Nuclear versus Coal plus CCS: A Comparison of Two Competitive Base-load Climate Control Options

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Abstract

Under a stringent climate control target in an otherwise unconstrained world for economic growth, energy-environment-economy (EEE) models in principle tend to be favorable for a widespread deployment of nuclear energy in the power sector. Usually, however, 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 often included to drastically limit the expansion of nuclear power. These boundary conditions, however, tend to have a significant impact on the economic performance of climate policy. In this paper we ask ourselves how in a climate-constrained world the prospects for nuclear energy would change if exogenous limitations on the spread of nuclear technology were relaxed. With a recently developed integrated assessment EEE model of climate change (WITCH) we find that until 2050 the ensuing expansion rates of nuclear electricity generation capacity become comparable to the historical ones observed during the 1980s. Given that nuclear energy remains a controversial technology, we investigate what the improvements of the main competing non-carbon base-load electricity alternative – coal-based power equipped with CO_2 capture and storage (CCS) – would need to be if our model is to significantly scale down the prospects for nuclear power.

1. Introduction

The development of nuclear power has experienced significant hindrance from serious and justified concerns over three main categories of its intrinsic negative features: 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 the past recent years a revival of the debate over the role of nuclear power has occurred, due to high fuel prices and concerns over global warming. For example, China, India, South Korea, Japan and Ukraine have planned a total nuclear capacity increase of 116 GW by 2020 (IEA, 2008).

Climate change in particular has gained broad public attention and is today appearing high on most countries' political agendas. Policymakers, notably those currently involved in negotiating a post-2012 climate agreement, rely increasingly on quantitative estimates of the possible implications of climate change. Similarly, they need to be informed more and more quantitatively about the possible effects of their policies on global technology diffusion and economic development. The economic analysis of climate policies 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). Within this strand of research, energy-environment-economy (EEE) models occupy a leading role, since they can generate quantitative estimates of the technological, climatic and economic variables at stake. Determining the values of these variables as well as their mutual interference requires the large-scale integrated assessment approach offered by these EEE models.

Essentially without exception, EEE models simulate for the 21st century, under conditions free of exogenous restrictions on energy technology growth rates, much higher shares for the deployment of nuclear energy than they actually do under a range of commonly applied dissemination and expansion constraints. The reason of course is that nuclear energy is essentially a carbon-free power production option. It is only through the imposition of external growth limitations that EEE models yield the more restricted outcomes for the diffusion of nuclear power as at present normally reported. Usually, nuclear energy expansion constraints are conjectured in such a way as to lead to modeling outcomes with a nuclear power contribution in line with the modeler's personal perception of what the prospects for this power option could be. Although EEE models, especially the detailed engineering linear programming ones, often include a series of constraints that span the entire simulated technology spectrum, in order to avoid outcomes that predominantly concentrate on nuclear energy, normally additional constraints on the maximum potential deployment of nuclear power are imposed. The latter we consider troublesome 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, when carbon is sufficiently priced, 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 ones judges unlikely or unacceptable may be considered at odds with the underlying methodology of economic optimization. However reasonable it may be to remain reserved about the prospects of a certain technology, as with nuclear energy in our case, the imposition of an external constraint on the speed with which this technology can be deployed contradicts the essence on which EEE models are based, i.e. cost minimization, and constitutes support for modeling skeptics who argue that the minimization of costs (or maximization of welfare) cannot constitute the main basis upon which the desirable composition of an energy system is determined or the direction is foreseen into which it could evolve naturally. Third, not rarely technological diffusion rates are imposed that are inconsistent with the ones historically observed. Rather, the assumed maximum growth rates often reflect the outcome the modeler desires to produce, or are more consistent with the technology judged preferable from a certain context of perspectives or system of values, than that they correspond to what could materialize in practice, which renders the calculated scenarios 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 social-optimizing institution, especially at the global level, that in our case would be in the position to impose a universal restriction on the expansion of a certain energy technology. At best, one could argue that through complex international agreements and intricate public organizations the nature of deployable technologies could be requested to satisfy certain minimum (preferably enforceable) quality, safety or environmental qualifications.

