy and coal plus CCS together increases with the assumed advancements of CCS, that is, nuclear energy is crowded out less than the increase in the use of coal plus CCS as a result of the latter's improvements.

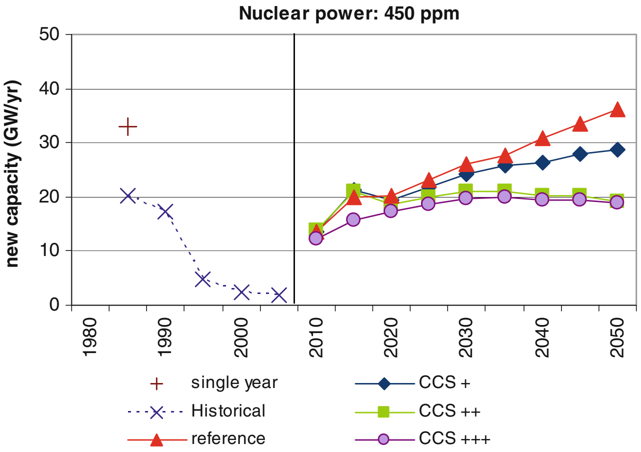

Fig. 4 WITCH simulations of future capacity additions of nuclear energy (gigawatts per year) in the 450-ppm scenario with various improvements for CCS technology

5 Discussion and Conclusions

Under a stringent climate control target in an otherwise unconstrained world for economic growth, EEE models tend to be favorable for a widespread deployment of nuclear energy in the power sector. Usually, analysts either consider a large expansion of nuclear power unrealistic or for other reasons prefer to avoid their scenario runs to yield an outcome concentrating considerably on nuclear energy. Consequently, specific technology diffusion constraints are

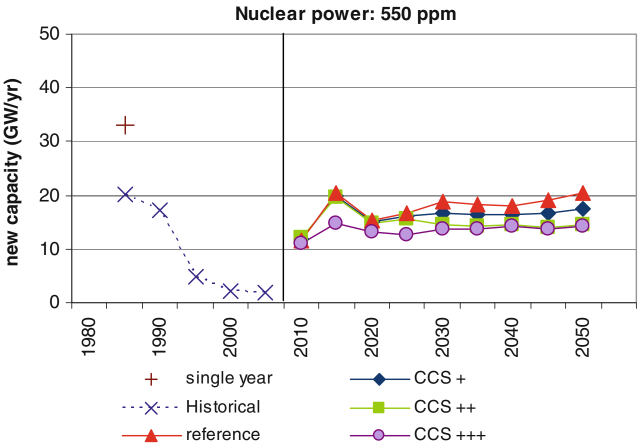

Fig. 5 WITCH simulations of future capacity additions of nuclear energy (gigawatts per year) in the 550-ppm scenario with various improvements for CCS technology

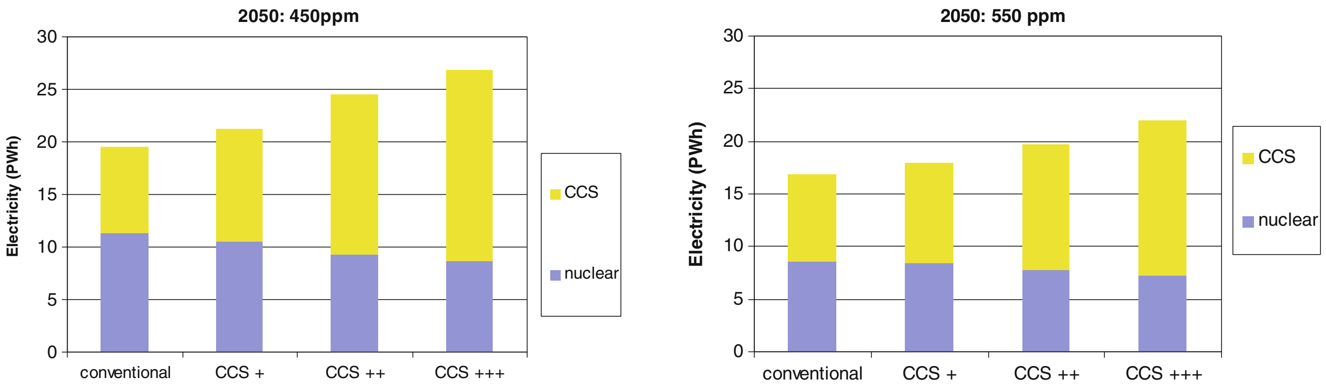

Fig. 6 WITCH simulations of electricity generation (petawatt-hours) in 2050 by coal plus CCS and nuclear power under the 450-ppm (*left*) and 550-ppm (*right*) scenarios

introduced to limit the expansion of nuclear power. Such boundary conditions, however, tend to have a significant impact on the economic performance of climate policy.

