Diffusion of low-carbon technologies and the feasibility of long-term climate targets[1]

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Abstract

Stabilizing the global climate will require large-scale global deployment of low-carbon technologies. Even in the presence of aggressive climate policies, however, the diffusion of such technologies may be limited by several institutional, behavioral, and social factors. In this paper, we review the literature on the sources of such diffusion constraints, and explore the potential implications of such constraints based on the GCAM integrated assessment model. Our analysis highlights that factors that limit technology deployment may have sizeable impacts on the feasibility and mitigation costs of achieving stringent stabilization targets. And such impacts are greatly amplified with major delays in serious climate policies. The results generally indicate that constraints on the expansions of CCS and renewables are more costly than those on nuclear or bioenergy, and jointly constraining these technologies leaves some scenarios infeasible.

1 Introduction

Stabilizing the global climate will require substantial reductions in greenhouse gas (GHG) emissions, especially CO_2, in all sectors of the global economy. This will in turn require dramatic reductions in fossil fuel use, enabled by increased efficiency and rapid and sustained global deployment of low-carbon technologies such as CO_2 capture and storage (CCS), nuclear, bioenergy and renewables (Clarke et al., 2007). Policy interventions are intended to affect not only the portfolio of new technologies that are deployed but also how rapidly and deeply they diffuse (Jaffe et al., 2003, 2005). However, the deployment of low-carbon technologies is influenced, sometimes strongly, by other factors, including institutional, behavioral, and social factors, which can distort deployment trajectories, even in the presence of ostensibly favorable climate change policies (Hultman et al., 2012). In addition to such factors, the deployment of low-carbon technologies is also likely to be hampered by the uncertainty in international policy response to climate change which imposes new constraints on the diffusion of low-carbon technologies.

Previous studies employing integrated assessment models (IAMs) to explore the role of low-carbon technologies have made simple assumptions regarding the availability of specific technologies. For example, some studies have prohibited the construction of new capacity for some technologies, such as renewables and nuclear, while others have completely excluded technologies (e.g., CCS) or capped their maximum deployment (e.g., bioenergy) (Edenhofer et al., 2010; Luderer et al., 2012; Richels et al., 2007; Tavoni et al., 2012). This paper contributes to the existing literature on limited technology availability by assessing the implications of expansion constraints that attempt to capture the drivers on the rate of technology up-scaling that are not well represented in IAMs. We also add a temporal dimension to the study by investigating the implications of constrained expansion when there are major delays in globally coordinated mitigation efforts to address climate change. Specifically, we seek to answer the following questions: i.) How much do constraints on the diffusion of low-carbon technologies impact the cost and feasibility of achieving long-term climate targets? and ii.) How do these impacts change in the presence of major delays in global mitigation action?

The remainder of the paper proceeds as follows. Section 2 provides a review of the factors that constrain the diffusion of low-carbon technologies. In Section 3, we review the historical diffusion rates of technologies in order to provide a background on the notion of “slow” and “fast” diffusion. In Section 4, we provide a description of the method and the scenario setting used in this study. Section 5 presents the results and findings of this study and Section 6 concludes with a summary of the findings and scope for future work.

2 Factors constraining the deployment of low-carbon technologies

An important common finding of several studies in the past is that accelerated technology development offers the potential to reduce costs of achieving stringent climate stabilization goals substantially (Clarke et al., 2008; Edenhofer et al., 2010; Luderer et al., 2012; McJeon et al., 2011; Richels et al., 2007). Although these studies vary in their approaches, they all assume that the final portfolio of technologies is dependent on relative prices. A direct inference of this assumption is therefore, that externality pricing and other pricing policies aimed at incentivizing the adoption of low-carbon technologies would induce profit-oriented firms to use low-carbon technologies and thus accelerate their diffusion. However, previous work has shown that while relative prices between energy technologies (and therefore, pricing policies) are influential in fostering a lower-carbon economy, they alone cannot fully account for the observed diffusion of technologies and that several other factors including institutional, behavioral, and social factors limit their actual adoption (Barreto and Kemp, 2008; Hultman et al., 2012; Jaffe et al., 2005; Kemp and Volpi, 2008; Montalvo, 2008; Weyant, 2011). In the context of low-carbon technologies, the factors that tend to influence diffusion rates of new technologies can be grouped under two categories. In the first category are factors that influence the growth of low-carbon technologies even in the presence of favorable climate change policy environments (such as a price on carbon or a cap-and-trade mechanism). Examples include increasing returns for incumbent technologies, slow response of capital markets to the needs of new technologies, lack of adequate institutional and governance structures and public perceptions and oppositions. The second set of factors is associated with the uncertainty involved in climate change policy. An example is the rational behavior of investors under such uncertainty.

2.1 Factors in the presence of favorable climate change policies

Several characteristics of the industry including the market structure and flow of information within the industry may constrain the diffusion of new technologies even in the presence of favorable climate policies. The value of a new technology to one user may depend on how many other users have adopted the technology. In general, new adopters will be better off the more other people use the same technology. This benefit associated with the overall scale of technology adoption is referred to as dynamic increasing returns (Jaffe et al., 2005). A new technology has to compete with existing substitutes that have already been able to undergo a process of increasing returns (Arthur, 1989). Diffusion of low-carbon technologies may be slowed down because it takes time for potential users to get information about the new technology, try it and adapt it to their circumstances, leading to slower generation of dynamic increasing returns (Jaffe et al., 2005). An important contributing factor to dynamic increasing returns is the existence of what is called “network externalities” (Jaffe et al., 2005).