The contribution of nuclear power to the mitigation effort required for global climate stabilization varies appreciably across different studies, depending on the climate policy architecture that is expected to be implemented in the near future (Weisser *et al.*, 2008). In some cases, nuclear power plays a negligible role in carbon mitigation scenarios. For example, in a recent modeling comparison exercise (Clarke *et al.*, 2007), the MIT IGSM stabilization scenarios present a use of nuclear energy not appreciably different from the no-climate policy case and limited at roughly today's values. The ex-ante hypothesis of the authors is that for security reasons nuclear power ought to be excluded from the portfolio of mitigation options. Although their assumption may be considered legitimate – indeed, nuclear power is currently not eligible for emissions avoidance under the Kyoto Protocol – the audience reading and interpreting the modeling results should be informed about the economic and technological consequences that stem from such assumptions. Unfortunately, modeling reports often lack transparency in this respect. In comprehensive studies such as produced by Working Group III of the IPCC in its most recent 4^{th} Assessment Report, nuclear power is found to play some mitigating role, but significantly less than other mitigation technologies such as CO_2 capture and storage (CCS) or renewables (see figure SPM 9 in IPCC, 2007), though little guidance on how this result is related to modelling assumptions on nuclear penetration rate is provided.

This article is meant to shed light on this issue: we use the EEE WITCH model (Bosetti *et. al.* 2006) to investigate how in a climate-constrained world the prospects for nuclear energy would change if exogenous restrictions on technological growth are relaxed. Given that nuclear energy continues to remain unpopular, largely for known reasons related to certain inalienable risks, we also evaluate the improvements of its main carbon-poor base-load electricity 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. 2008 evaluate the optimal portfolio of investments in energy technologies and in R&D from an economic viewpoint, for a range of stabilization scenarios. This paper extends their work by explicitly focusing on the role of nuclear electricity vis à vis with other power generation technologies, especially its main competitor for base load provision of electricity, coal plus CCS.

Despite a growing body of literature that has focused on carbon mitigation options, little general equilibrium analysis has concentrated on the specific role of nuclear power in global climate stabilization scenarios. Chakravarty et. al (2005) provide a partial equilibrium analysis accounting for the exhaustibility of nuclear ore reserves. A similar analysis is found in van der Zwaan (2002). Vaillancourt et al. (2008) use the energy system model World-TIMES to explore a range of nuclear deployment scenarios. Our analysis also markedly differs from a recent article with a similar title by Rogner *et al.* (2008) in that ours is an integrated modeling assessment: unlike these authors we do not calculate country-dependent levelized life-cycle electricity costs.

In section 2 of this article we describe the main features of the climate change integrated assessment EEE model, WITCH, that we use for our analysis. Section 3 presents our simulation 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 a technology like CCS needed to downsize the deployment of nuclear energy. Section 5 presents a discussion of our findings and finishes with some main conclusions.

2. WITCH model

The World Induced Technical Change Hybrid (WITCH) model has been developed by the climate change team at FEEM, and it has recently been used successfully for the investigation of several climate-related research subjects[1].It belongs to the collection of integrated assessment models dedicated to enhancing our understanding of the economic implications of climate change mitigation policies and determining economically efficient strategies to achieve 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 introduces a series of novelties that places itself in a position to capture additional aspects of the climate change conundrum.

WITCH features a neo-classical optimal growth structure, so that 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.

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[1] For more details visit the model's website at http://www.feem-web.it/witch.

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.[2] As a result, today's decisions are important determinants of future responses, the climatic and economic dynamics of which are modeled in WITCH. The simulation of the energy sector, the largest source responsible for the emission of greenhouse gases (GHGs), 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: traditional coal (pulverized coal, PC, without CCS), advanced coal (integrated gasification combined cycle, IGCC, with CCS), oil, natural gas, hydropower, nuclear energy, renewables (in our case the combination of wind and solar energy).

