Implications of Small Modular Reactors for Climate Change Mitigation[1]

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Abstract

Achieving climate policy targets will require large-scale deployment of low-carbon energy technologies, including nuclear power. The small modular reactor (SMR) is viewed as a possible solution to the problems of energy security as well as climate change. In this paper, we use an integrated assessment model (IAM) to investigate the evolution of a global energy portfolio with SMRs under a stringent climate policy. Technology selection in the model is based on costs; we use results from previous expert elicitation studies of SMR costs. We find that the costs of achieving a 2°C target are lower with SMRs than without. The costs are higher when large reactors do not compete for market share compared to a world in which they can compete freely. When both SMRs and large reactors compete for market share, reduction in mitigation cost is achieved only under advanced assumptions about SMR technology costs and future cost improvements. While the availability of SMRs could lower mitigation costs by a moderate amount, actual realization of these benefits would depend on the rapid up-scaling of SMRs in the near term. Such rapid deployment could be limited by several social, institutional and behavioral obstacles.

Keywords: small modular reactor; climate change; nuclear; integrated assessment model

1 Introduction

The international community has established a target of keeping global mean temperature rise below 2°C in order to prevent dangerous anthropogenic interference with the climate system (UNFCCC, 2010). Achieving such stringent climate goals will require substantial reductions—in the order of 50% below current levels— in the emissions of greenhouse gases (GHG) by 2050 and deeper cuts beyond (IPCC, 2007). Nuclear energy, along with other low-carbon technologies, is expected to play a significant role in

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contributing to the growing demand for energy without emitting CO_2 (IAEA, 2013; Kim and Edmonds, 2007). However, perspectives vary widely on the potential for substantial increases in the deployment of nuclear power— a divergence that hinges on expectations of future cost reductions, risk of accident, proliferation dangers, waste disposal solutions and public acceptance of conventional nuclear power (see for example, Dittmar (2012) and Joskow and Parsons (2012)). In this context, there has been considerable interest in small modular reactors (SMRs) which are defined by the International Atomic Energy Agency (IAEA) as reactors whose sizes are smaller than 300 MW_e (IAEA, 2012). Proponents view these reactors as more likely to overcome many of the problems faced by the nuclear industry today, with improved economics, proliferation resistance, and easier integration into energy systems. They promise to provide an improved approach to the dual problems of energy security and climate change, especially in the developing world. However, like any new technology, SMRs face a number of challenges for successful commercial deployment. Current cost estimates are highly uncertain because of the early stage of development, and the evolution of SMRs in the overall portfolio—competing with not only conventional nuclear but also all other energy sources—is therefore hard to estimate without a systematic method.

In this paper, we investigate the implications of the availability of SMRs as a technology alternative for climate change mitigation. To do so, we add a new technology category of SMRs to an integrated assessment model (described in section 3.1), and use cost estimates from the recent expert elicitation published by Abdulla et al. (2013). Then, we seek to answer the following questions: How much would the availability of SMRs impact the costs of achieving a stringent climate policy target? How would these impacts change if there is no new investment in large reactors?

2 Background

2.1 Technical and economic advantages of the SMR option

Three major types of SMR designs are being developed (see Vujić et al. (2012), Kessides and Kuznetsov (2012) and WNA (2013a) for comprehensive reviews of SMR designs). The first type is based on the pressurized water reactor (PWR) technology, which is in widespread use today in large reactors. Examples include the International Reactor Innovative and Secure (IRIS), which involves an international team coordinated by Westinghouse; the Russian KLT-40 and VBER-300; the NuScale 45 MW_e; the Babcock and Wilcox 180 MW_e mPower and the Westinghouse 225 MW_e (Carelli et al., 2004; IAEA, 2012; NuScale, 2013; Vujić et al., 2012; Westinghouse, 2013). In addition to the PWR concept, some SMR designs are also based on the boiling water reactor and heavy water reactor concepts (IAEA, 2012). The second type consists of high temperature gas-cooled reactors (HTGRs) that use helium gas as the coolant and graphite as moderator. The outlet temperature of the secondary fluid in these reactors is typically very high, which makes these reactors useful for cogeneration applications. Examples include the ANTARES developed by AREVA, the Chinese Shidaowan project and the Gas Turbine Modular Helium Reactor (GT-MHR) by General Atomics (WNA, 2013a, b). The third group includes SMRs that are cooled by liquid metal or molten salt. An example is the Toshiba 50 MW_e S4 sodium-cooled fast reactor. The latter design concepts are expected to be the most difficult to license, since there is not much experience in operating such reactors or available test facilities for verifying new designs (Vujić et al., 2012).

From an economic standpoint, the smaller size of the SMR means a potential loss of economies of scale in generation associated with large reactors, but promises future economies of scale in manufacture and deployment. Recent expert elicitations have reported higher overnight (capital) costs for SMRs compared to GW-scale Gen II and Gen III systems (Abdulla et al., 2013; Anadon et al., 2012; Anadón et al., 2013). Nevertheless, SMRs have a number of technical and economic advantages compared to large reactors (Carelli et al., 2010; Ingersoll, 2009; Kessides and Kuznetsov, 2012; Kuznetsov, 2008; Rosner and Goldberg, 2011). First, unlike large reactors, SMR designs are compact because a number of components such as steam generators, pressurizer and reactor coolant pumps are integrated within the reactor vessel itself rather than outside of the reactor. Most SMR designs incorporate passive safety features[2] that reduce or eliminate the risk of fuel damage and radiation releases related to loss of coolant or loss of coolant flow. In addition, other features of the SMR such as a larger surface-to-volume ratio and reduced core power density, facilitate easier removal of heat and the use of advanced passive features (Bae et al., 2001; Carelli et al., 2004; IAEA, 2009). SMRs also have a smaller fuel inventory which reduces the maximum possible release during an adverse event (Kessides, 2012).

Second, because of their smaller sizes, SMRs would require reduced construction times and therefore smaller interest payments during construction (Abdulla et al., 2013). In other words, SMRs are likely to be financially less risky compared to large reactors. Third, the modularity of SMRs permits scaling the power plant to larger sizes based on incremental needs for energy and compatibility with the electrical grid infrastructure. Modularity offers other benefits not only by reducing the front-end investment and facilitating initial deployment but also enhancing temporal and spatial flexibility in investment. The latter feature is an important distinction from large reactors because it creates an option value: under uncertainty in future electricity prices, investment in large reactors is very risky as a large portion of the investment is sunk and irreversible. On the other hand, in spite of higher overnight costs, the modularity feature of SMRs offers a better control over market risk to investors (as investment can be split more easily to match market demand) and so the risk premium is lower(Gollier et al., 2005).

Finally, SMRs can be mass produced in a factory and shipped to the site. Mass production could facilitate and accelerate cost reductions due to learning. Empirical evidence on cost reductions due to increasing capacity in the nuclear industry is mixed. In the past, several scholars found evidence of learning and experience spillovers leading to a lowering of costs in the nuclear industry (Lester and McCabe, 1993; Zimmerman, 1982). On the other hand, other scholars argued that increased construction times due to increased size and complexity of reactors coupled with new environmental, health and safety regulations led to escalating capital as well as operating and maintenance costs (Cantor and Hewlett, 1988; Hewlett, 1996; Joskow and Rose, 1985). Similar findings have been reported by more recent studies that emphasize that the site-specific nature of deployment makes standardization difficult, so cost reductions have not been achieved and are not likely in the future (Cooper, 2010; Grübler, 2010;

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[2] Passive safety features involve the use of natural forces such as convection as opposed to active systems which use safety valves and pumps.

Hultman and Koomey, 2007; Hultman et al., 2007). However, in the case of SMRs, several scholars argue that cost savings can be achieved through off-site fabrication of modules (which facilitates standardization), as well as learning-by-doing through the production of multiple, simple modules with shorter construction times (Abdulla et al., 2013; Kessides, 2012; Rosner and Goldberg, 2011). In addition, Rangel and Lévêque (2012) used detailed data for French reactors and argued that while overall experience did not translate into lower costs, some gains were achieved due to the construction of standard reactor types. This finding is relevant to SMRs, which are likely to be co-sited and the same type of reactors are likely to be produced in larger numbers (Abdulla et al., 2013; Carelli et al., 2010). In the subsequent section, we discuss some of the policy rationales put forth by SMR proponents for promoting the deployment of SMRs.

2.2 Policy rationales for promoting SMRs

Scholars have put forth a number of rationales for promoting SMRs. One important rationale for promoting nuclear energy in general and SMRs in particular is improving energy security. Access to energy sources depends on a complex system of global markets, vast cross-border infrastructure networks, a small group of primary energy suppliers, and interdependencies with financial markets and technology. Industrialized as well as developing nations have shown renewed focus on energy security because of the exceedingly tight oil market, high oil prices, instability in some exporting nations and geopolitical rivalries (Chester, 2010; Yergin, 2006). Nuclear power has been relatively unaffected by disruption in commodity markets. Natural uranium represents a very small fraction of the price of nuclear electricity, and uranium resources are spread throughout politically stable regions; the largest producers and exporters are Canada and Australia (IAEA, 2013). SMR proponents argue that because of their small size and inherent safety features, SMRs could be sited in areas with small electric grids or in remote locations with little or no grid access, thereby accessing a wider range of markets than is possible with traditional reactor technology (Kessides and Kuznetsov, 2012; Kuznetsov, 2008).