Network externalities exist when the utility derived from a technology depends on the number of other users of the same or a compatible technology (Katz and Shapiro, 1986). Network externalities can be created by alliances and social networks between firms. Such networks influence the diffusion of new technologies greatly as these are important means for transfer of knowledge and spread of information, thereby stimulating mutual dependence between actors and reducing the risks of adoption of new technologies (Barreto and Kemp, 2008; Jacobsson and Johnson, 2000; Lin et al., 2009). Firms may therefore decide to delay adoption of a new technology until they have information about the experiences of other firms (Nelson, 1981). Jacobsson and Johnson (2000) identified that the expansion of new technologies is slowed down not only when firms are not well connected to other firms with an overlapping technology base but also when individual firms are guided by others (i.e., by the network) in the wrong direction and/or fail to supply one another with the required knowledge. In the case of energy technologies, network externalities are also produced by infrastructures. Infrastructures produce externalities that enable compatible technologies to diffuse faster than incompatible ones. (Grübler, 1997; Grübler et al., 1999). Inter-dependencies between individual technologies and long-lived infrastructures may also impede the development of new technologies which may require new infrastructures. For example, nuclear power benefits from an electricity transmission and distribution infrastructure that is already largely in place. On the other hand, the development of CCS, will require significant expansion of CO_2 transport infrastructure from the points of emission to underground storage sites (Brown et al.). Technological inter-dependencies also lead to considerable inertia in technological systems. For example, decisions made in the past may lead to technologies getting "locked in" to particular configurations because it is difficult to break out of them in a short period of time. Such co-evolution of technology clusters over time, also referred to as "path dependence" creates constraints for the large scale deployment of new technologies (Arthur, 1989; Grübler et al., 1999).

A new technology often requires a long period of nurturing and diffusion before it achieves a price/performance ratio that makes it attractive to larger segments in the market (Jacobsson and Johnson, 2000). Therefore, financial support, even on the long term may be required to ensure deployment of such technologies (Isoard and Soria, 2001; Mathews et al., 2010). This is especially true in the case of low-carbon technologies because of the intensive upfront capital cost requirement which is different from conventional fossil technologies, the cost structures of which rely more on fuel and operation costs (Brown et al., 2008). Previous work has shown that lack of adequate financial resources is an important problem for setting up low-carbon technologies such as renewable energy especially in developing countries (Jagadeesh, 2000). In addition, the venture capital market, which sometimes serves as an important source of capital for new and risky technologies, is more sensitive to factors beyond the needs of a new technological system. Moreover, in a small country, it may be difficult to find highly competent and willing venture capitalists domestically, necessitating the need to look for options in the international market and consequently, bring about changes in legislations affecting the functioning of capital markets (Carlsson and Jacobsson, 1997; Jacobsson and Johnson, 2000).

Diffusion rates are also influenced by how risk-averse stakeholders are about technology decisions and their preferences for a new technology (Isoard and Soria, 2001; Kemp and Volpi, 2008). In a case study of wind energy in Canada, Richards et al. (2012) (Richards et al., 2012) found that complacency and preference for status quo were important constraints to wind energy development. Lack of experience with new technology, and uncertainties related to regulations and various policies (such as taxes and subsidies) influence investors' valuations of risks. For example, Barradale (2010) (2010) demonstrated, on the basis of a survey of energy experts, that the boom-bust cycle observed in the investment in wind power in the U.S. is caused not by the underlying economics of wind but by the negotiation dynamics of power purchase agreements in the face of uncertainty regarding federal production tax credit.

Scholars have noted that public perceptions about the benefits and drawbacks of low-carbon technologies affect diffusion rates (Montalvo, 2008; West et al., 2010; Wüstenhagen et al., 2007). For example, Upreti (2004) observed that because the British general public are not much aware of the advantages of biomass energy, they often treat it as a dirty source of energy, creating problems for the development of bioenergy in the U.K.. Likewise, Pickett (2002) observed that although the Japanese government was resolute in its commitment to develop a closed nuclear fuel cycle, international security concerns over plutonium (which is one of the products of reprocessing) and increasing public opposition following a series of nuclear accidents delayed the actual adoption of the technology. Similarly, CCS might experience public opposition as a consequence of social concerns about injection and transportation (IEA, 2009; Lilliestam et al., 2012; Slagter and Wellenstein, 2011). Political and media support can also influence the diffusion rates of new technologies. In a case study of wind energy development in Canada, Richards et al. (2012) found that the government's lack of leadership on renewable energy emerged as an important constraint to the diffusion of wind energy. Likewise, Walker (2000) observed that technology lock-in effects got reinforced in the case of the Thermal Oxide Reprocessing Plant in the U.K. because the close nexus between industrial and political actors prevented markets and democratic processes from operating effectively. Along similar lines, Jacobsson and Lauber (2006) studied the diffusion of renewable energy in Germany and argued that establishment of some of the elements of an advocacy coalition by firms was an important driver in the initial period of technological development.

Previous work has also shown that lack of adequate institutional frameworks constrains the diffusion of low-carbon technologies such as renewables, especially in developing countries (Jagadeesh, 2000). In spite of the presence of conducive policy environments, government involvement and the type of governance may hinder the diffusion process. For example, Burer & Wustenhagen (2009) surveyed professionals from European and North American venture capital and private equity funds and found that although experienced investors consider conducive policy environments as an important way to encourage investment in low-carbon technologies, some investors were deeply skeptical about government involvement in any form. This view may be a factor that hampers their entry into new and emerging sectors.

Legislation may bias the choice of technology in favor of the incumbent technology (Jacobsson and Johnson, 2000). For example, Mitchell and Connor (2004) argued that the UK's New Electricity Trading Arrangements was "technology and fuel blind" and promoted incumbent technologies over renewables. Similarly, inadequate regulatory frameworks for nuclear waste management, reactor safety and risks of nuclear proliferation serve as important barriers for the diffusion of nuclear energy (van der Zwaan, 2002). Likewise, the absence of appropriate legal and regulatory frameworks for the transport and geological storage of CO_2 are likely to impede commercial deployment of CCS (Gibbins and Chalmers, 2008; IEA, 2009). Along similar lines, high intellectual property transaction costs, techniques such as patent warehousing and weak or nonexistent patent protection in developing countries are likely to impede the diffusion of low-carbon technologies (Brown et al., 2008).

