

NOTA DI LAVORO

100.2009

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SUSTAINABLE DEVELOPMENT Series

Editor: Carlo Carraro

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Summary

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 CO₂ emissions: nuclear energy and coal-based power production complemented with CO₂ capture and storage (CCS). We also investigate how, in scenarios from 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 WITCH we find that until 2050 the resulting growth rates of nuclear electricity generation capacity 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 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

This paper is a contribution to the project “PLANETS”, funded by the European Commission under the 7th framework program.

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21 September 2009

DRAFT – not for quotation or distribution

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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 CO₂ emissions: nuclear energy and coal-based power production complemented with CO₂ capture and storage (CCS). We also investigate how, in scenarios from 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 WITCH we find that until 2050 the resulting growth rates of nuclear electricity generation capacity 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 model is to significantly scale down the construction of new nuclear power plants.

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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 fuel prices and the 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 world-wide over the years to come. Before the start of this crisis in the fall of 2008, China, India, South Korea, Japan and Ukraine were reported to have planned a total nuclear capacity increase of even some 100 GW by 2020 (IEA, 2008).

During the past decade climate change has gained broad public attention and is today appearing 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 need to be informed more and more quantitatively about the possible implications of climate policies on 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 research energy-environment-economy (EEE) models occupy a leading role, since they generate figures on the technological, climatic and economic variables at stake. Determining the values of these variables and their mutual interference requires the large-scale integrated assessment approach offered by EEE models.

Various modeling techniques are employed to prevent a restricted number of technologies from either dominating the entire mitigation portfolio or hardly contributing to it at all. Usually these techniques involve means of slightly changing input assumptions, a practice known colloquially as "penny switching". For example, constraints on technology penetration rates or the use of supply cost curves are frequently an essential element of EEE models. Given the distinctive nature of nuclear power, however, the use of non techno-economic assumptions to capture its drawbacks warrants particular attention. The uncertainties governing quantitative estimates of the costs associated with waste management and nuclear proliferation are such that ex-ante hypotheses on the attractiveness of nuclear power are often based on the modelers' perception rather than on un-ambivalent objective analysis. This approach can be questioned for at least three 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. However reasonable it may be to remain reserved about the prospects of any 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 can also be inconsistent with historical records. This practice often renders the calculated scenarios subjective. Third, 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 contribution of nuclear power to the mitigation effort required for global climate stabilization varies appreciably across different studies, and depends in particular on the type of climate policy architecture 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 Integrated Global System Model stabilization scenarios report a use of nuclear energy not much 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 constrained in the portfolio of mitigation options. Their assumption is probably legitimate – indeed, for these reasons nuclear power is currently not eligible for emissions avoidance under the Kyoto Protocol – but we argue that the audience reading and interpreting such modeling results should be informed about the economic and technological consequences that stem from such an assumption.²

Unfortunately, economic climate 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 Fourth Assessment Report, nuclear power is found to play some mitigation role, but significantly less than other technologies such as CO₂ capture and storage (CCS) or renewables (see figure SPM 9 in IPCC, 2007). Little insight is provided in how this result is related to modeling assumptions such as regarding the nuclear penetration rate.

This article is meant to shed light on this issue. We use the 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 (Bosetti *et al.*, 2006). Given that nuclear energy continues to remain unpopular in many countries, largely for reasons related to its inalienable risks, we also evaluate the improvements of its main

² More recently, some modeling assumptions in the MIT scenarios were revised and nuclear power is now projected to increase more rapidly than in the previous study (see Paltsev *et al.*, 2009).

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.* (2009) evaluate the optimal portfolio of investments in energy technologies and energy 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 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.* (2005) 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 is found in van der Zwaan (2002). Rogner *et al.* (2008) calculate country-dependent levelized life-cycle electricity costs for nuclear energy. Vaillancourt *et al.* (2008) use the detailed energy system model TIMES to explore a range of nuclear deployment scenarios, under various sets of assumptions on technology parameters and exogenous constraints on nuclear development to reflect for instance social perceptions. The analysis presented in this paper is a further contribution to this under-explored subject. In attempting to overcome the aforementioned modeling issues, 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 specific comparison of nuclear energy with its most competitive base-load low-carbon power generation alternative.