WITCH distinguishes itself from many EEE models by an important characteristic that gives its representation of negotiations towards future climate agreements a high degree of realism: it possesses a game-theoretical set-up that allows mimicking the 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 the emissions of CO_2 (reflected by a damage function and a global atmosphere-climate module), extraction limits of exhaustible resources such as fossil fuels, as well as 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 into the design of climate protection policies and inform policymakers 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.[3]

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 and IGCC plus CCS are described by rather similar parameter values in some respects: relatively high investment costs, a high utilization factor as typical of base-load electricity, and relatively low fuel cost inputs, especially for nuclear. Coal reserves are assumed to be abundant, with an equilibrium price not exceeding 80$/t throughout the century in a business-as-usual (BAU) coal-intensive scenario. Similarly, uranium ore is assumed to be sufficiently abundant to satisfy a significant revival of the nuclear industry during the 21st century. Uranium reserves are assumed to be abundant at prices below 300$/kg, at which point reprocessing spent fuel and fast breeder reactors become approximately competitive (hence preventing any further rises in the price of uranium and corresponding cost

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

[3] For more details on the WITCH model, see the above references, Bosetti *et al.* (2006), as well as the model's website at http://www.feem-web.it/witch.

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 of uranium ore on the basis of data reported recently (MIT, 2003). Nuclear waste management fees are initially set at 0.1 ¢/kWh as in MIT (2003), and are assumed to increase linearly with the quantity of spent fuel stored. For CCS, CO_2 transport and storage costs are accounted for via regional supply cost curves calibrated on data available in the literature (Hendriks *et al.*, 2004). The fraction of CO_2 captured is assumed to be 90%. Wind and solar energy are characterized by relatively low unit costs, but also by a low load factor. It is the only technology that we assume is subject to significant technological change through learning-by-doing: especially for solar power plants the literature suggests that there is 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%, a rather conservative value in comparison to learning rates observed in practice (IEA, 2000).

Table 1. Techno-economic assumptions for the main electricity generation alternatives in WITCH: coal + CCS, nuclear energy and renewables (wind and solar energy).

	Coal + CCS	**Nuclear Energy**	**Wind + Solar**
Investment Cost ($2005/kW)	2500	2500	1900
Utilization Factor	85%	85%	25%
Thermal Efficiency	40% [4]	35%	-
CO_2 Capture Rate	90%	100%	100%
Learning Rate	-	-	13%

3. Simulation 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, that roughly correspond to 550 and 650 of all green house gases. While 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 three (clusters of) technologies only: nuclear power, coal with CCS, and renewables (wind and solar energy combined).

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[4] This value accounts for the energy penalty imposed by the CO_2 capturing process.

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, under BAU, nuclear power additions over the forthcoming decades reach a value of 10-15 GW/yr, much like the annual additions realized during the 1970s, while in recent years this annual new capacity did not amount to more than a few GW/yr at most. This result connects to the reality in especially several countries of rapid economic development, like China and India but not exclusively these two obvious examples, that reveal an increased interest for this power option for reasons of notably energy security management 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/yr, and reaches a value over 35 GW/yr by the middle of the century under a 450 ppm scenario. Similar deployment rates are reported in IEA (2008).

We also observe that in the 550 ppm scenario, annual additions of nuclear capacity reach the level of the 1980s, while in the 450 ppm scenario they obtain after several decades a value consistently similar to the one-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 scenario, the marginal cost of CO_2 abatement breaches 100\$/tCO_2 already in 2030 and grows markedly even after that. This growth in the value of CO_2 abatement naturally provides a large incentive for the deployment of CO_2 free power technologies.