Characteristics of the individual firms that adopt a new technology also affect its diffusion rate. Rose and Joskow (1990) found that large firms and investor-owned electric utilities are likely to adopt new technologies earlier than their smaller and publicly-owned counterparts. Likewise, Delmas and Montes-Sancho (2011) found that because investor-owned and publicly-owned utilities in the U.S. respond to different type of stakeholders and have different capabilities, investor-owned electric utilities respond more to the implementation of policies such as renewable portfolio standards than do publicly-owned utilities. Scholars have also emphasized that the adoption of low-carbon technologies by a firm depends on its physical capacity to adopt the technology and the timing of investments with respect to other business cycles (Kemp and Volpi, 2008; Montalvo, 2008; Nelson, 1981).

Apart from the above, specific low-carbon technologies face special constraints that might hinder their adoption. For example, successful implementation of renewable technologies such as wind and solar depend on the availability of natural capital, defined by Daly (1996) as "the stock that yields the flow of natural resources". Russo (2003) also argued that natural capital such as wind and solar are geographic site specific i.e. it is difficult to move the capital around. Additionally, Sovacool (2009) (Sovacool, 2009) observed that according to various stakeholders, intermittency, forecasting complexity, need for backup electricity, and the distance of generating sources from the grid act as serious obstacles to the wide deployment of renewables in the United States. Technical barriers such as high energy penalty and the consequences of injection under high pressure (e.g. phase change of CO_2 during injection) impose special constraints on the deployment of CCS (Slagter and Wellenstein, 2011).

2.2 Factors due to uncertainty in climate change policy

In the context of climate change, there are large uncertainties surrounding future impacts of climate change, the time and magnitude of policy response, and thus the likely returns to R&D investment (Jaffe et al., 2005). International negotiations are moving slowly and may prove inadequate over the next several decades (Jakob et al., 2012; Weyant, 2011). Unless externalities from conventional electricity production are internalized, price distortion will be an important obstacle for the diffusion of low-carbon technologies (Jaffe et al., 2002; Jaffe and Stavins, 1995). Uncertainty in climate change policy creates uncertainty in the price of carbon and thus affects the valuations of the costs of externalities. This creates several barriers to the diffusion of low-carbon technologies as explained below.

Uncertainty in the price of carbon induces an "option value" of postponing the adoption of new technology 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 an 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 the 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). The adoption is likely to be delayed even further if the firm has optimistic expectations regarding technological improvements or price reductions (Stoneman and Diederen, 1994).

Uncertainty in climate policy also contributes to the valuations of risk by investors. High discount rates, and the resulting under-valuing of long term benefits of high political and capital investments in environmental reform are likely to discourage necessary investments to advance alternative options (Jaffe et al., 2005; Jaffe and Stavins, 1995). For example, Fuss et al. (2012) showed that several uncertainties including those related to climate sensitivity, international commitments to specific targets and the stability of CO_2 prices impact the behavior of risk-averse and risk-neutral investors.

Combinations of the factors outlined above serve to slow down the diffusion of new technologies. The multi-level perspective on technological transitions can be used to understand how these different factors influence the overall technological transformation process and in particular, technology diffusion. According to this framework, technological transitions take place in a “socio-technical landscape” where the factors such as those outlined above bring about changes in user practices, regulation, industrial networks, infrastructure, symbolic meanings, etc. These changes create pressure on the linkages between social groups (known as the “socio-technical regime”) that enable radical novelties – that are not affected by market forces– to create new linkages at the regime as well as the landscape levels. These changes usually take place slowly and tend to slow down the overall transition process (Geels, 2002; Geels and Schot, 2007; Rip and Kemp, 1998).

In the following section, we compile historical diffusion rates of various technologies to provide a background on the notion of “slow” and “fast” diffusion.

3 Historical diffusion rates of energy technologies

It is useful to study historical dynamics of technologies in the energy sector to understand the notion of “slow” and “fast” diffusion. Kramer and Haigh (2009) postulated two laws for transitions in the global energy sector based on the growth of energy technologies in the twentieth century. First, when technologies are new, they go through a few decades of exponential growth with an average growth rate of 26% per annum until the technology “materializes” i.e. it becomes around 1% of world energy. Second, once the technologies “materialize”, growth changes to linear as the technology settles at a market share. At the outset, it is important to clarify that historical technological transitions may not provide sufficient guidance on how technologies will evolve in the future. As noted by Fouquet and Pearson (2006), using past trends to anticipate future developments is risky: it may be appropriate, if we are in a period of technological lock-ins, or erroneous, if new technologies, fuels, networks and policies are likely to develop. In this paper, we review historical growth rates only to provide reference points for “slow” and “fast” diffusion.

A number of studies in the past have investigated the historical growth of technologies and dynamics of technological transitions in the energy system (Fouquet and Pearson, 2006; Grübler et al., 1999; Hook et al., 2012; Wilson and Grübler, 2011; Wilson et al., 2012). We compile the growth rates for different technological transformations from these studies in Table 1. These studies have used two types of metrics to analyze the dynamics of growth. In the first metric used by Hook et al. (2012), growth is defined as the percentage change from one point in time to the next. They showed that the annual growth rate of a technology is inversely proportional to the size of the output. In the second metric used by Grübler et al. (1999), Wilson et al. (2012) and Wilson and Grübler (2011), historical growths of technologies are modeled as logistic (S-shaped) growth functions. These studies assume the following typology of diffusion. Once a new technology is developed and demonstrated, it is introduced in niche markets where it has substantial performance advantages over existing technologies. During this phase, the technology achieves commercial market shares up to 5%. This is followed by extensive use in a wider array of markets, known as "pervasive diffusion" wherein market shares rise rapidly before they saturate when these markets are exhausted (Grübler et al., 1999). The time Δt required for the technologies to grow from 10% to 90% of the market is then used to describe the development of technologies over time. In the current study, we use the first metric (the one used by (Hook et al., 2012)) as it enables me to specify future growth trajectories in terms of various annual growth percentages from existing levels of output. In order to express the findings of Grübler et al. (1999), Wilson et al. (2012) and Wilson and Grübler (2011) in terms of annual percentage growth, we assume that the growths of technologies during the period when their outputs are between 10% and 90% of the asymptotes of the S-curves are linear (in line with the second "law" of the growth of energy technologies postulated by Kramer and Haigh (2009)). Using the mathematical definition of growth rate provided by (Hook et al., 2012), the average annual growth rate in percentage during this period can be shown to be equal to $219.7/\Delta t$.