In section 2 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 a technology like CCS 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 World Induced Technical Change Hybrid (WITCH) model, developed by the climate change team at FEEM, has been widely used for the investigation of several climate-related research subjects.³ 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 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, 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.

³ For more details see e.g. Bosetti *et al.* (2006) and 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 CO₂ has an atmospheric lifetime of hundreds of years and investments in the energy sector usually generate lock-ins that last for decades.⁴ As a result, today's decisions lead to future 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 (GHG) 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: 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, renewables (in our case a combination of wind and solar energy).

WITCH 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 CO₂ (reflected by a damage function and a global atmosphere-climate module), extraction limits of exhaustible resources 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 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.

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 to satisfy a significant revival of the nuclear industry during the 21st century. Uranium reserves are assumed to be large at prices below approximately 300\$/kg, at which point reprocessing spent fuel and fast breeder reactors become competitive (hence preventing any further rise in the price of uranium and corresponding cost increase of nuclear energy; see Bunn *et al.*, 2005). 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 (MIT, 2003). 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 (MIT, 2003). For CCS, CO₂ transport and storage costs are accounted for via

⁴ The half time of atmospheric CO₂ is roughly 100 years, and the lifetime of a power plant can surpass half a century.

regional supply curves calibrated on data available in the literature (Hendriks *et al.*, 2004). The fraction of CO₂ captured is supposed to be 90% and a zero CO₂ leakage rate is assumed. Wind and solar energy are characterized by relatively low investment costs, but also by a low load or utilization factor. It is the only technology 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 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, because we argue learning will not continue indefinitely (IEA, 2000; Ferioli and van der Zwaan, 2009).

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% ⁵ | 35% | - |
| CO₂ Capture or Avoidance Share | 90% | 100% | 100% |
| Learning Rate | - | - | 13% |

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 CO₂ at 450 and 550 ppm. The latter roughly correspond to 550 and 650 ppm stabilization scenarios for all greenhouse gases combined. These scenarios can each be compatible with a stabilization of the global atmospheric temperature at 2.5 and 3 °C increase, at a climate sensitivity of 3. 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 1100 and 750 GtCO₂ respectively. Because of the convex marginal abatement cost curve in our model, the additional effort to achieve the

⁵ This value accounts for the energy penalty resulting from the CO₂ capture process.

most stringent target would come at a considerably higher price. The scenarios are run up to 2150, but for our present purposes it suffices to report results until 2050 only.

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).

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 10-15 GW/yr, 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 with rapid economic growth, like (but not exclusively) China and India, that there is increased interest 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/yr, and reaches a value of over 35 GW/yr by the middle of the century under a 450 ppm scenario. We also see that in the 550 ppm scenario, annual additions of nuclear capacity reach the level as observed in 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 CO₂, 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 CO₂ abatement exceeds 100\$/tCO₂ already in 2030 and grows markedly even after that. This growth in the value of CO₂ abatement naturally provides a large incentive for the deployment of CO₂-free technologies for power generation, a sector characterized by marginal abatement costs less steep than in other parts of the economy such as the transportation sector.

Total installed capacity for nuclear power in 2050 amounts to roughly 1150 and 1500 GW for the 550 and 450 ppm cases respectively. These numbers are somewhat higher in comparison to estimates reported in the literature. For example, Vaillancourt *et al.* (2008) determine a nuclear capacity of about 1000 GW in a 450 ppm scenario, and slightly lower numbers for the 550 ppm and the BAU cases than ours. The International Energy Agency (IEA, 2008), which analyzes scenarios with somewhat different climate objectives, projects nuclear capacity in 2050 to lie in between 860 and 1150 GW.