Another rationale cited for encouraging the deployment of SMRs is to make use of the “early mover advantage” (Kim and Chang, 2012; SEAB, 2012). SMRs are relatively new entrants in the energy markets and promoting SMRs could improve the positioning and competitiveness of domestic industries in the global value chain and also create employment opportunities. For example, Denmark became a world leader in wind energy by mastering the commercialization process (Lund, 2009). This not only improved the international competitiveness of the industry but also compensated for the welfare loss in the infant period (Hansen et al., 2003).

Although scholars envision an optimistic future for SMRs, several factors could create constraints for the expansion of nuclear power in general. In the next section, we review some of these factors.

2.3 Challenges to the future expansion of nuclear power

A number of factors create impediments for the availability and future deployment of nuclear technologies in general. Technological and institutional inter-dependencies lead to considerable inertia in technological systems. Decisions made in the past may lead to technologies getting locked into particular configurations. Such co-evolution of technology clusters over time, also referred to as path dependency, creates constraints for the diffusion of alternate technologies, leading to a “carbon lock-in”

(Arthur, 1989; Grübler et al., 1999; Unruh, 2000). Among the various sources of lock-in and path dependencies in the energy system are increasing returns for incumbent technologies and substitutability in the electricity sector (Grubb, 1997; Grübler, 1997; Grübler et al., 1999; Unruh, 2000). Increasing returns can be caused by economies of scale and learning effects. Currently expensive low-carbon technologies remain expensive because they are not adopted, leading to a lock-in of existing carbon-intensive technologies (del Río, 2009). Also, as technologies in the energy sector are perfect substitutes, new technologies compete with fossil-fuel technologies only based on price and not on other features (Kalkuhl et al., 2012; Lehmann and Gawel, 2013). These phenomena are particularly relevant in constraining the deployment of nuclear technologies, especially large reactors because they are more capital-intensive than fossil-fuel technologies.

The deployment of technologies is influenced by stakeholder and investor perceptions of risk. Investment in currently available large reactors is deterred by high upfront capital costs, uncertainties in cost and construction time, and the possibility of catastrophic accidents (Ramana, 2009). Public perceptions and negative attitudes about nuclear power could slow or halt the deployment of nuclear reactors in some regions. In the mid-1970s majority of Americans favored the building of more nuclear power plants in the United States. However, after the Three-Mile Island (TMI) and Chernobyl accidents public opinion shifted dramatically against the use of nuclear power (Bolsen and Cook, 2008; Hultman and Koomey, 2013; Rosa and Dunlap, 1994). Apprehensions about nuclear energy have been exacerbated by the reaction to the Fukushima accident in Japan (Joskow and Parsons, 2012; Kessides and Kuznetsov, 2012), leading to an accelerated phase-out of nuclear power in Germany. Previous research has shown that negative events such as nuclear accidents have a greater influence on public attitudes compared to positive ones and have led to a general loss of trust in the nuclear industry. Therefore, despite the opportunities and potentially better risk profile presented by new nuclear technologies such as the SMRs, the nuclear industry faces the challenge of regaining the lost trust (Poortinga and Pidgeon, 2004; Slovic, 1992; Slovic, 1993 ; Whitfield et al., 2009).

Concerns about disposal of spent nuclear fuel have persisted for decades. In their study of public perceptions about nuclear waste, Slovic et al. (1991) observed that public perceptions of risk were deeply rooted in images of fear and dread that have been present since the discovery of radioactivity and the development of the use of nuclear energy in weapons of mass destruction.

Finally, gaps in the supply chain and need for infrastructure pose another challenge for nuclear technologies, especially large reactors. The manufacturing infrastructure for major nuclear plant components is limited, with few options existing internationally for heavy forgings for reactor pressure vessels, steam turbines and generators. Likewise, transmission capacity limitations in some regions can make construction of large capacity nuclear reactors more difficult, or even preclude them entirely (Brown et al., 2008).

Combinations of these factors can influence the commercial success and availability of SMRs and large reactors in the future. In the subsequent sections, we use the GCAM integrated assessment model to analyze how the availability of SMRs will impact the costs of achieving stringent climate goals.

3 Methodology

3.1 The GCAM integrated assessment model

In this paper, we use the Global Change Assessment Model (GCAM), to assess the implications of the availability of nuclear technologies in a world with aggressive climate policies[3]. GCAM combines partial equilibrium economic models of the global energy system and global land use with a reduced-form climate model, the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC) (Edmonds et al., 2004; Edmonds and Reilly, 1985; Kim et al., 2006; Sands and Leimbach, 2003). Assumptions about population growth, labor participation rates and labor productivity in 14 geo-political regions, as well as assumptions about resources and energy and agricultural technologies, drive the outcomes of GCAM. GCAM operates in 5 year time periods from 2005 (calibration year) to 2095 by solving for the equilibrium prices and quantities of various energy, agricultural and GHG markets in each time period and in each region. GCAM is a dynamic-recursive model in which decisions are made on the basis of current prices alone. GHG emissions are determined endogenously based on the resulting energy, agriculture, and land use systems. GHG concentrations, radiative forcing, and global temperature change are determined using MAGICC.

The energy system in GCAM comprises of detailed representations of extractions of depletable primary resources such as coal, natural gas, oil and uranium along with renewable sources such as solar and wind (at regional levels). The GCAM also includes representations of the processes that transform these resources to final energy carriers which are ultimately used to deliver goods and services demanded by end users. Each technology in the model has a lifetime, and once invested, technologies operate till the end of their lifetime or are shut down if the average variable cost exceeds the market price. The deployment of technologies in GCAM depends on relative costs and is achieved using a logit-choice formulation which is designed to represent decision making among competing options when only some characteristics of the options can be observed (Clarke and Edmonds, 1993; McFadden, 1980; Train, 1993). An important feature of this approach is that not all decision makers choose the same technology option just because its observed price is lower than all competing technologies; higher-priced options may take some market share. GCAM thus has the ability to describe the development of nuclear technologies along with other power generation technologies in the context of the long-term development of the global energy system. A detailed description of how the energy system is represented in GCAM is available in Clarke et al. (2008b).

GCAM includes representations of global uranium availability, nuclear fuel sectors and advanced nuclear power technologies for electricity generation, and permanent nuclear waste disposal capacities (Figure 1). The fuel cycle considered is once-through[4]. Nuclear fuel costs include the cost for ore extraction, conversion, enrichment, fabrication, interim storage and waste disposal. The availability of uranium in GCAM is represented by means of a supply curve based on a generalized simple crustal model of the relationship between uranium abundance and concentration (Kim and Edmonds, 2007; Schneider and

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[3] Available online at: http://www.globalchange.umd.edu/models/gcam/

[4] The once-through fuel is a representative case as most of the reactors in the world employ this fuel cycle. Although recycling options can be included in the GCAM, the uranium supply curve does not justify this.

Sailor, 2008). In this study, we modified the supply curve to take into account the effects of economies of scale and learning in extraction processes (see Appendix A for details). GCAM includes two groups of reactors: currently operational conventional light water reactors (LWRs) (Gen II) and next generation advanced thermal neutron spectrum reactors (Gen III). The Gen III category includes advanced LWR designs such as the Gen III+ that have advanced reactor designs with improved economics and safety features. The principal characteristics of all Gen III reactors are improved operating and safety features compared to Gen II reactors (Kessides, 2012; Kim and Edmonds, 2007). For the purpose of this study, we also model the SMR option, the details of which are discussed in the following section.

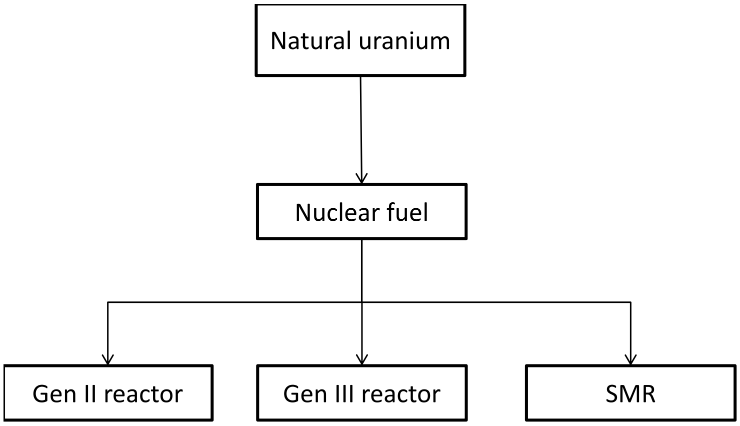

Figure 1 Modeling of nuclear energy in GCAM

3.2 Modeling of SMRs in GCAM

SMRs differ from large reactors in a number of ways. In this analysis, we address a subset of these differences, namely, capital costs, financial risk and future cost improvements. As actual experience with SMRs is not available, our choice of values used to characterize the SMR in GCAM is subject to uncertainty. In order to understand the effects of uncertainty in our assumptions to the outcomes of the model, we consider three broad levels of SMR technologies based on assumptions about their current and future costs: “LowTech-SMR”, “MediumTech-SMR” and “HighTech-SMR”[5] (Table 1).