A look at the historical diffusion rates compiled in Table 1 shows that most technological transitions have happened at low rates[2]. Fossil fuel energy has grown at less than 10% per year while hydropower and biomass energy have grown at even lower rates. Energy intensive technologies such as railways and aircrafts have grown at around 4% per year. In addition to the technologies reviewed in Table 1, Wilson and Grübler (2011) studied the patterns and characteristics of two important energy transitions since the Industrial Revolution namely, the emergence of steam power relying on coal and the displacement of the previously dominating coal-based steam technology by electricity. They found that it takes 8 to13 decades for new energy technology clusters to achieve market dominance at the global scale; corresponding to an average annual growth of only 2-3% per year. If the entire technology life cycle from first introduction to market maturity is considered, it takes about twice as long.

In contrast, environmental pollution control technologies such as flue gas desulfurization (FGD) systems have grown at faster rates. The development of such technologies is different because the market stimulated by government regulation was primarily responsible for their widespread diffusion. For example, in the 1970s, the stringency of the New Source Performance Standards, the limited availability of low-sulfur coal, and the tight deadline for attainment of primary SO_2 emissions standards provided an important incentive for the development of FGD technology in the U.S (Taylor et al., 2005). These systems have grown at roughly 15% per year.

[2] Note that these growth rates are long term averages – they indicate, in most cases, the average growth rates at which technologies grew from 10% to 90% of their market shares.

Table 1Historical growth rates of various technologies surveyed in literature

Range of annual growth rate	Technology transitions	Regional scope	Average annual growth rate
≤ 5%	**Bioenergy** [64]	Global	2%
	Coal (as a substitute for traditional energy) [23]	Global	2%
	Coal (as a substitute for traditional energy) [23]	USA	3%
	Open-heart steelmaking [23]	Global	3%
	Cars [63]	Global	3%
	Railways [23]	Global	4%
	Aircrafts [63]	Global	4%
	Steam (as a substitute for sailships) [23]	Global	4%
	Open-heart steelmaking [23]	USA	4%
	Railways [23]	France	5%
	Electrification of homes [23]	USA	5%
	Coal power [63]	Global	5%
6-10%	**Oil refineries** [63]	Global	6%
	Oil energy [64]	Global	7%
	Natural gas power [63]	Global	7%
	Hydropower [64]	Global	<8%
	Mechanization in coal mining [23]	Russia	8%
	Railway track electrification [23]	Russia	8%
	Air in intercity travel (as a substitute for rail) [23]	USA	8%
	Chemical preservation of railway ties [23]	USA	8%
	Percentage of households with radio [23]	USA	9%
	Basic oxygen furnace [23]	Global	9%
	Coal and Gas energy [64]	Global	5-10%
11-15%	**Basic oxygen steel furnace** [23]	USA	11%
	Nuclear energy [63]	Global	11%
	Air conditioners in homes [23]	Japan	12%
	Car air conditioners [23]	USA	12%
	Automobiles (as a substitute for carriages) [23]	UK	14%
	Cars (as a substitute for horses) [23]	UK and France	14%
	Cars (as a substitute for horses) [23]	France	15%
	Transistors in radios (as a substitute for vacuum tubes) [23]	USA	15%
	Black and white TV (as a substitute for color TV) [23]	USA	15%
	Flue gas Desulfurization [66]	USA	15%
	Compact fluorescent lamps [63]	Japan	15%
15%	**Cars (as a substitute for horses)** [23]	USA	18%
	Locomotives [23]	USA, Russia and UK	18%
	Wind energy [63]	Denmark	20%
	Washing detergent (as a substitute for soap) [23]	USA	24%

In subsequent analyses, we specify low, medium and high growth rate constraints (consistent with the above review) on the expansions of low-carbon technologies.

4 Methodology

4.1 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. 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). 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. A detailed description of how the energy system is represented in GCAM is available in (Clarke et al., 2008). In this study, we employ a version of GCAM that imposes explicit expansion constraints on top of the current technology choice framework.

4.2 Scenario setting

To help answer our questions, we explore a number of scenarios. Scenario analysis is a well-established analytical tool to investigate complex interrelationships of a large numbers of variables and for making decisions under uncertainty (Clarke et al., 2008). It is important to note that scenarios are not predictions; rather, they are sketches of alternative future conditions. Scenario analysis has been used extensively in the climate change context, for e.g. studies of the Energy Modeling Forum (Clarke et al., 2009).

In this study, scenarios vary across four dimensions: the climate target, technologies that are constrained, expansion rates for the constrained technologies and the length of delays in globally coordinated mitigation action. we impose two long-term climate targets corresponding to 450 and 550 ppm CO_2e by the end of the century. These targets are associated with limiting global mean temperature rise to less than 2°C and 3°C respectively, targets 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). Expansion constraints are specified for major low-carbon technologies—nuclear, CCS, renewables (solar and wind) and bioenergy in the electricity sector.[3] These low-carbon technologies still need to be economical relative to other technologies, but the diffusion constraints limit how quickly they enter the energy system. The expansions of these technologies are constrained individually as well as in unison (renewables and bioenergy; nuclear and CCS; nuclear, CCS, renewables and bioenergy). Constraints on the diffusion of the low-carbon technologies are represented as fixed annual rates of growth of net technology deployment. While constraints on the expansions of nuclear, CCS and renewables are imposed at the regional level, those for bioenergy are specified at the global level. We specify three levels of growth rate constraints at 5% (low), 10% (medium), and 15% (high) per year. The review of diffusion rates in Table 1 can be used as reference points to help understand how to think of these numbers. For instance, the low expansion rate of 5% per year is similar to the historical growth rates of coal power (1959-1999) and oil refineries (1950-1984) (Wilson et al., 2012). Likewise, the medium expansion rate of 10% per year is comparable to the historical growths of nuclear energy (1974-1992). And finally the high growth rate constraint of 15% per year is close to the historical growths of CFLs (1994-2003) and FGD systems (1978-2000) (Taylor et al., 2005; Wilson et al., 2012). Finally, we consider delays of 0, 10, 20 and 30 years from 2020. Thus, globally coordinated mitigation action (i.e. the first year in which a carbon price is introduced in the model) is assumed to begin from 2020, 2030, 2040 and 2050. The delayed scenarios follow the baseline until the year in which mitigation begins. Combinations of these variables give rise to a total of 176 scenarios (see Table 2 for the scenario layout).