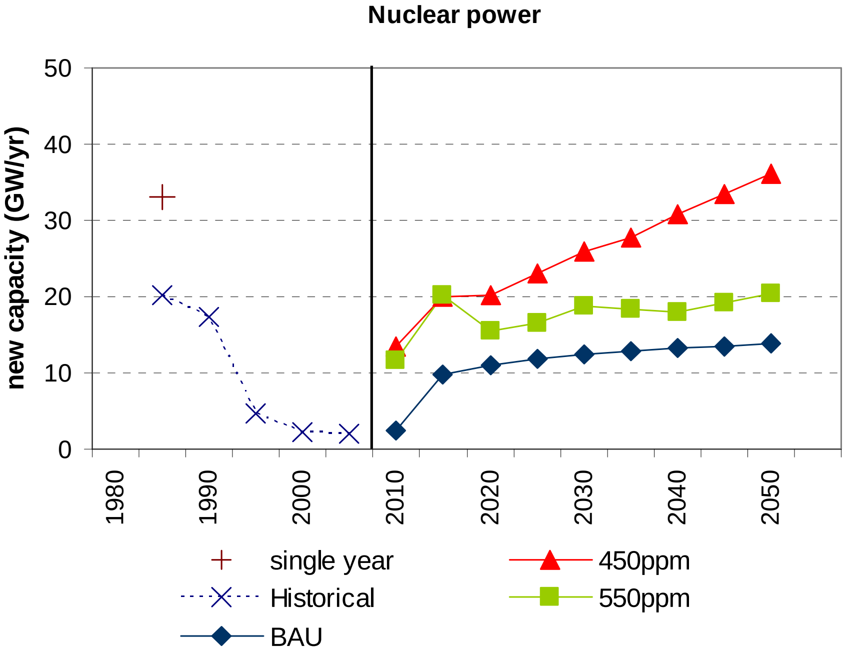

Figure 1. WITCH simulations of future capacity additions of nuclear power (in GW) under BAU, 450 and 550 ppm scenarios, as well as realized during 1985-2005.

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 for either a 450 or 550 ppm climate stabilization target. Under a 550 ppm scenario in less than two decades yearly as much as 30 GW new coal power plants are equipped with complete 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 coal-based power plants (without CCS) built since the 1990s. Under a 450 ppm climate target the use of CCS explodes, reaching a peak around 2020 of over 40 GW/yr. This exceedingly high level (although still below the record level of new coal-based power plants taken in operation in 2005) vanishes over time, however, given that the low but unequal to zero CO_2 emission rate of CCS (see Table 1) is penalized by the progressively stringent climate obligations, for which totally carbon-free technologies are preferred. Nonetheless, for both climate policies the deployment of CCS is very significant, reaching 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 $\$/tCO_2$.

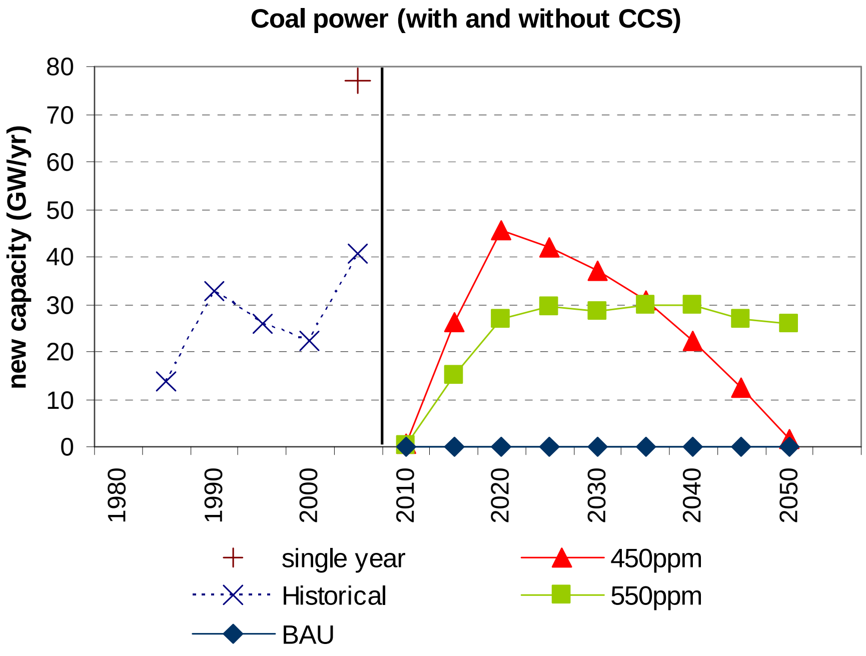

Figure 2. WITCH simulations of future capacity additions of coal-based power plus CCS (in GW) under BAU, 450 and 550 ppm scenarios, as well as realized without CCS during 1985-2005.