The increasing necessity to achieve globally significant CO_2 emission reductions, imminently and affordably, is beneficial for the prospects of nuclear energy. Whether one favors an expansion of nuclear power or not, this energy supply option emits essentially no CO_2, or at least very low levels even when considering the entire nuclear fuel cycle. The analysis presented in this paper shows that if in the EEE model WITCH and probably in other numerical models designed for the integrated assessment of the economics of climate change, no growth constraints are imposed on the deployability of nuclear energy, this technology could well experience the renaissance that is predicted by some analysts. We demonstrate that nuclear power can at most be part of the solution to global climate change and does not constitute a silver bullet. Hence, if at all, it needs to be employed in conjunction with (probably many) other CO_2 mitigation options (as also described in [18]). Nuclear energy could become a significant necessary part of the total solution, if agreed climate targets are as stringent as 450–550 ppm CO_2 stabilization levels. In particular, we show that under these climate-constrained scenarios, the expansion rate of nuclear energy during the forthcoming 50 years does probably not need to largely exceed the growth rates as experienced during the heydays of nuclear energy deployment in the early 1980s.

The analysis we performed cannot address the question whether the nuclear industry will be able to handle the capacity additions and corresponding capital requirements implied by our modeling runs. Our research does indicate, though, that the total investments necessary for a large-scale expansion of nuclear energy are feasible from an aggregate perspective of economic production and growth. According to Bosetti et al. [2], also on the basis of scenario analysis with WITCH, the challenges associated with global climate change suggest an imminent return to the energy R&D levels of the 1980s. In this paper, we expand on their conclusions by reporting that also in terms of annual nuclear electricity capacity additions we may need to return to those that prevailed a couple of decades ago. Of course, the predominant energy concern of the 1970s was mostly energy insecurity, while that preoccupying scientists and policy makers today is also climate change. We find that the possible response to these two different crises (oil versus climate) may be similar, at least in certain respects.

While the nuclear expansion rates calculated in this study could resolve significant part of the global climate change challenge and would possess benefits in other domains such as reducing air pollution and diminishing energy dependence in many countries, from several perspectives an increase in the use of nuclear energy as simulated by WITCH would be of serious concern, notably in terms of radioactive waste and nuclear proliferation. We demonstrate that the technological and economic improvement of CCS required to significantly scale down the expansion needs of nuclear energy is certainly not negligible. Yet a better CO_2 capture rate, as well as reduced CO_2 storage and CCS investment costs, would allow CCS to overtake nuclear energy as leading cost-efficient mitigation technology in the base-load power sector.

The improvements needed for CCS arguably necessitate dedicated investments in innovation, R&D, and pilot and demonstration programs, which would require the mobilization of substantial economic resources. Their quantifica-

Table 2 NPV of cost savings with respect to the CCS reference case (trillion US dollars)

	CCS+	CCS++	CCS+++
550 ppm	0.19	1.38	2.23
450 ppm	2.77	4.23	5.12

tion is difficult, but the economic benefits resulting from such improvements can provide a reference threshold, below which it would be profitable to endorse them. Table 2 shows the cost savings resulting from CCS improvements, calculated in terms of the net present value of global welfare over the current century, at a 5% discount rate, expressed as difference with respect to the CCS reference case. Our simulations indicate that improvements in all three CCS areas identified in this paper can lead to substantial savings, with a maximum of over US $5 trillion for the most stringent climate policy and more than US $2 trillion for the less ambitious one. Indeed, the benefits of CCS improvements also depend on the climate objective. For the 450-ppm case, increasing the capture rate proves to provide the highest overall cost reduction leverage. For the 550-ppm scenario, on the other hand, lowering storage costs and capital investments proves instead the most valuable strategy.

Even when one assumes that CCS can be significantly improved, nuclear power would still need to be expanded sizably, typically by some 15-GW/year added capacity, in order to reach stringent climate goals. These additions alone would justify higher investments that allow improving nuclear technology and empowering institutions in charge of controlling its safe and secure international deployment. Still, progress in CCS technology could reduce the expansion needs for nuclear energy and thus the extent of the classical problems encountered with nuclear power. According to our cost minimization framework, a nuclear power renaissance of some sort may be unavoidable, so concerns surrounding several aspects of nuclear energy ought to be solved in any case. We think these concerns have to be adequately and acceptably addressed even if nuclear power were to be phased out altogether, given that radioactive and fissile materials have been produced abundantly since the advent of the nuclear era.

Surely the last word has not been said about nuclear energy, nor about climate change. In this paper, we bring forward findings at the cross section of these two subjects. Topics abound for further work. One question to be addressed is what the extra costs incurred would be if one imposes a growth constraint on nuclear energy, in line with what so far has been common practice but that we personally have reasoned objections against. This case would need to be compared with the scenario in which no such constraint is applied. It is also interesting to see what the effects would be in our modeling setting of the recent commodity price surge for the investment cost requirements for CCS facilities and nuclear power plant construction. These and related issues we plan to assess in the future.

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