5 Results and discussion

5.1 Pathways toward 450 and 550ppm CO_2e without explicit constraints on technology expansion

Without constraints on the deployment of low-carbon technologies, CO_2 emissions pathways achieving 450 and 550 ppm targets peak around 2035 and 2040, respectively, and start to decline, exhibiting substantial negative emissions by the end of the century (Figure 1 a). Delays in policy action extend the period of growing CO_2 emissions, followed by more drastic emissions reduction, eventually generating greater negative emissions by the end of the century compared to the case without delays. Nevertheless, a large part of the catch-up in emissions reductions after the delays takes place within about 10 years as the deployment of low-carbon technologies are not constrained. The relative degrees of mitigation effort can be seen in terms of carbon price paths, which rise exponentially following the

[3] In this paper, we restrict the analysis to supply-side electricity generation technologies.

Hotelling-Peck-Wan rule (Peck and Wan, 1996). The 450 ppm target demands higher carbon price than the 550 ppm target (Figure 1b). The rapid catch-up in emissions reductions with delays lead to increases in carbon prices as soon as the policy regime starts.

Table 2 Feasibility of achieving targets under constraints on the expansion of low-carbon technologies and delays in policy action[a]

		550 ppm CO_2e target				450 ppm CO_2e target			
Technologies constrained	Nature of expansion rate	No delay	10 year delay	20 year delay	30 year delay	No delay	10 year delay	20 year delay	30 year delay
None	-	48	49	52	56	71	74	78	88
Bioenergy	High	48	49	52	57	71	74	78	88
	Medium	48	49	53	57	72	75	80	89
	Low	48	50	54	58	73	75	80	90
Nuclear	High	48	50	53	58	71	75	80	89
	Medium	49	50	53	58	71	75	80	89
	Low	50	50	55	59	73	77	83	91
CCS	High	48	49	53	58	73	76	80	91
	Medium	49	50	54	59	76	79	83	95
	Low	55	56	58	64	85	88	93	X
Renewables	High	49	51	53	59	74	76	83	90
	Medium	50	52	55	61	75	79	83	92
	Low	52	53	57	61	76	79	85	X
Renewables and Bioenergy	High	49	51	54	59	74	78	83	91
	Medium	51	52	56	61	75	79	83	92
	Low	51	53	57	61	76	79	85	X
Nuclear and CCS	High	48	50	53	58	73	76	82	91
	Medium	49	50	54	61	77	79	X	X
	Low	57	59	62	67	90	X	X	X
Nuclear, CCS, renewables and bioenergy	High	50	51	54	59	74	78	83	91
	Medium	53	55	59	65	83	X	X	X
	Low	67	70	X	X	X	X	X	X

[a] Values in the table are CO_2 prices in 2050 in 2010 USD/tCO_2. Shaded cells with an 'X' indicate infeasible scenarios.