As suggested by others, it is unlikely that one or a couple of CO_2 abatement options alone can address any reasonable level of climate control (IPCC, 2007). Indeed,

Figure 3 confirms that renewables such as wind energy and solar power are strong additional favorites for necessary 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 from the present value of about 5 GW/yr. When global climate policy is adhered to, renewables grow much faster: their additions may even exponentially increase to values over 30 GW/yr by 2050 in the case of a 450 ppm climate objective. Such stringent climate policy would rapidly render renewables an energy option at a similar footing as the traditional ones currently in use, thanks to their increased competitiveness following policy-induced learning-by-doing effects.

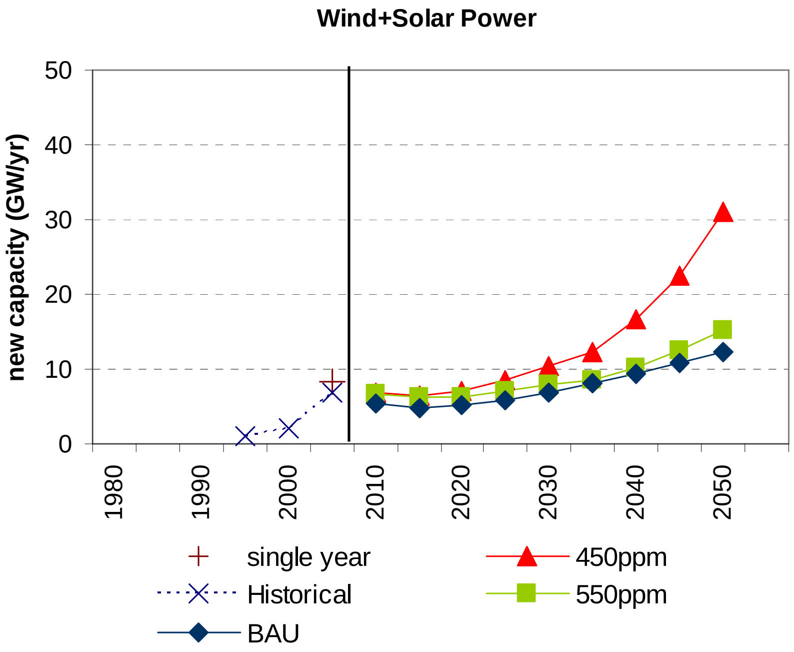

Figure 3. WITCH simulations of future capacity additions of renewables (wind plus solar, in GW) under BAU, 450 and 550 ppm scenarios, and realized since 1995.

The overall observation is that each of the three types of power technologies – nuclear energy, coal plus CCS and renewables – is needed to respond to serious climate control. 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 massive scale, and in most cases all three. We also see that, when the commonly applied growth constraints on nuclear power are relaxed, it is expanded massively 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. Similar results can be found in Bosetti et al (2008).

4. Implications and alternatives

All scenarios depicted in Figure 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 expanded by about a factor of three with respect to the currently installed global capacity that amounts to about 350 GW. What does this imply for nuclear energy? Obviously, the simulated growth paths for nuclear energy respond, along with several 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 (that are no subject of this paper). A positive effect would be that such an expansion would spur further innovation in the nuclear industry and generate incentives to develop and deploy new reactors of so-called generation III (and eventually generation IV) types that possess several benefits with respect to reactors presently in operation (see e.g. van der Zwaan, 2008). In economic terms an expansion of the nuclear sector could also produce economies-of-scale with corresponding cost reductions. Troublesome, however, is that an expansion of nuclear power exacerbates 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 world-wide 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 as of 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 (Sailor *et al*., 2000). Also, both through more advanced reactor designs and improved operation standards, risks for serious reactor 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 and gaseous states, 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 external environment from spent fuel storage can be minimized through several layers of physical containment, most likely including geological deposition deep underground. While progress on deep geological disposal has been made in e.g. Finland, France and Sweden, most governments delay decisions on this subject. The main issue concerning underground storage remains uncertainty about the integrity of spent fuel canisters, and 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 start to leak and consequently contaminate groundwater in the far future. Several channels exist through which the problem could be mitigated, in particular organizing it’s the disposal of waste regionally through Internationally Monitored Waste Repositories (IMWRs). 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 problematique of nuclear energy, its role in future power supply remains severely handicapped and a possible expansion of nuclear energy worldwide gives much reason for concern (van der Zwaan, 2002 and 2008).