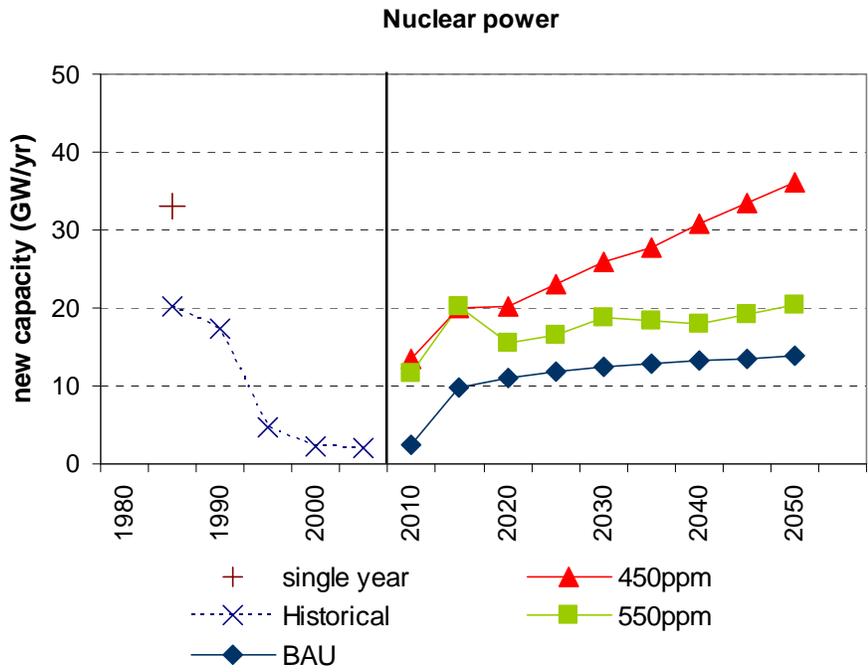


Figure 1. WITCH simulations of future capacity additions of nuclear power (in GW/yr) in BAU, 450 and 550 ppm scenarios, as well as realized during 1985-2005. The “single year” point shows the historic maximum realized.

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 CO₂, 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 as much as 30 GW/yr 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 non-CCS coal-based power plants taken in operation in 2005) vanishes over time, however, given that the low but unequal to zero CO₂ emission rate of CCS (see Table 1) is penalized by the progressively stringent climate obligations, for which totally carbon-free technologies are preferred.⁶ Nonetheless, for both climate policies the deployment of CCS is very significant, and reaches a level as high as 550 GtCO₂ of cumulative storage by the end of the century, with a world average transport and storage cost by then of about 25 \$/tCO₂.

⁶ It should be noted that a higher CO₂ capture rate or the use of CCS in conjunction with biomass would allow CCS to remain competitive in a stringent climate scenario even beyond 2050.