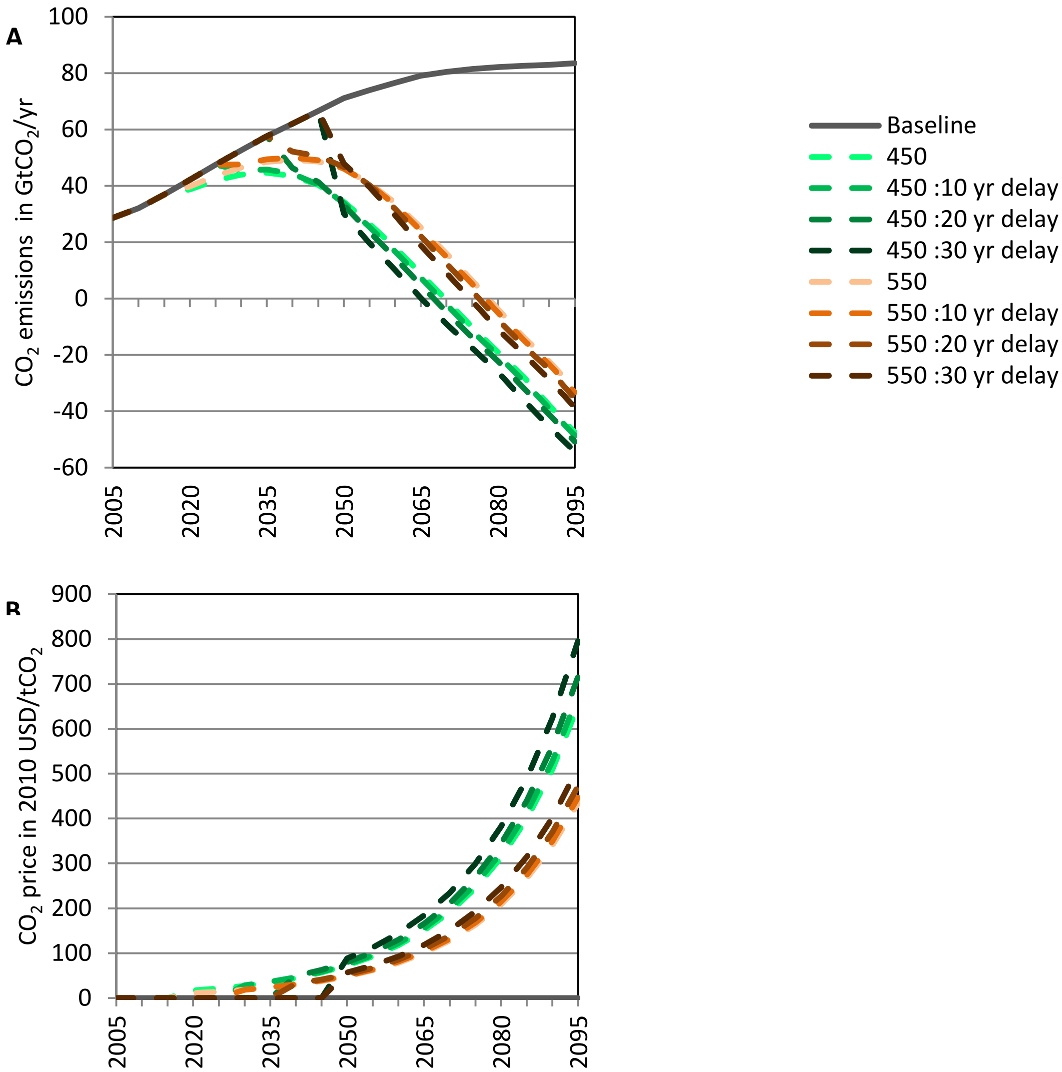

Figure 1a.) Fossil fuel and industry emissions and b.) CO2 prices in scenarios under unconstrained expansion of low-carbon technologies

Due to higher carbon prices, the net present value (NPV) of mitigation costs (throughout this paper, we assume a discount rate of 5%) of stabilizing the climate increases with the number of years of delay in climate policies, although the impact is not particularly large (Figure 2)[4]. In addition, delayed action requires faster emissions reductions after the peak, as manifested by the drastic transformation of the

[4] 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.)

energy system within a short period of time, which is costly. This is consistent with findings of previous studies on the effects of delayed action (Bosetti et al., 2009; Calvin et al., 2009; Jakob et al., 2012). A delay of 30 years increases the mitigation costs for 450 ppm and 550 ppm targets by 18% and 15% respectively. Note also that the mitigation costs of stabilizing the climate increase with the year of delay in a convex manner, and the convexity is greater for 450 ppm targets. That is, delays in climate policies require increasingly rapid transitions when the policy regime is strengthened, and the required transitions become even more rapid for a more stringent climate stabilization target.

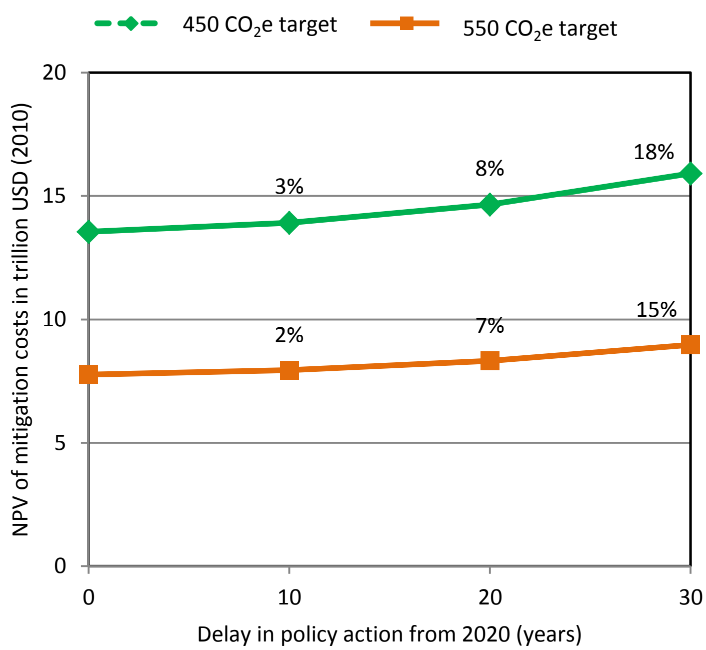

Figure 2 NPV of mitigation costs under unconstrained expansion but with delays in policy action. The numbers above each data point show the percentage increase with respect to the no delay case.

The general behavior of modest near-term mitigation followed by drastic longer-term mitigation mainly originates from the presence of low-carbon technologies, such as renewables, nuclear, and most importantly, bioenergy in combination with CCS technologies (bio-CCS), which are deployed on a large scale over the second half of the century. This is especially true in the presence of delays in policy action (Figure 3). In particular, 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.

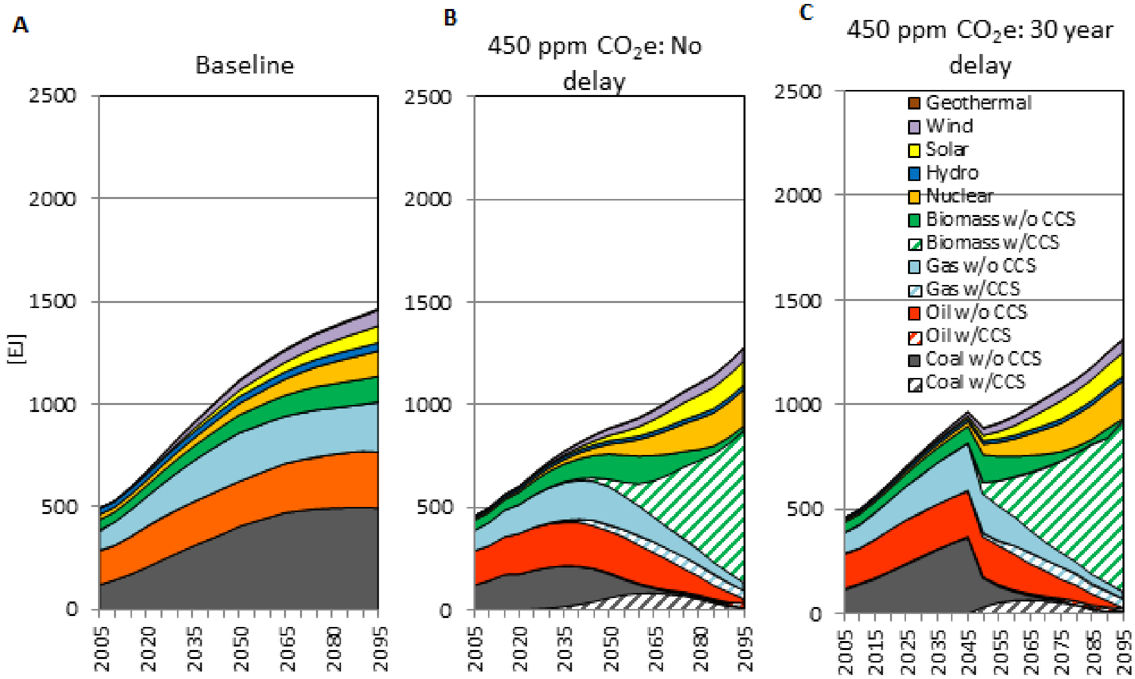

Figure 3Primary energy by fuel under unconstrained expansion of low-carbon technologies