For overnight capital costs, we use estimates for the Westinghouse 225 MW_e reactor from the expert elicitation conducted by Abdulla et al. (2013). These estimates are based on interviews with technical experts in the nuclear industry and national laboratories. They exclude site-work, transmission up-grades and other “owner’s costs” and are estimates of the lump-sum payment that a customer would transfer to a vendor to acquire an nth-of-a-kind (NOAK) plant, excluding the cost of financing (Abdulla et al., 2013). Median estimates for the cost of the Westinghouse 225 MW_e SMR range from \$3264 to \$7142 per kW_e (in 2012 USD). As explained earlier, the smaller a reactor becomes, the greater the

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[5] Note that because outcomes in the GCAM are influenced by relative economics, the three SMR cases are designed with respect to reference assumptions for large reactors.

diseconomies of scale in the cost of pressure vessel and similar components. It is therefore no surprise that most experts in the expert elicitation of Abdulla et al. (2013) estimated higher overnight capital costs for SMRs compared to a 1000 MW_e Gen III reactor (the estimate for the overnight capital cost of a Gen III reactor as per Annual Energy Outlook 2013 is $5538 per kW_e in 2012 USD) (EIA, 2013a). The lower cost estimates for the SMR can be assumed to correspond to a case where multiple SMRs can be co-sited (although Abdulla et al. (2013) do not consider a scenario in which multiple Westinghouse 225 MW_e reactors can be co-sited; they consider co-siting of NuScale 45 MW_e reactors). Site-specific lessons learned during the installation of the first module can be applied to later units, reducing costs. In our analysis, we use maximum, median and minimum estimates of the overnight capital costs from the Abdulla et al. (2013) study for the LowTech-SMR, MediumTech-SMR and HighTech-SMR technology cases respectively (Table 1).

Table 1 Characteristics of the SMR cases and Gen III reactors considered in this study[a].

	Gen III	LowTech-SMR	MediumTech-SMR	HighTech-SMR
Overnight capital cost (2012 USD/ kWe)	5538	8394	5844	4008
Fixed charge rate	13%	13%	11.7%	10.4%
Improvement in capital cost (% per year)	0.1%	0.1%	0.2%	0.3%
Fixed O&M cost (2012 USD/kWe)	94	94	94	94
Variable O&M cost (2012 USD/MWh)	2	2	2	2
Lifetime (years)	60	60	60	60
Burnup (MWd/kgHM)	50	50	50	50
Heat rate (BTU/kWh)	10542	10542	10542	10542
Enrichment (%)	4.51%	4.51%	4.51%	4.51%

[a] Overnight costs of SMRs are based on expert elicitations by Abdulla et al. (2013). Assumptions regarding fixed and variable O&M costs and burnups are based on Annual Energy Outlook (2013) (EIA, 2013a). Assumptions regarding fixed charge rates and improvements in capital cost are explained in the text.

As explained previously, one of the key advantages of the SMR is that they are likely to face lower financial risks compared to large reactors. In GCAM, differences in financial risk can be represented by means of the fixed charge rate (FCR) that is used to amortize capital. The FCR represents the levelized annual carrying charges including interest or return on capital, depreciation, tax and insurance expenses associated with the installation of a power plant (Shaalan, 2003). Financing costs depend on a range of factors including interest rates, debt to equity ratios in the investing entity, overall capitalization or asset value of the investing entity, sources of financing, depreciation schedules and construction periods. Financial risks also depend on the ownership structure of the utility. For a government-owned facility or a facility owned by a regulated utility with a rate of return effectively guaranteed by government regulators, money can be borrowed at relatively low rates because the risk of default is low. On the other hand, the cost of money would be much higher for a private or investor-owned utility (Bunn et al., 2003). In this study, we have set the FCR of large reactors to 0.13, which corresponds to a simple interest rate of 12.5% amortized over 30 years, typical of values used for other technologies (Brenkert et al., 2003; NETL, 2011). This value lies between those recommended by National Energy Technology Laboratory (NETL, 2011) for investor-owned utilities and independent power producers (0.11-0.21) and by Bunn et al. (2003) for reactors owned and financed by government and private ventures(0.06-0.21). In order to represent the differential in financial risks associated with large reactors and SMRs, we discount the FCR by 0%, 10%, and 20% respectively in the LowTech-SMR, MediumTech-SMR, and HighTech-SMR cases (FCR = 0.130, 0.117, 0.104 for the SMR cases; and for comparison, FCR=0.13 for large reactors).

Another difference in the SMR over large reactors is that, given their smaller size and modularity, it is plausible that cost reductions in the future are likely to be faster for SMRs. However, as explained earlier, empirical evidence for cost reductions in the nuclear industry is mixed. In this study, we assume cost reduction rates of 0.1% per year for large reactors and 0.2% for SMRs (MediumTech-SMR). These values are consistent with assumptions made in prior studies on technological advance (Clarke et al., 2010; Clarke et al., 2008b; McJeon et al., 2011). For the LowTech-SMR and HighTech-SMR cases, we specify annual cost reduction rates of 0.1% (which is the same for large reactors) and 0.3% respectively (corresponding to assumptions for advanced technologies in the above studies).

Note that technological change in GCAM is exogenous. In other words, the analysis is silent about the source of technological advance. It is agnostic as to whether technology advances are because of intensive R&D, learning-by-doing or spillovers from other industries (see Clarke et al. (2006) and Clarke et al. (2008a) for a discussion on the implications of different modeling approaches). This reduces our ability to capture the full detail on how the size and modularity of SMRs will affect costs over time. However, we believe that the alternate cost profiles specified in the three SMR technology cases provide a reasonable approximation to the expected results from a model that generates future technology costs endogenously.

3.3 Scenario design

In this study, we consider a number of scenarios to explore the implications of the availability of SMRs in a world with stringent climate policies. The scenarios explored in this study can be classified under two broad groups based on the availability of large reactors. In the first group, large reactors compete for market share and in the second, they do not. The assumption in the second group of scenarios is that new investment in large reactors cannot take place because of the barriers to nuclear deployment noted in Section 2.3. In each of these groups, we consider four SMR cases: no-SMR, LowTech-SMR, MediumTech-SMR and HighTech-SMR. This gives rise to a total of eight scenarios. The no-SMR cases represent a world in which SMRs remain prohibitively expensive or otherwise unviable due the factors described in Section 2.3. The assumptions that large reactors or SMRs do not compete for market share might seem unrealistic since new large reactors as well as SMRs have recently been licensed for operation in several countries, including India, China and South Korea. An alternative approach would be to limit the expansions of these technologies (see for example, the study by (Iyer et al. (2013))). However, these assumptions are useful to understand the “value” of the technologies in climate change mitigation under constrained conditions and provide a baseline for comparison without complicating the scenario design of the study. In the LowTech-SMR case, SMRs have higher capital costs compared to large reactors and have no additional advantages in terms of financial risks or cost reductions. On the other hand, in the HighTech-SMR case, SMRs have lower capital costs, lower financial risks and better cost improvement rates. The MediumTech-SMR case is designed as a “median” of the above two cases.

The LowTech-SMR and HighTech-SMR technology assumptions serve the role of both, spanning the range of what might be plausible (although there is a great deal of uncertainty in choosing what is plausible) and also as well-described departures from the MediumTech-SMR technology assumptions.

All climate policy scenarios lead to a global CO_2e concentration of 450 ppm, corresponding to a radiative forcing of 2.6 W/m^2 by the end of the century. This target is associated with limiting global mean temperature rise to less than 2°C, a target endorsed by the UNFCCC in the Copenhagen Accord, in order to prevent dangerous anthropogenic interference with the climate system (UNFCCC, 2010; Vuuren et al., 2011).

4 Results and Discussion

4.1 Mitigation under the 450 ppm CO_2e target

In the absence of a climate target, the future energy system is dominated by fossil fuels (Figure 2). Nuclear energy contributes to a relatively smaller share of the total electricity generation because the higher upfront costs of nuclear reactors compared to fossil fuel technologies make the nuclear option less competitive. These dynamics change dramatically when a stringent climate target is imposed on the system.