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 enrichment facilities and the production of fissile materials (see notably IPFM, 2007). Countries operating enrichment technologies or organized terrorist groups possessing highly enriched uranium (HEU) may relatively easily construct a basic fission 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 explosive device. 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 deletion of fissile materials, like HEU and plutonium, are central to the solution of nuclear proliferation. 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/yr, under a 550 ppm climate control scenario, and that may increase to 35 GW/yr 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 artificially created growth constraints, hence while sticking to cost minimization as the fundament of our scenario analysis? In order 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 does CCS need to accomplish in order to avoid the widespread expansion of nuclear energy that many fear for the above listed set of 'classical' arguments?

We address these questions by focusing on the combustion of coal for power production equipped 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 used to be main competitors until the last was essentially phased out as a result of broad deployment of the former, see Toth and Rogner, 2006). Indeed, coal-based power generation plus CCS and nuclear energy are both base-load electricity options.[5] We focus on three potential areas of improvement for CCS technology:

- **CCS+**: the CO_2 emission capture rate is raised from 90% to 99%, making CCS an essentially zero-emission technology;
- **CCS++**: in addition, the storage costs are assumed not to exceed 12 $\$/tCO_2$, i.e. the availability of repositories is assumed to be large;

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[5] Renewables could be subjected to similar tests, but we find their comparison with nuclear power slightly less pertinent because of the intermittent nature of the former.

- **CCS+++**: in addition, CCS investment costs are assumed to gradually decrease to 50% over 20 years.

Figure 4 shows the results of 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 to addition-levels of about 20 GW/yr, which constitutes a sort of bottom line threshold for nuclear power.

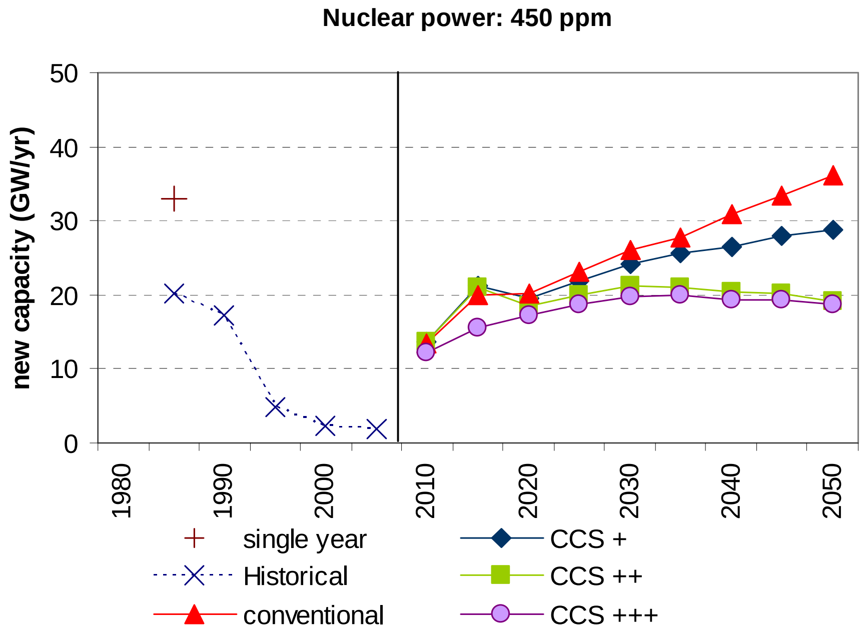

Figure 4. WITCH simulations of future capacity additions of nuclear energy (GW) in the 450 ppm scenario, with various improvements of CCS technology.