The scenarios without explicit technology expansion constraints indicate that the low, medium and high growth rate constraints (5%, 10% and 15% per year) that are imposed on the low-carbon technologies may or may not be binding (Figure 4). Without any delays, nuclear power and bioenergy expansion rates are modest, and hence the constraints would be only binding in brief periods of time. This is because nuclear power is relatively mature in its stage of development and bioenergy supply is limited by land use competition with crop lands and forest that becomes increasingly intense under a carbon price regime. By contrast, the constraints would limit the expansion of relatively new technologies, such as renewables and CCS, mostly during the first half of the century. In all scenarios, for example, the up-scaling of wind power would be limited by both the medium (10% per year) and the low constraints (5% per year) until the middle of the century, but not by the high constraint (15% per year) throughout the century. Solar power shows rapid near-term expansion, making even the high constraint (15% per year) binding through 2025, followed by a continued decrease in its expansion rate, leaving even the low constraint (5% per year) non-binding beyond 2060. Similarly, CCS technology, after its introduction as early as in 2020, expands very rapidly through 2025 (much greater than 15% per year), followed by a continued decrease in expansion rate with less than 5% growth after 2065. The decreasing diffusion rates can be explained by the increasing size of technology deployment (see (Hook et al., 2012), who derive the inverse relationship between growth rate and system size) offset by increasing market competition.

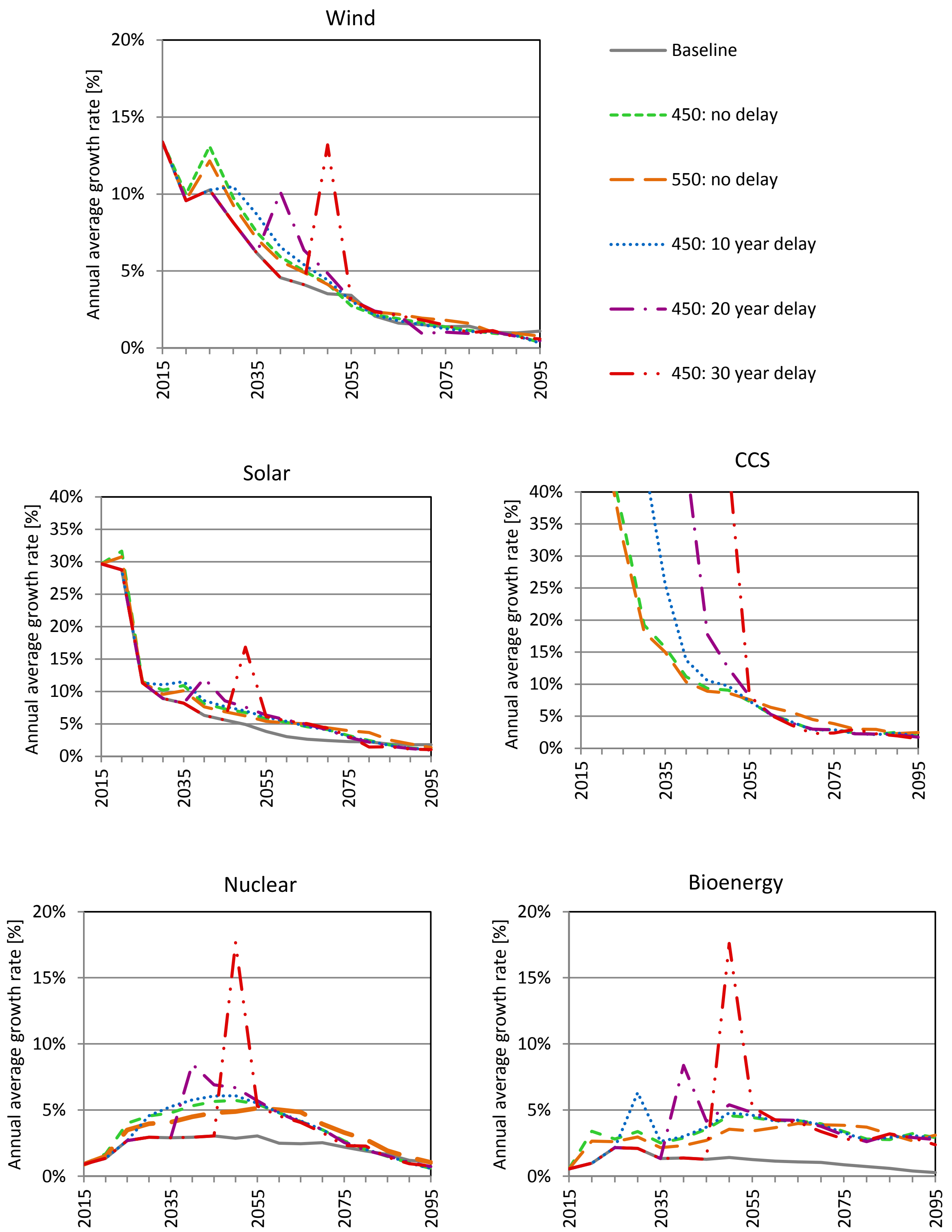

Figure 4Annual growth rates of low-carbon technologies under different long-term stabilization (450 ppm with and without delays in policy action and 550 ppm without delays) under unconstrained expansion of low-carbon technologies.