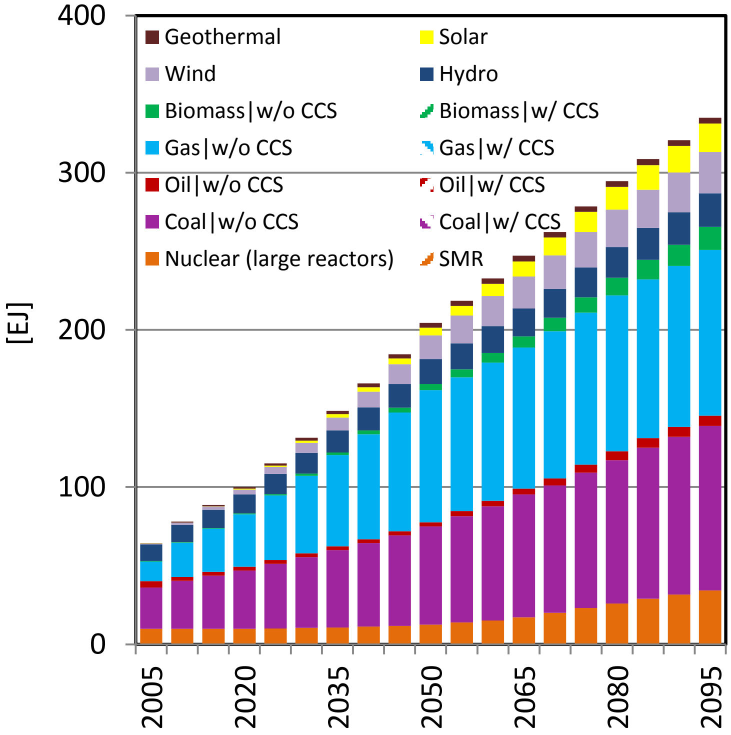
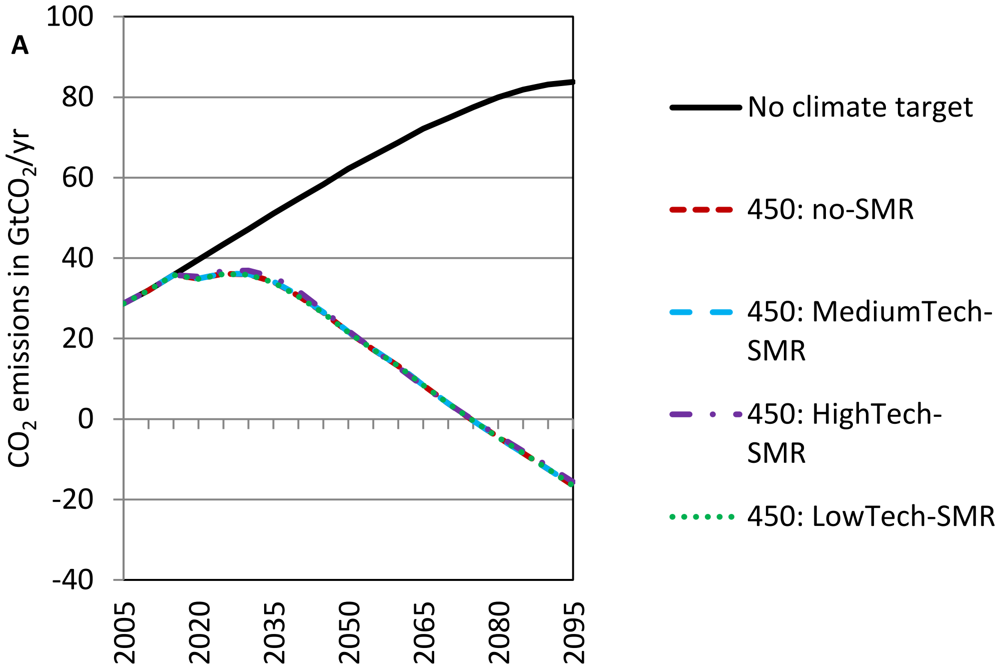


Figure 2 A representative reference case of electricity generation by fuel under no climate target and an assumption of no SMRs.

Under the 450 ppm CO_2e target, the CO_2 emissions pathways peak around 2030 and then start to decline, exhibiting substantial negative emissions by the end of the century (Figure 3). The degree of mitigation effort can be seen in terms of carbon price paths, which rise exponentially following the Hotelling-Peck-Wan rule from about \$30/tCO_2 in 2020 to about \$1,200/tCO_2 by the end of the century (Peck and Wan, 1996). The emissions pathways for the 450 ppm scenarios with SMRs included are not very different as all the scenarios achieve the same concentration targets. On the other hand, the carbon price path for the HighTech-SMR case is lower than the others indicating that the cost of achieving the target in this case is likely to be significantly lower.



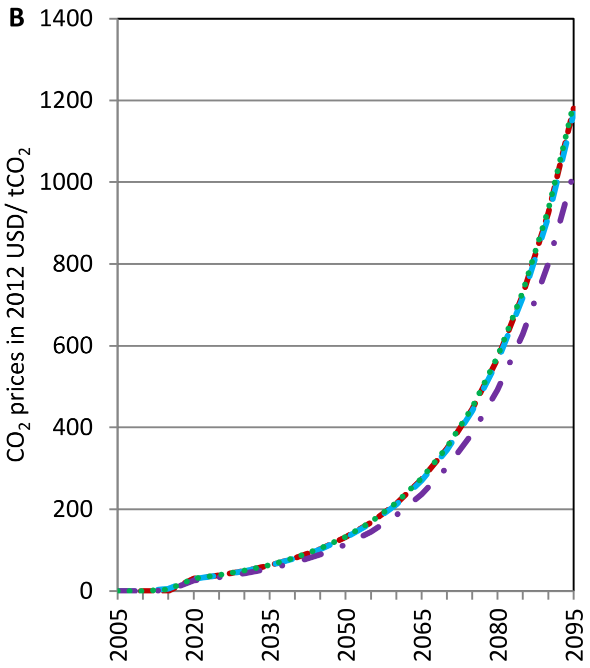


Figure 3 a.) CO$_2$ emissions from fossil fuel and industry and b.) corresponding CO$_2$ prices to achieve the 450 ppm CO$_2$e target with no constraint on the expansion of large nuclear reactors

Under the stringent climate target, the trend of modest mitigation in the near term followed by dramatic mitigation by the end of the century happens because of the expansion of technologies such as renewables, carbon capture and storage (CCS) and nuclear, which are deployed on a large scale over the second half of the century, especially in the electricity sector (Figure 4a). In particular, bioenergy in combination with CCS technologies (bio-CCS), which generates net negative emissions, offers considerable flexibility in the timing of mitigation action, leading to a major part of emissions mitigation being conducted in the longer term. With a price on carbon, nuclear becomes a competitive option and offers considerable flexibility, along with bio-CCS, to the timing of mitigation action. By the end of the century, nuclear contributes almost a third of global electricity generation. If SMRs are allowed to compete for market share, the overall dynamics are not very different and the share of overall nuclear in the electricity generation mix (meaning both large reactors and SMR) is not altered significantly (Figure 4 b). However, because of their lower financial costs and better future cost improvements, the share of nuclear made up by SMRs expands rapidly to provide up to 40% and 61% of the electricity generation from nuclear by the middle and end of the century respectively. In contrast, if there are no large reactors, SMRs get deployed even more rapidly, especially after existing Gen II reactors are phased out at the end of their lifetimes. In this case, nuclear energy contributes a little over a third of global electricity generation by the end of the century. In the following sections, we discuss how the availability of SMRs affects the costs of achieving the 450 ppm CO$_2$e target and the broader challenges for SMR deployment.

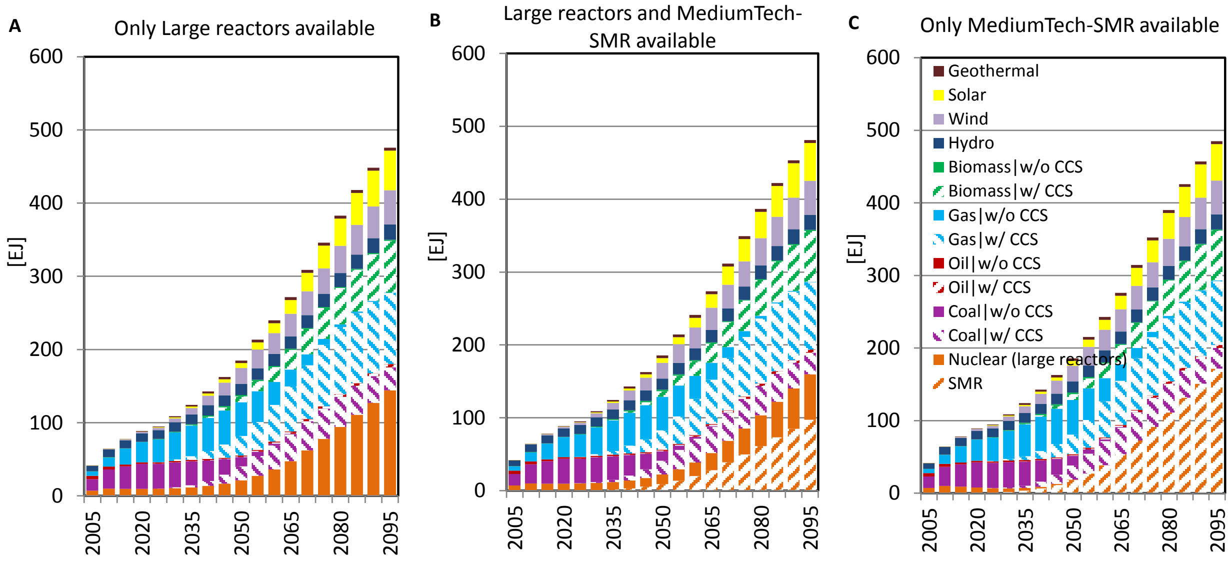


Figure 4 Electricity generation by fuel for the 450 ppm CO_2e target when a.) only large reactors are available b.) SMRs (MediumTech-SMR technology case) and large reactors compete for market share and c.) No new investment in large reactors can occur

4.2 Impacts on mitigation costs

Relative degrees of mitigation effort across scenarios can be seen in terms of the net present value (NPV) of mitigation costs of stabilizing the climate (throughout this paper, we assume a discount rate of 5%)[6]. The availability of SMRs has significant impacts on the abatement costs of achieving the aggressive climate target – in general, the costs with SMRs are lower than without (Figure 5). In addition, among the cases with SMRs, mitigation costs are highest for the LowTech-SMR cases and lowest for the HighTech-SMR cases. In other words, mitigation costs are lower in the cases with more advanced SMR technologies. Further, irrespective of the SMR technology scenario, mitigation costs with both SMRs and large reactors competing for market share (green bars) are lesser than or equal to the cases where only SMRs are available (red bars). In other words, when there is substitutability, mitigation costs are lower or remain unchanged. These observations are consistent with the findings of previous studies on the availability of technology and benefits of advanced technologies (Clarke et al., 2008b; McJeon et al., 2011).