Figure 5 shows our results for the 550 ppm scenario under the same three cases of progress in CCS technology development. Like under 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 to an additive minimum level of approximately 15 GW/yr. In both Figures 4 and 5, the evolution of nuclear energy over the coming half-century never drops below the BAU reference curve shown in Figure 1.

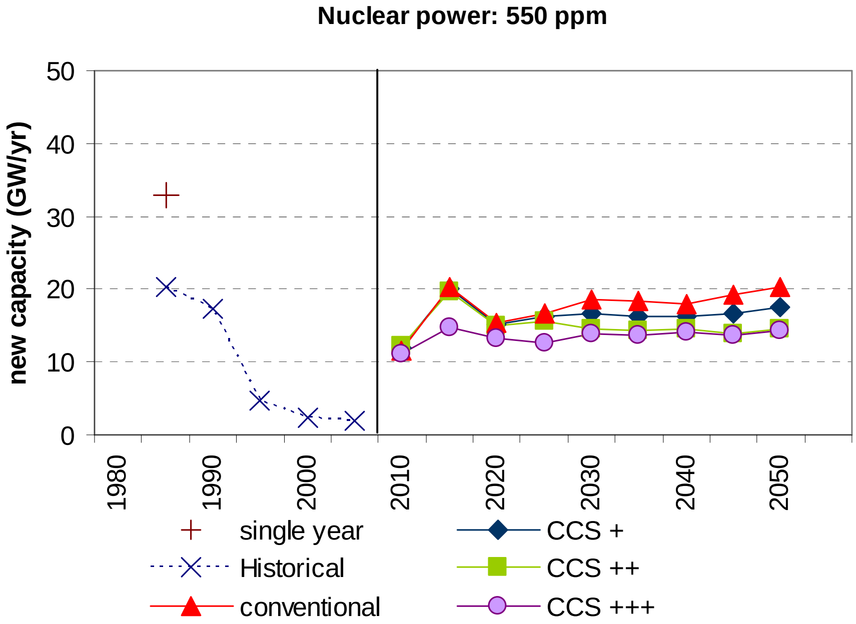

Figure 5. WITCH simulations of future capacity additions of nuclear energy (GW) in the 550 ppm scenario, with various improvements of CCS technology.

What do these results imply for the amounts of consumed electricity, generated by nuclear energy and coal based power 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 change if the technological advancements reported earlier 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 are attained, as shown by the histogram bars on the left in the left plot. Under optimistic assumptions for CCS technological 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 technology improvements are effectively realized. If only the capture rate for CCS can be improved, the level of electricity generated by these two options almost equalizes. In the 450 scenario, the higher relative achievement of CCS over nuclear energy derives from the wider availability of repository sites under the low transport and storage cost assumption. In that case the gap in favor of the former increases to 5.8 PWh. The capture rate and investment cost factors rank behind with a CCS gain of roughly 3.3 PWh each. For the 550 scenario, increasing the capture rate possesses the lowest valuable innovation, bringing about a 1.5 PWh gains to CCS, followed by storage and investment costs with about 3.2 PWh each.