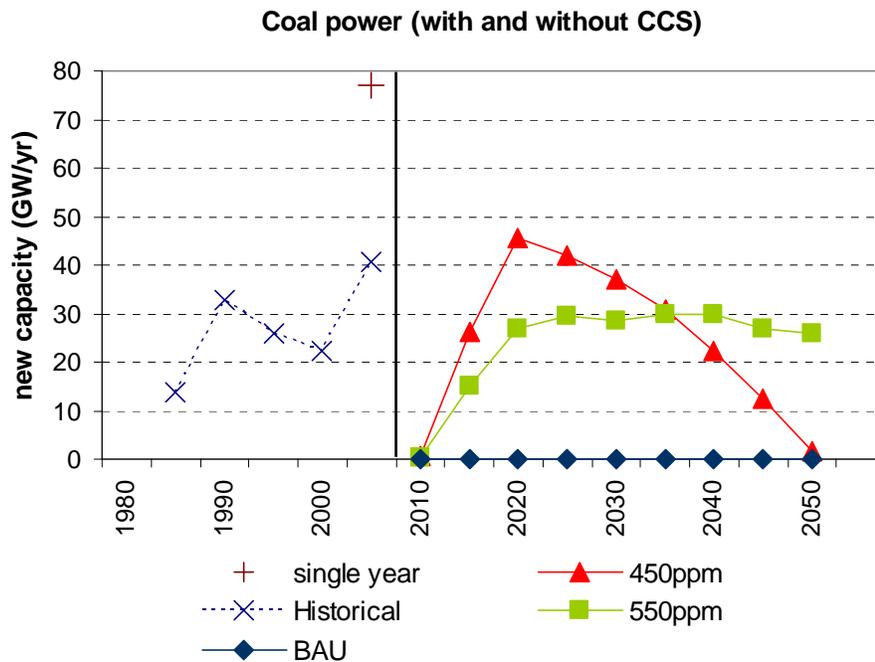


Figure 2. WITCH simulations of future capacity additions of coal-based power plus CCS (in GW/yr) under BAU, 450 ppm scenarios, as well as realized without CCS during 1985-2005. The “single year” point shows the historic maximum realized.

As extensively described in the literature, it is unlikely that one or a couple of CO₂ 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 favorites for 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 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, as a result of their increased competitiveness following policy-induced learning-by-doing effects. Renewables, however, are characterized by relatively low initial deployment rates due to their high early investment costs and low capacity factors, especially for solar energy.

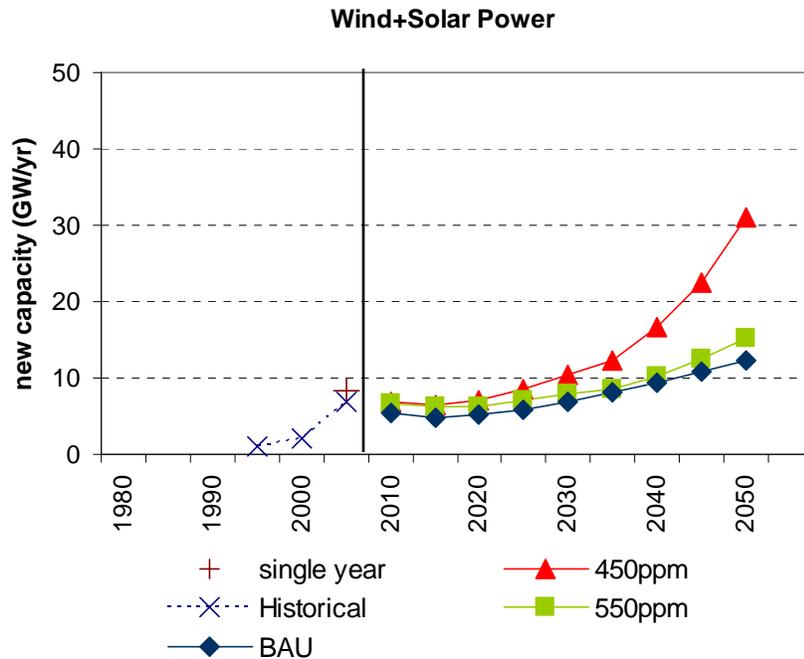


Figure 3. WITCH simulations of future capacity additions of renewables (wind plus solar, in GW/yr) under BAU, 450 and 550 ppm scenarios, and realized since 1995. The “single year” point shows the historic maximum realized.

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 order to reach CO₂ emission reduction targets that avoid increasing the atmospheric CO₂ concentration to more than 450 or 550 ppm, at least two of these three options are needed at a globally very large scale, and probably all three. 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. Similar results can be found in Bosetti *et al.* (2009).

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 increased by about a factor of three with respect to the currently installed global capacity that amounts to about 370 GW. What does this imply for nuclear energy? 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. Another effect would be that such an expansion would spur innovation in the nuclear industry and generate incentives to develop and deploy new reactors of

generation III and eventually generation IV types that can profit from improvements 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 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 (Sailor *et al.*, 2000). 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 US. 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 the problem could be mitigated, in particular organizing 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 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 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 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 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 Toth and Rogner, 2006). 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 CO₂ emission capture rate is raised from 90% to 99%, making CCS an essentially zero-emission technology⁷;
- **CCS++**: in addition, transport and storage costs do not exceed 12 \$/tCO₂, 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.

Figure 4 revises Figure 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/yr. This level thus constitutes a bottom-line requirement threshold for nuclear power.