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[6] Standard metrics of mitigation cost include GDP loss, consumption loss, the area under the marginal abatement cost curve, and compensated variation and equivalent variation of consumer welfare loss. In this study, mitigation costs are calculated as the area under the marginal abatement cost curve. This measures the loss in both consumer and producer surplus plus the tax revenue under a carbon policy but not the surplus gains through avoided climate damages (Calvin K, Patel P, Fawcett A, Clarke L, Fisher-Vanden K, Edmonds J, Kim SH, Sands R, Wise M. The distribution and magnitude of emissions mitigation costs in climate stabilization under less than perfect international cooperation: SGM results. Energy Economics 2009;31; S187-S197.)

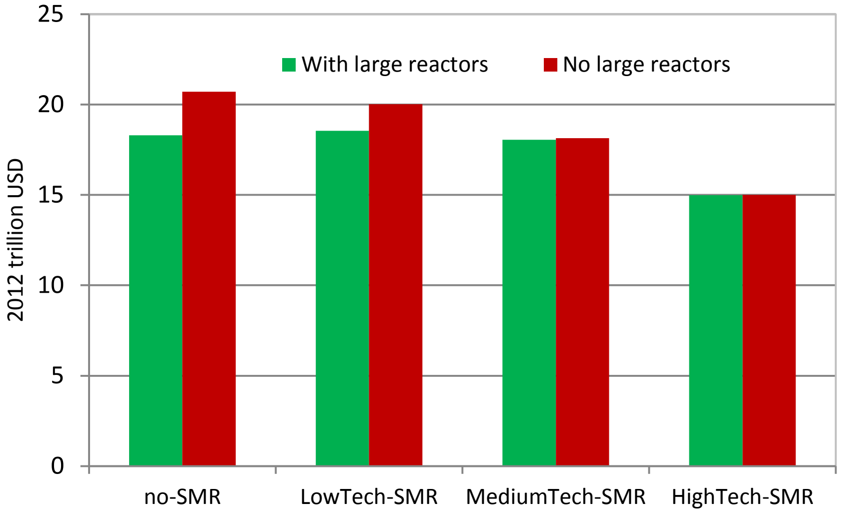

Figure 5 Abatement costs of achievhing the 450 ppm CO_2e target

The difference between abatement costs for the scenarios with and without SMRs can be seen as a measure of the economic "value" associated with SMRs (Figure 6). While the reduction in mitigation costs associated with SMRs increases with more advanced technology, the reduction is notably greater when large reactors are not available. For instance, when SMRs and large reactors compete freely, the mitigation cost with MediumTech-SMRs is reduced by 1%. On the other hand, if large reactors are not available, the reduction in cost is 12%. This is because, in the latter scenario, the SMR is the only nuclear technology option available. Therefore, compared to a nuclear moratorium (where both large reactors and SMRs are not available), the availability of a nuclear technology option is important, especially on the long term; and if SMRs are the only nuclear technology option available, the reduction in mitigation cost may be as high as 27% (for the HighTech-SMR).

Our analysis also shows that when SMRs have to compete with large reactors, only the HighTech-SMR technology case leads to substantial reduction in mitigation costs: while the reduction in abatement costs with the HighTech-SMR case is as much as 18%, the reduction in costs with the MediumTech-SMR and LowTech-SMR cases are much smaller (2% and virtually nothing respectively). This is because, in these scenarios, SMRs and large reactors are imperfect substitutes. Therefore, differences in technology costs and characteristics will have large impacts on their deployments and consequently, on the mitigation costs. In contrast, in the scenarios with no new investment in large reactors, the availability of even the LowTech-SMR technology leads to a modest reduction in abatement costs. This is again due to the fact that compared to a nuclear moratorium, the deployment of even an expensive nuclear technology option can accrue some benefit.

Although the above analysis indicates that the availability of SMRs can lead to substantial reductions in mitigation costs, the realization of these benefits is subject to the assumption that the deployments of SMRs are not constrained by other social, institutional and behavioral factors that are typically not accounted for in integrated assessment models used for climate policy analysis. In the following section, we discuss the broader challenges and implications associated with rapid SMR deployment.

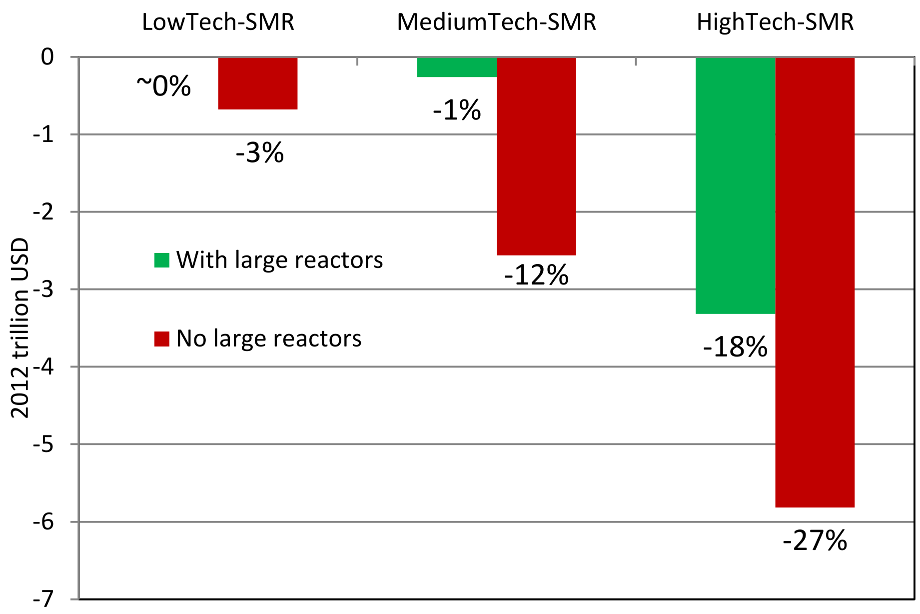

Figure 6 Differences between the net present values of abatement costs relative to scenarios without SMRs. Values on the outside end of the bars represent the percentage differences.

4.3 Deployment of SMRs: real world challenges to scaling up

In the last few years, the growth of nuclear technologies has been modest because the diffusion of nuclear technologies has been constrained by many factors described in Section 2.2 (Iyer et al., 2013; Wilson et al., 2012). In contrast, the results of this analysis suggest very rapid deployment of SMRs in the future. While the absolute deployments vary substantially across the scenarios considered in this paper, the rates of deployment do not vary considerably. In general, there is rapid deployment of greater than 20% per year in the near to medium term followed by modest rates in the long term (Figure 7). The decreasing diffusion rates can be explained by the increasing market competition to satisfy a finite demand and substitutability with other low-carbon technologies caused by increasing size of technology deployment[7]. Moreover, although the deployment rates in the cases with no new investment in large reactors are initially higher than the cases with both types of reactors competing freely, the rates decrease to similar levels by the end of the century as the deployment increases. Interestingly, the growth rates in the HighTech-SMR cases are lower than the MediumTech-SMR and LowTech-SMR cases. This can also be explained by the inverse relationship between growth rate and the size of technology deployment (which is higher in the HighTech-SMR cases) in the presence of increasing market competition.

Figure 7 suggests rapid deployment of SMRs over the next decade. For example, total installed capacity of SMRs in 2035 varies from about 16 GWe in the LowTech-SMR case to 500 GWe in the HighTech SMR case. Much of these deployments occur in developing regions (Figure 8). Rapid economic growth coupled with the need to achieve the stringent climate goal lead to a substantial deployment of SMRs in

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[7] See Hook M, Li J, Johansson K, Snowden S. Growth Rates of Global Energy Systems and Future Outlooks Natural Resources Research 2012;21; 23-41. who derive the inverse relationship between growth rate and system size mathematically

regions such as China and India, especially in the case with no new investment in large reactors. While the results of this modeling exercise suggest the potential for very high deployment rates for SMRs, this is under the assumption that deployment is dependent on relative prices alone. In reality, however, several factors, apart from the ones described in Section 2.3 could constrain the expansion of SMRs and pose challenges for fast up-scaling, particularly in the near term.