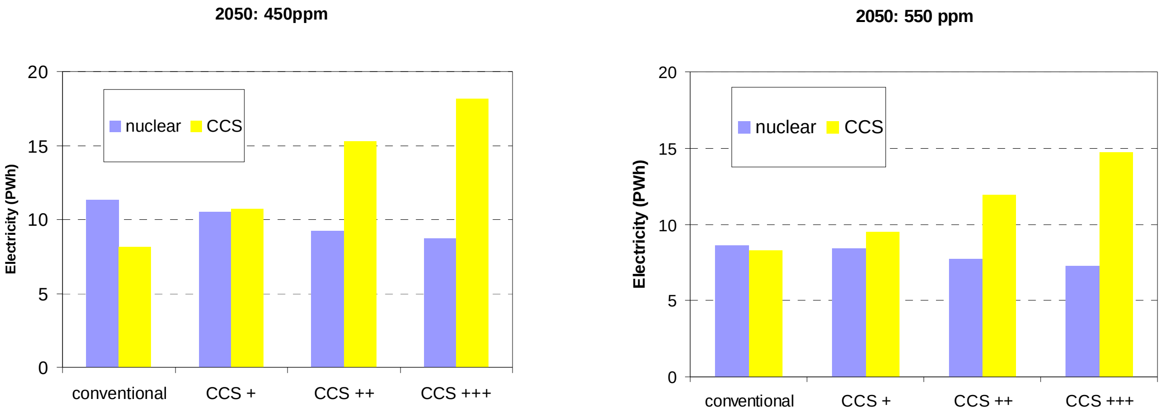

Figure 6. WITCH simulations of electricity generation (PWh) in 2050 by coal plus CCS and nuclear power under the 450 ppm (left) and 550 ppm (right) scenarios.

5. Discussion and conclusions

The increasing necessity to achieve globally significant CO_2 emission reductions over the years to come is beneficial for the prospects of nuclear energy. Whether one is in favor of an expansion of nuclear power or not, the fact is that it essentially emits no CO_2, or at least very low levels when considering the entire nuclear fuel cycle. The analysis presented in this paper shows that if in the EEE model WITCH, and quite possibly in other numerical models designed for the integrated assessment 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 climate change and does definitely not constitute a silver bullet, so if at all it surely needs to be employed in conjunction with other CO_2 mitigating energy options (as also described in van der Zwaan, 2002). It could become a significant necessary part of the total solution, however, 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 1980s.

The analysis we performed cannot address or answer the question whether the nuclear industry will be able to handle the additions as suggested 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. Bosetti *et al*. (2008) found, also on the basis of analysis with WITCH, that the challenges associated with global climate change imply 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, at least on the basis of scenario investigations with the WITCH model. Of course, the predominant energy concerns of the 1970s were very different from those that preoccupy scientists and policy makers today: energy insecurity versus climate change. We find that the possible responses to these two different crises, however, may be similar, at least in certain respects.

While the nuclear expansion rates calculated in this study could respond to significant part of the climate change challenge, and would also 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 in our work would be of serious concern, notably in terms of reactor accidents, radioactive waste and nuclear proliferation. We demonstrate that the requirements for technological and economic improvement of CCS, which according to WITCH could significantly scale down the expansion of nuclear energy, are not negligible. A better CO_2 capture rate, as well as reduced storage and investment costs, would allow CCS to overtake nuclear energy as leading mitigation technology in the power sector. The improvements needed for CCS would arguably necessitate dedicated investments in innovation, R&D and/or pilot and demonstration programs, which would require the mobilization of substantial economic resources. Their quantification 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 5% discount rate) and expressed as differences with respect to the conventional CCS reference case. Our simulations indicate that improvements in all three CCS areas identified in this paper can lead to substantial savings, of over 5 trillion US$ for the most stringent climate policy, and more than 2 trillion US$ for the less ambitious one. We also find that the benefits of CCS improvements depend on the climate objective. For the 450 ppm case, increasing the capture rate provides the highest overall cost reduction leverage. For the 550 ppm scenario, on the other hand, lowering storage costs and capital investments prove instead the most valuable strategy.

Table 2. Cost savings with respect to conventional CCS reference case (trillion US$).

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

Even when one assumes that CCS is significantly improved, nuclear power would still need to be expanded sizably, typically in the order of 15 GW added capacity yearly, in order to reach meaningful climate goals. These additions alone would justify significantly higher investments that allow improving nuclear technology and empowering institutions that control its international deployment. Still, progress in CCS technology could reduce the extent of the classical problems encountered with nuclear power. In our cost minimization framework a renaissance of nuclear power cannot be avoided, however, so concerns surrounding several aspects of nuclear energy ought to be solved in any case. We think these concerns even have to be adequately and acceptably addressed if nuclear power were to be phased out altogether, given that radioactive and fissile material has 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 some new findings at the cross-section of these two subjects. Topics abound for further work. One aspect would be to address the question what the extra costs incurred would be if one nevertheless imposed a growth constraint on nuclear energy, in line with what so far has been common practice but that we personally have reasoned objections against, in comparison to a scenario in which no such constraint is applied. This and related issues we plan to assess in the future.

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