⁷ This could be either achieved by improving CO₂ capture technology or by co-firing coal with biomass.

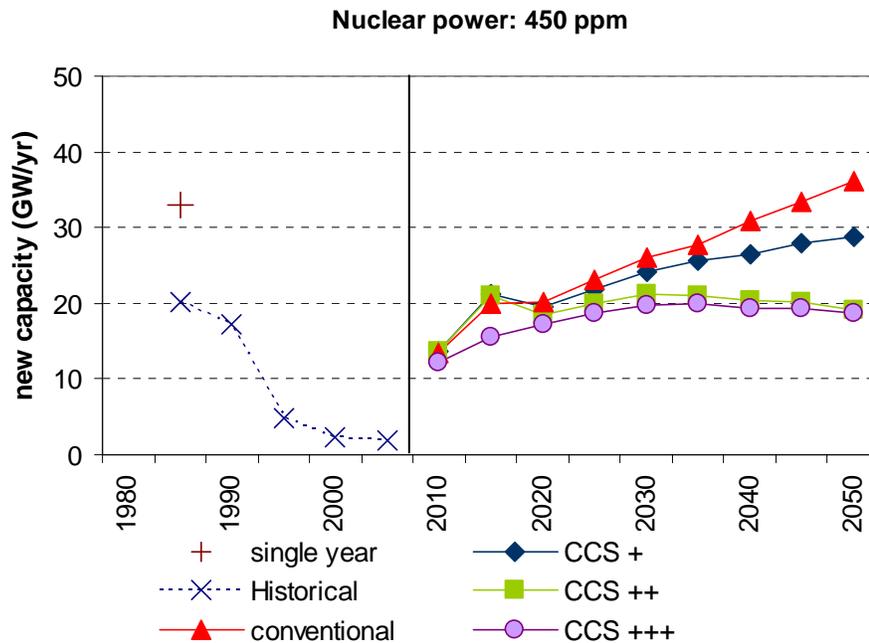


Figure 4. WITCH simulations of future capacity additions of nuclear energy (GW/yr) in the 450 ppm scenario with various improvements for CCS technology.

Figure 5 shows our results for the 550 ppm scenario under the same three cases of progress in the development of CCS technology. 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 a minimum level of annual additions 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.

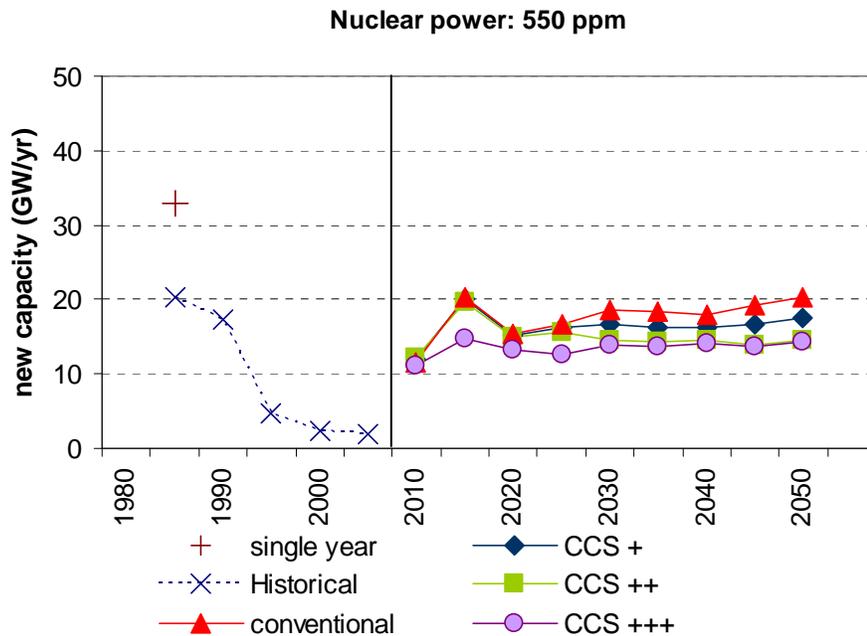


Figure 5. WITCH simulations of future capacity additions of nuclear energy (GW/yr) in the 550 ppm scenario with various improvements for CCS technology.