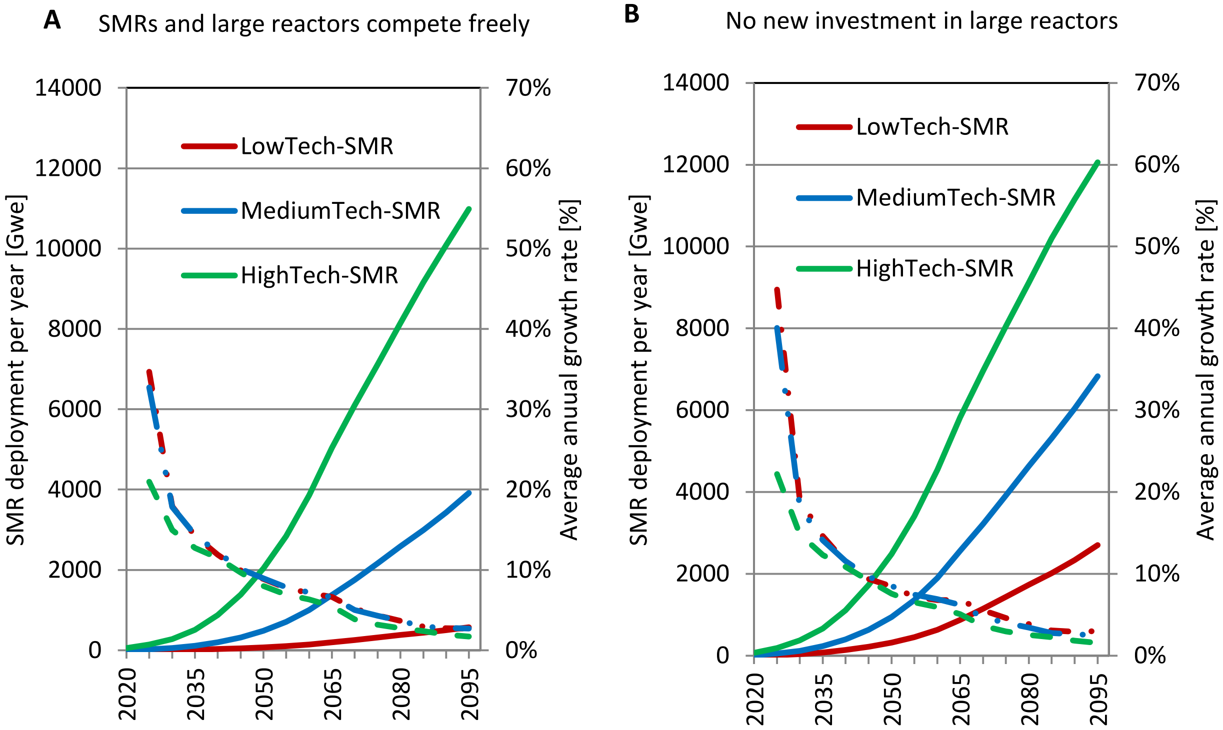

Figure 7 Global deployment of SMRs under the 450 ppm CO_2e target when a.) Large reactors compete for market share freely and b.) No new investment in large reactors can occur. The dashed lines represent average annual growth rates (plotted on the right axes)

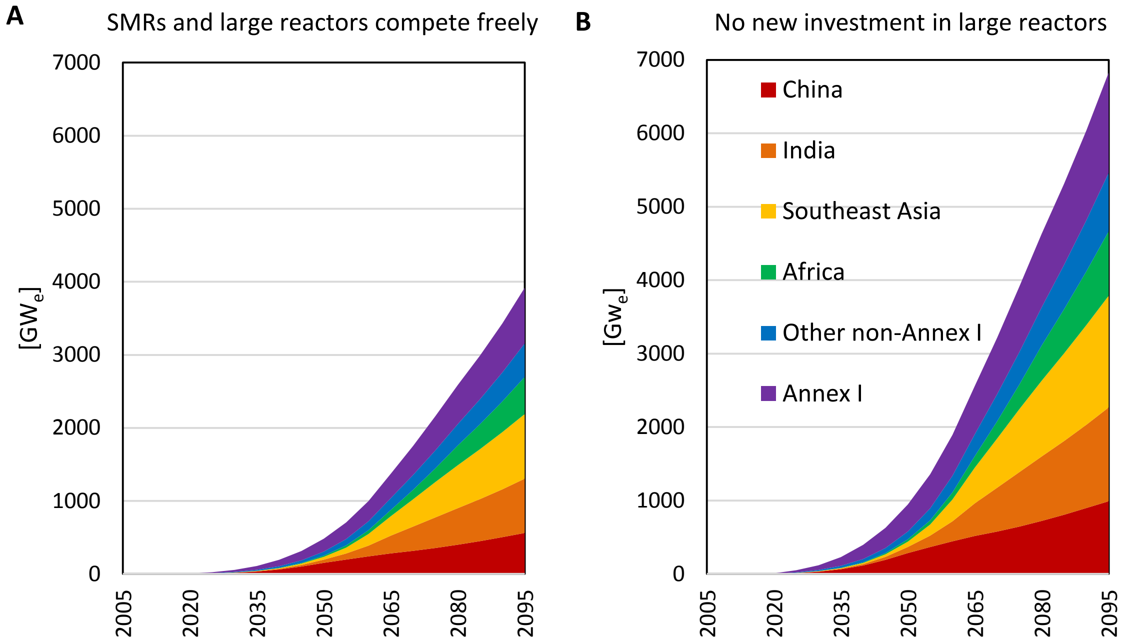

Figure 8 Regional distribution of SMR (MediumTech-SMR) deployment under the 450 ppm CO_2e target when a.) SMRs and large reactors compete freely and b.) no new investment in large reactors can occur. Annex I regions include OECD, Former Soviet Union and Eastern Europe. Other non-Annex I regions include the rest of the world except Africa, Southeast Asia, India and China.

First, institutions and regulatory frameworks co-evolving with technologies are known to reinforce lock-in effects described earlier (Unruh, 2000). While regulatory institutions are designed as a response to emerging technologies, the institutions themselves are subject to path dependencies, leading to a potential bias of regulations toward incumbent technologies. For example, SMR proponents suggest that as demand grows locally, SMRs would allow investors to make incremental capacity additions to existing sites leading to co-siting economies (Abdulla et al., 2013; Carelli et al., 2010). However, current licensing rules in some countries such as the United States do not allow more than two reactors to be operated from a single control room (NRC, 2012)[8]. Likewise, differences in regulatory processes related to country specific factors, primarily relating to the characteristics of the nuclear energy programs would also affect the deployment of SMRs internationally. Also, countries may be more hesitant to purchase SMRs employing newer designs if the design has not received approval in the originating country (Ramana et al., 2013).

Second, public good characteristics of information could discourage investment, creating an impediment for fast diffusion of SMRs in the near-term. From the perspective of early adopters of a technology, once information is created, it can be used by others at little or no additional cost (Jaffe et al., 2005). For example, in the case of SMRs, early adopters would invest significant resources into technology development and certification. If approved, it would be much easier for other venders to certify an SMR.

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[8] Sharing a control room is only one component of the cost savings from co-siting. Others include the cost of the site, emergency planning and transmission and distribution infrastructure.

However, if they do not win approval, the investment becomes stranded. This would discourage potential adopters[9].

Third, lack of information about unproven technologies creates uncertainties regarding performance and future technological improvement. These in turn generate an “option value” of postponing the adoption of a technology such as the SMR to the future (Clarke and Weyant, 2002; Jaffe et al., 2002; Stoneman and Diederen, 1994). From the perspective of an investor, there may be a benefit of delaying investment, which occurs as new information (e.g., performance, cost, market demand, substitutes and policy signals) is incorporated into the decision making. This benefit needs to be compared with the benefit of exercising the option, which includes earlier earnings from the investment and the ability of extracting more rents from competitors. Under uncertainty, an investment will be postponed until a certain threshold for new information is reached (Dixit, 1994). With respect to SMRs, a number of features are unique and are not incorporated in currently available reactors. Therefore, although many newcomer countries have expressed interest in SMRs, they are still in favor of proven technology, so they want SMR technology to be first deployed in the country of origin to minimize risks (IAEA, 2013).

In addition to economics, perceived and actual safety, waste-disposal, proliferation, and terrorism concerns will also affect the deployment of nuclear reactors. For example, SMR proponents believe that deploying SMRs would improve proliferation resistance[10]. Some SMR proponents envision a *hub-and-spoke* configuration in which reactors would be fueled at a central “*nuclear park*” and then sealed and sent out to client countries. The reactors would not require refueling, and at the end of the core life would be sent back to the central facility unopened (see for example, Feiveson et al. (2008)). Not only do such configurations imply proliferation benefits that may not be reflected in market prices, they also have implications for early-mover advantages of promoting SMRs explained earlier. Nevertheless, whether SMRs will have significant advantages or disadvantages over large reactors will depend on the particular reactor and fuel cycle technologies that are chosen and in what countries they are deployed. A detailed examination of these factors is beyond the scope of this paper.

5 Conclusions

As a carbon free source of energy, nuclear power may prove to be a valuable technology for climate change mitigation (IAEA, 2013; Kim and Edmonds, 2007). In this context, SMRs have been receiving considerable attention as an important nuclear technology option. In this paper, we have analyzed the implications of the availability of SMRs on the costs of achieving a stringent climate target of 2°C by the end of the century. This analysis uses the GCAM integrated assessment model to investigate how the availability of SMRs matters under different assumptions regarding SMR costs and the availability of conventional large reactors. This study contributes to the literature on technology availability by

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[9] Note, however, that early mover advantages, especially in the case of new reactor technologies based on advanced concepts may serve to encourage investment.

[10] The IAEA defines proliferation resistance as “*that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States in order to acquire nuclear weapons or other nuclear explosive devices”* (IAEA, 2010. Technical features to enhance proliferation resistance of nuclear energy systems. International Atomic Energy Agency, Vienna, Austria.)

analyzing the implications of and issues surrounding the deployment of nuclear technologies in general and SMRs in particular.

