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Coal-Based Power Generation with CCS versus Nuclear Energy: 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 WITCH 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

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1. Introduction[2]

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

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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 world-wide 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 (IEA, 2008). Today countries with ambitious and increasingly concrete nuclear energy plans can also and especially be found in the Middle East.

In this paper we report how we used the WITCH model to investigate how in a climate-constrained world the prospects for nuclear energy would change if the commonly imposed restrictions on technological growth are relaxed (for details on the WITCH model see e.g. Bosetti *et al.*, 2006). 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.* (2009) 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 and coal-based electricity production complemented with CCS in particular. In section 2 of this paper we very briefly describe some of our main assumptions in 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 World Induced Technical Change Hybrid (WITCH) model, developed by the climate change team at FEEM, has been extensively used for the investigation of 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. 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.

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). Tavoni and van der Zwaan (2009) 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$/t throughout the century in a business-as-usual (BAU) coal-intensive scenario. Similarly, uranium is assumed to be sufficiently abundant at low prices to satisfy a significant revival of the nuclear industry during the 21st century (Bunn *et al.*, 2005). The cost of uranium is modeled endogenously via resource extraction curves. Reserves are assumed to be particularly large at prices up to a level of approximately 300$/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 MIT, 2003). Nuclear waste storage and management fees are assumed to

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[3] For more details see e.g. Bosetti *et al.* (2006) and the model's website at http://www.witchmodel.org.

increase linearly with the quantity of spent fuel produced and are set at 0.1 ¢/kWh (MIT, 2003). For CCS, CO_2 transport and storage costs are accounted for via regional supply curves calibrated on data available in Hendriks *et al*. (2004). 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 (IEA, 2000; Ferioli and van der Zwaan, 2009).

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 and 3 ºC, respectively, if the climate sensitivity is lower than 3 ºC. Although the IPCC suggests a considerably more stringent target of 2 ºC, 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 $GtCO_2$ 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 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).

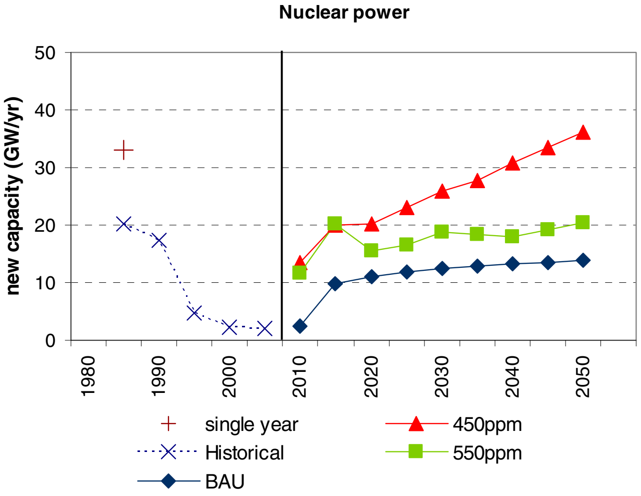

Figure 1. WITCH simulations of future capacity additions of nuclear power (in GW/yr) in BAU, 450 and 550 ppm scenarios, as well as realized during 1985-2005. The "single year" point shows the historic maximum realized.

Figure 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/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 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/yr, and reaches a value of over 35 GW/yr 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 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 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. 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, for example, Vaillancourt *et al.* (2008), who determine a nuclear capacity of about 1000 GW in a 450 ppm scenario and slightly lower numbers for 550 ppm and BAU cases. The International Energy Agency (IEA, 2008), which analyzes scenarios with somewhat different climate objectives, projects nuclear capacity in 2050 to lie between 860 and 1150 GW.

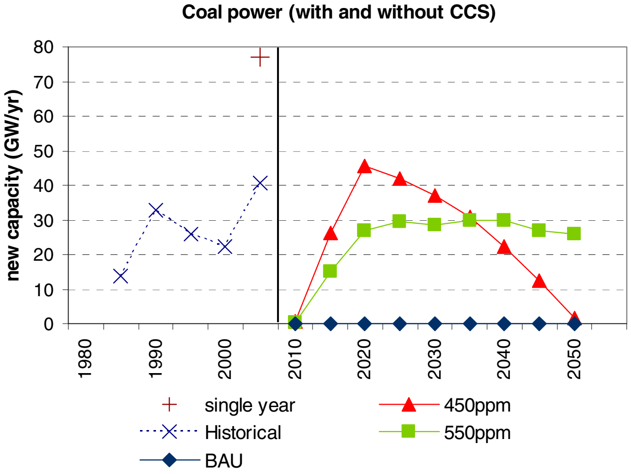

Figure 2. WITCH simulations of future capacity additions of coal-based power plus CCS (in GW/yr) under BAU, 450 and 550 ppm scenarios, as well as realized without CCS during 1985-2005. The "single year" point shows the historic maximum realized.

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/yr 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/yr 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 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 address any reasonable level of climate control (IPCC, 2007). Indeed, in Tavoni and van der Zwaan (2009) we confirm 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/yr. When global climate policy is adhered to, renewables will 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 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.

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.* (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 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. van der Zwaan, 2008). 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 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.

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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.

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 this problem could be mitigated, in particular by 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 significantly handicapped. A possible expansion of nuclear energy worldwide would continue to give substantial 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 uranium enrichment facilities and the production of fissile materials like plutonium (see notably IPFM, 2007). 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 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/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 CO_2 emission capture rate is raised from 90% to 99%, making CCS an essentially zero-emission technology;
- **CCS++**: in addition, transport and storage costs do not exceed 12 $/t$CO_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). In Tavoni and van der Zwaan (2009) we revise Figure 1 for the simulated nuclear energy expansion for these three CCS-favorable cases under the 450 ppm scenario. We conclude that each of these three cases generates a reduced reliance on nuclear power for climate control purposes. We also see, 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 sort of bottom-line requirement for nuclear power. In Tavoni and van der Zwaan (2009) we also 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/yr. In these new CCS-plus scenarios, the evolution of nuclear energy over the coming half-century never drops below the BAU reference curve shown in Figure 1. In Tavoni and van der Zwaan (2009) we also assess what our 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 as simulated by WITCH.

5. Discussion and conclusions

Under a stringent climate control target in an otherwise unconstrained world for economic growth, integrated assessment 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. 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 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 van der Zwaan, 2002). 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.

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.

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