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. Note that the total electricity generated by nuclear and CCS together increases with the assumed advancements of CCS, that is, nuclear energy is crowded out less than the increase in the use of CCS as a result of the latter's improvements.

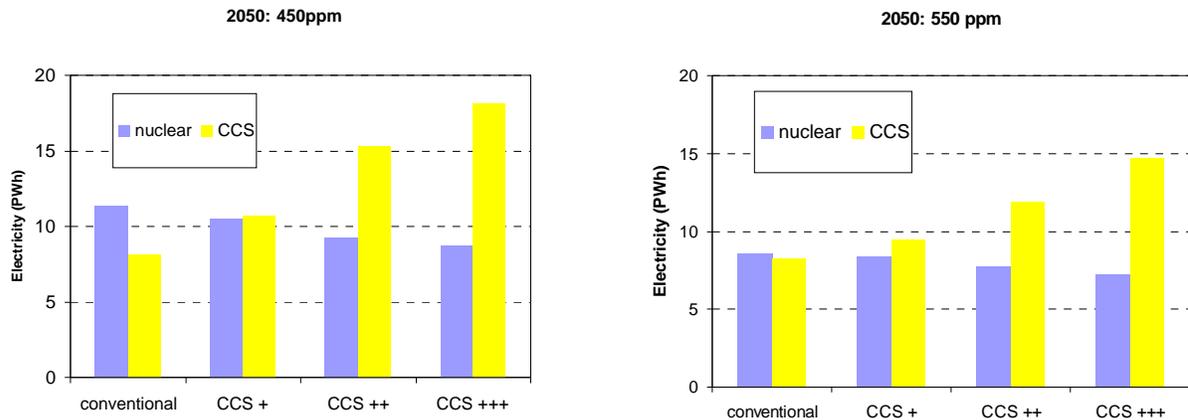


Figure 6. WITCH simulations of electricity generation (PWh) in 2050 by coal plus CCS and nuclear power under the 450 ppm (left) and 550 ppm (right) scenarios.

5. Discussion and conclusions

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

The increasing necessity to achieve globally significant CO₂ emission reductions, imminently and at affordable costs, is beneficial for the prospects of nuclear energy. Whether one favors an expansion of nuclear power or not, this energy supply option essentially emits no CO₂, 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 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 not constitute a silver bullet. Hence, if at all, it needs to be employed in conjunction with other CO₂ 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 CO₂ 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 capacity additions and corresponding capital requirements as 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. Bosetti *et al.* (2009) found, also on the basis of analysis with WITCH, that 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, at least on the basis of scenario investigations with WITCH. Of course, the predominant energy concern of the 1970s was different from that preoccupying scientists and policy makers today: energy insecurity versus climate change. We find that the possible response to these two different crises, however, may be similar, at least in certain respects.

While the nuclear expansion rates calculated in this study could resolve significant part of the 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 in our work would be of serious concern, notably in terms of 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 needs of nuclear energy, are not negligible. A better CO₂ capture rate, as well as reduced storage and investment costs, would allow CCS to overtake nuclear energy as leading cost-efficient mitigation technology in the power sector.

The improvements needed for CCS arguably necessitates dedicated investments in innovation, R&D and 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 a 5% discount rate, and expressed as difference 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. 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 prove instead the most valuable strategy.

Table 2. Cost savings with respect to the 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 by some 15 GW/yr added capacity, in order to reach stringent climate goals. These additions alone would justify higher investments that allow improving nuclear technology and especially empowering institutions that control 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 cannot be avoided, 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 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. It would also be interesting to see what the effects are in our modeling setting of the recent commodity price surges on 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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(lxxxv) This paper has been presented at the 14th Coalition Theory Network Workshop held in Maastricht, The Netherlands, on 23-24 January 2009 and organised by the Maastricht University CTN group (Department of Economics, http://www.feem-web.it/ctn/12d_maa.php).