Our study provides two key insights. First, the availability of SMRs has significant impacts on the costs of achieving stringent climate goals - the costs with SMR are lower than without. In addition, when both SMRs and large reactors compete for market share, reduction in mitigation costs is achieved only under advanced assumptions about SMR technology costs and future cost improvements. Second, the abatement costs are higher if large reactors are not available. In these scenarios, even pessimistic assumptions about SMR technology costs and technological advance can lead to reductions in mitigation costs. However, realization of these benefits in reality would depend on the rapid up-scaling of SMRs, especially in the near term which is likely to be limited by several challenges to deployment such as institutional inertia, preference for proven technologies and concerns about spent fuel management.

This study is not without limitations. First, we have presented results from an integrated assessment model in which the market share of a technology depends on relative levelized costs alone. Actual deployment of technologies depends on a number of non-economic factors that we have not accounted for explicitly. Our results could be improved by imposing limits on the rate of deployment of SMRs and large reactors (such as the study by (Iyer et al. (2013))) rather than prohibiting the construction of new capacity. Nevertheless, the broad qualitative insights from the study would remain unchanged. Second, we have not been able to capture the effects of the size of power plants fully; instead, we account for differences in financial risks and future technological advance between SMRs and large reactors that arise among other factors, because of difference in sizes. Future analyses could employ more detailed investment models that take into account the effects of size more explicitly. In addition, future analyses could explore the effects of learning and R&D by treating technological change endogenously. Third, we have assumed that nuclear technologies are available throughout the world at the same costs. Future studies must investigate the implications of regional differences in terms of availability of technology, technology costs, deployment capacities and investment risks. Finally, we have not taken into account, the risks associated with safety, waste-disposal, proliferation and terrorism which may affect rates of deployment, in ways that might be different for SMRs and large reactors.

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Appendix A: Uranium supply curves

The Global Change Assessment Model (GCAM), used for this study, employs a supply curve for natural uranium based on a generalized simple crustal model of the relationship between uranium abundance and concentration, fitted to the resource estimates and costs from the IAEA Redbook (IAEA, 2011; Kim and Edmonds, 2007; Schneider and Sailor, 2008). The crustal model is based on two assumptions. First, the cost of extracting a unit mass of uranium is a decreasing power-law function with ore grade from which it is obtained: $K/K_0 = (P_0/P)^{\beta}$, where K is the ore grade, P is the marginal cost of production, K_0 and P_0 are the reference grade and cost data points, and β is a parameter used to calibrate the model. Second, the relationship between ore grade and quantity mined (Q) is also a power-law function: $Q/Q_0 = (K_0/K)^{\alpha}$, where larger values of α imply that the mass of extractable uranium increases more rapidly as the grade decreases. The supply curve is thus given by: $Q/Q_0 = (P/P_0)^{\alpha\beta}$, where the product $\alpha\beta$ is similar to the price elasticity of supply. The value of α used for the GCAM supply curve is 2.5, which lies within the range of values used in literature (Schneider and Sailor, 2008). Data from the Red Book are then used to calculate the fit parameter β and also to calibrate the curve. The above modeling approach, however, has several shortcomings which can be related to the crustal model or the data used to calibrate the supply curve (Bunn et al., 2003; Kazimi et al., 2011; Schneider and Sailor, 2008):

i. *Shortcomings related to the crustal model:* The crustal model does not include economies of scale, which are an important driver in lowering commodity costs over time. Economies of scale are likely to reduce administrative and operational costs (Kazimi et al., 2011). In addition, the supply curve obtained by the above approach is based on current mining methods, not methods that may be available in the future when the resources are actually mined. The crustal model also does not include learning effects which could reduce costs considerably. In addition, in the above approach, the values of β obtained are less than one (Schneider and Sailor, 2008), which is implausible because the cost of extraction is highly unlikely to increase by a factor greater than the amount of ore mined and processed. In other words, if one must process ten times as much ore to extract 1 kg of product, the cost should not rise by more than a factor of ten. The fact that Red Book data imply $\beta < 1$ indicates that the resource estimates at high cost are too low.

ii. *Shortcomings related to the point used to calibrate the model:* The supply curve discussed above uses data from the Red Book for calibration. This involves several drawbacks. First, Red Book resource estimates are limited to regions where some uranium exploration has taken place and some estimates of mineral concentrations have been made. Because relatively little exploration has taken place over the last 30 years, actual resources are likely to be larger than the Red Book estimates. Second, because many countries do not report resources in high-cost categories, these resources are omitted from the total. Third, Red Book estimates include only conventional resources and do not include historical production.

In order to overcome the shortcomings related to the crustal model, we employ scale and learning parameters in the model, consistent with the MIT study on the nuclear fuel cycle (Kazimi et al., 2011). Kazimi et al. (2011) included scale and learning parameters to obtain the following modified supply curve: $Q/Q_0 = (P/P_0)^{1/\theta}$, where $\theta = n/\alpha\beta + ln(f)/ln(2)$, n is the scale parameter, and the learning parameter f is the factor by which the cost of production declines for each doubling of uranium produced ($f < 1$ indicates learning; $f = 1$ indicates no learning). Assuming $\beta = 1$, Kazimi et al. (2011) obtained bounding values for n, f and α from literature and conducted a Monte-Carlo analysis to generate a cumulative probability distribution function for θ. In this study, we use the values of θ corresponding to the 85%

confidence level, which is close to the value used in the “optimistic crustal” model (a non-probabilistic model) given in Schneider and Sailor (2008) and also by Bunn et al. (2003).

As noted above, the use of the Red Book resource estimates for calibration is problematic. We therefore use historical production data to calibrate the supply curve. We obtained global uranium production data for 1945-2003 from the Red Book Retrospective (OECD, 2006). Data for 2004-2011 is obtained from World Nuclear Association (WNA, 2013c) (Figure A.). As the largest consumer of uranium in the world, a good proxy for global uranium prices is the average uranium price paid by utilities in the US, adjusted for inflation. This data is obtained from the EIA (EIA, 2013b) (Figure A.). Note that price does not increase steadily with cumulative production as one might expect from above models, in which price is based on the depletion of high-grade resources and the need to exploit lower-grade, higher-cost resources. Indeed, figure A.2 shows that there have been wide swings in the prices of uranium, due to temporary imbalances between supply and demand and changes in future expectations about supply and demand. For calibration, we therefore use the production corresponding to the lowest price ($32/kg in 2001), at which cumulative uranium production was 2.1 Mt. This is the only point that is consistent with a model that assumes steadily increasing cost and price with cumulative production, due to depletion and increasing resource scarcity. This is evidence that large amounts of uranium could be produced at a marginal cost of less than $32/kg even after cumulative production of 2.1 Mt. One can reasonably assume that the future price will not fall below the minimum price observed in the last 40 years. We also assume that uranium markets are largely competitive, so that the market price is the long-run marginal cost plus a reasonable profit (Bunn et al., 2003). We therefore obtain the marginal cost of production as the market-determined price minus a profit margin (assumed to be 10%) and use this value for the calibration point. The modified supply curve thus obtained lies below the current supply curve, indicating that the cost of uranium is lower for a given cumulative production and more uranium is available at a given price (Figure A.).

With the new supply curve, the deployment of nuclear in GCAM is not affected considerably because natural uranium is a very small portion of the overall generation costs (Figure A.). This is consistent with the findings of Kim and Edmonds (2007), who found that alternative assumptions of uranium supply have little impact on the long-term development of nuclear energy; only an extremely pessimistic assumption about uranium availability affects the deployment of nuclear energy significantly. Nevertheless, we believe that this modification of the supply curve provides a higher-quality and more accurate input to GCAM calculations, and would certainly begin to influence deployment if nuclear capital costs drop dramatically over decades, as some advocates argue might be the case.

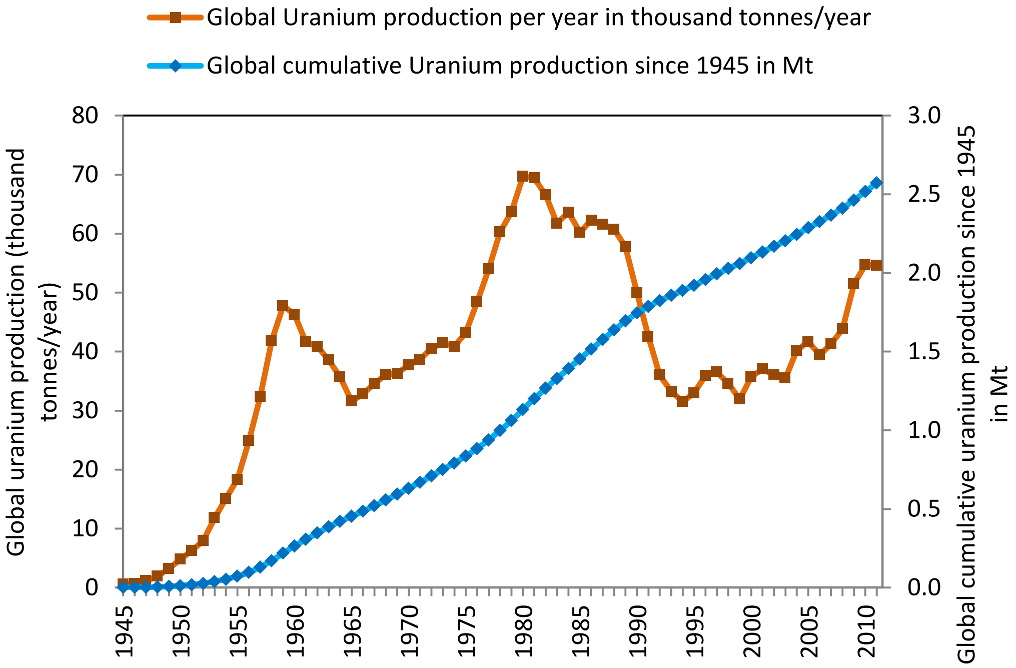

Figure A.1 Global uranium production

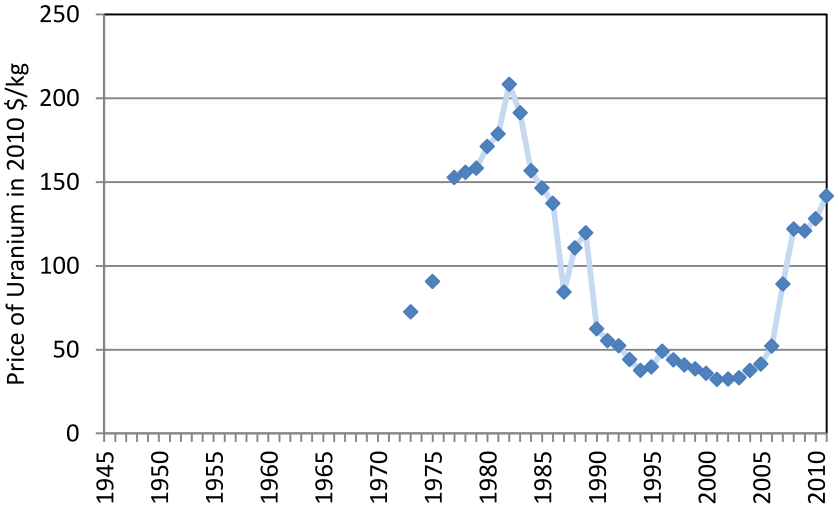

Figure A.2 Uranium prices paid by US utilities

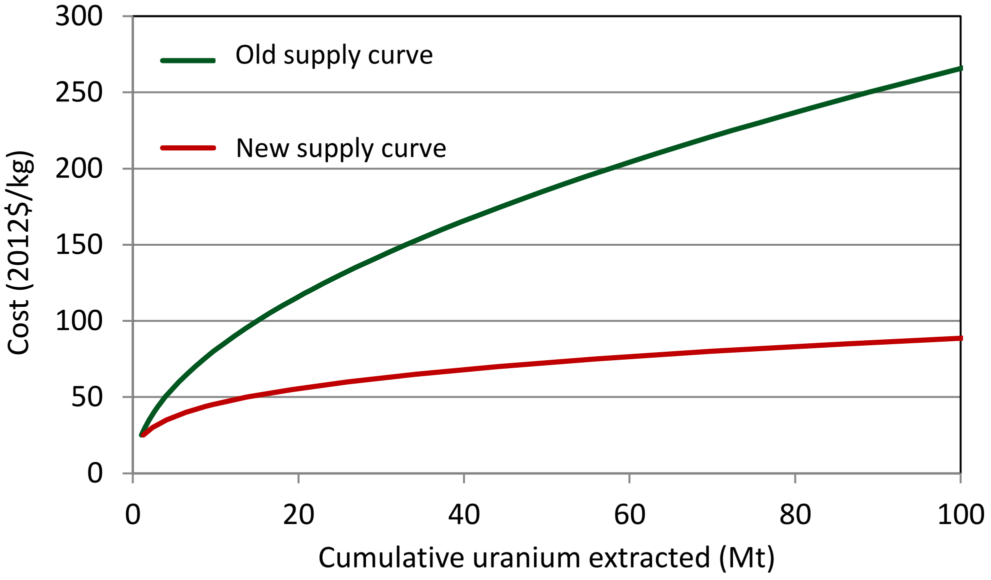

Figure A.3 Global Uranium supply curve used in GCAM

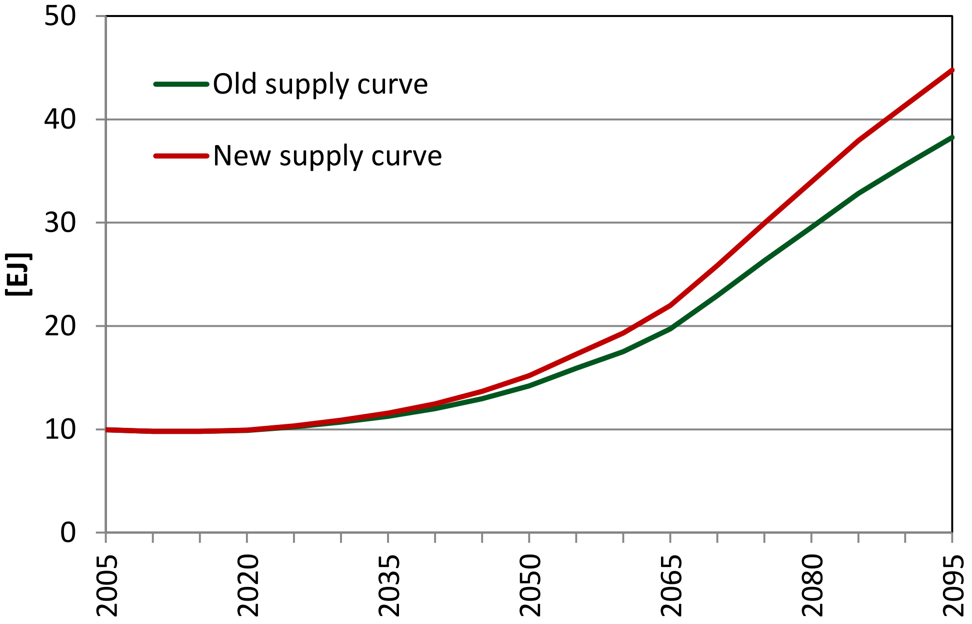

Figure A.4 Electricity generation from nuclear (under no climate policy) with old and modified uranium supply curves

Appendix B: Technology cost assumptions

Figure B-1 shows the comparison of overnight capital cost assumptions for nuclear technologies and other energy technologies. Operations and maintenance (O&M) costs and other assumptions vary by technology. For SMR and Gen III technologies, the fixed and variable O&M costs are assumed to be USD 94 per kW_e and USD 2 per MWh respectively. These assumptions are consistent with the Annual Energy Outlook (2013) (EIA, 2013a). Further, we assume that O&M costs remain constant with time. Although the literature is divided regarding cost reductions in O&M costs of nuclear power plants (see for example Lester and McCabe (1993) and Grübler (2010)), this assumption would not affect the outcomes of the analysis as capital costs account for a major portion of the cost structure of nuclear power plants (in per kW or per kWh terms). Fuel costs are calculated endogenously by the model on the basis of resource supply curves. Detailed descriptions of the assumptions are available in Clarke et al. (2008b).

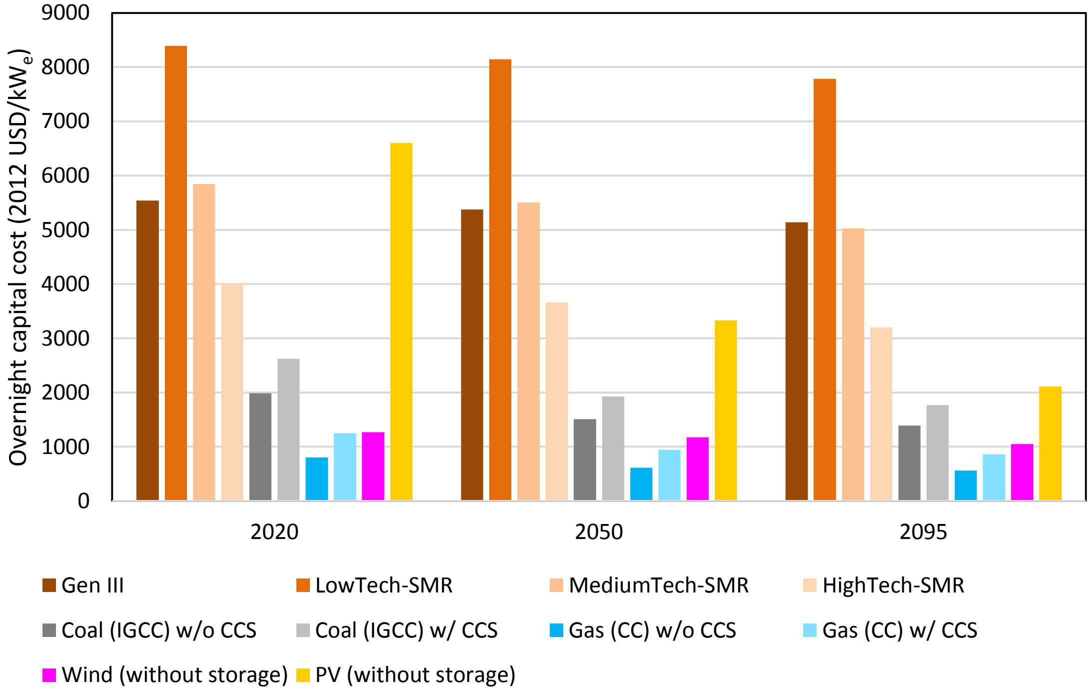

Figure B-1 Overnight capital costs assumptions for various electricity generation technologies in GCAM. This figure shows costs only for some of the technology options available in GCAM in order to avoid cluttering. The reader is referred to Clarke et al. (2008b) for more details.