With delays in climate policy action and no expansion constraints, low-carbon technologies grow at the same rates as the baseline case until the globally harmonized carbon price is imposed (Figure 4). In this year these technologies are introduced on a large scale, exhibiting major spikes in expansion rates. Interestingly, the accelerated deployment due to delays in policy action spans over the 5-10 year time frame. The varying degrees to which expansion constraints limit the deployment of low-carbon technologies may translate into varying opportunity costs of having barriers to technology diffusion with or without delays in policy action. These interesting dynamics will be discussed in the next section.

5.2 The effect of expansion constraints

Constraints on the expansions of all low-carbon technologies considered in this study have the effect of postponing mitigation; resulting in slower introduction of renewables and CCS until the mid-century and faster deployment of bio-CCS and nuclear power thereafter (Figure 5). In the first half of the century, expansion constraints limit the optimal deployment of renewables and CCS technologies. During this period, the reduction in energy demand is compensated for by the growth of conventional fossil fuel and bioenergy, which remain non-binding. In the latter half of the century, however, as the expansion constraints are no longer binding in most regions, CCS technologies are rapidly installed for the production of electricity from biomass, the expansion of which has remained unconstrained anyway. The residual energy demand is fulfilled by faster up-scaling of nuclear power, which is cheaper to be integrated to the system than renewables. Consequently, with expansion constraints in place, the mid-century transformation in the energy system becomes much more pronounced than the unconstrained case, as indicated by the temporary reduction in energy demand. This would necessarily result in higher carbon price and mitigation costs compared to the case without the constraints.

In a broader sense, whether or not low-carbon technologies are available on a large scale at the right timing will influence the efficient pathway of emissions mitigation, raising the level of carbon price to be imposed on the emissions from fossil fuel and industry. Constraining the deployment of low-carbon technologies that would play a major role in the mid-century, for example renewables, would delay emissions mitigation (as shown by the lower emissions in the long term compared to the unconstrained case in Figure 6 (a)). In this case, greater and cheaper mitigation can be done later in the century using bio-CCS (Figure 6 (b)). Similarly, if the low-carbon technologies that would play an important role in the long term are severely limited, for example CCS (which would constrain the deployment of bio-CCS), greater mitigation in the near term would be required (as shown by the lower emissions in the near term compared to the unconstrained case in Figure 6 (a)).

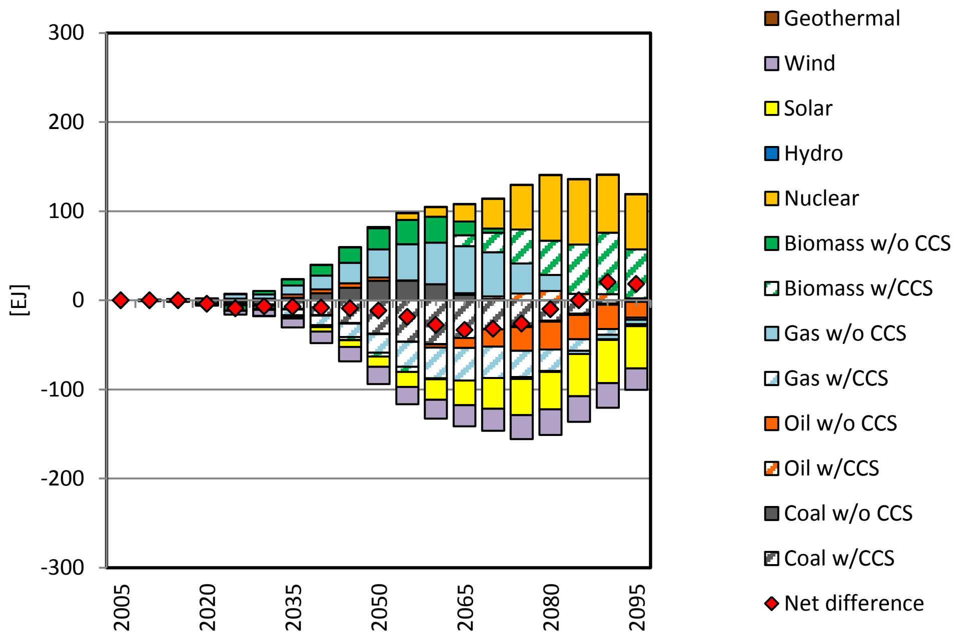

Figure 5Change in primary energy consumption by fuel for the 450 ppm target with constraints on the expansion of nuclear, bioenergy, renewables and CCS at medium rates (10% per year), without delay in policy action, relative to the case without expansion constraints

The departure from the optimal schedule of technology deployment due to factors that constrain their diffusion indeed has the effect of raising mitigation costs (Figure 7). The cost of limited technology diffusion varies substantially across the type of technologies that are constrained and the availability of technology substitutes that could be deployed on a larger scale. Expansion constraints on CCS and renewables have the largest impact. This is because, if not constrained, these technologies would have the greatest potential to contribute to the de-carbonization of the global energy system with rapid up-scaling, particularly before the mid-century. Expansion constraints on bioenergy and nuclear power are not as expensive because they remain largely nonbinding throughout the century in most regions. In addition, the responsiveness of mitigation costs to expansion rates varies across the type of technologies that are constrained. For example, the costs of achieving the 450 ppm target with the low expansion rate constraint (5% per year) for CCS or renewables are 16% and 13% higher, respectively, than the cases with the high expansion rate constraint (15% per year). In comparison, the cost of achieving the same target with the low expansion rate for nuclear power is only 3% higher. The relatively higher cost increase in the case with constrained CCS is due to the decreased opportunity of negative emissions from bio-CCS in the second half of the century, requiring more drastic, immediate mitigation action in the near term, which is costly. When nuclear power and CCS are jointly constrained, the mitigation cost with the low expansion rate is 28% higher than the case with the high rate, as these technologies no longer serve as substitutes. Note that expansion constraints themselves could have impacts on the mitigation cost as large as several decades of delays in mitigation action (Figure 2).

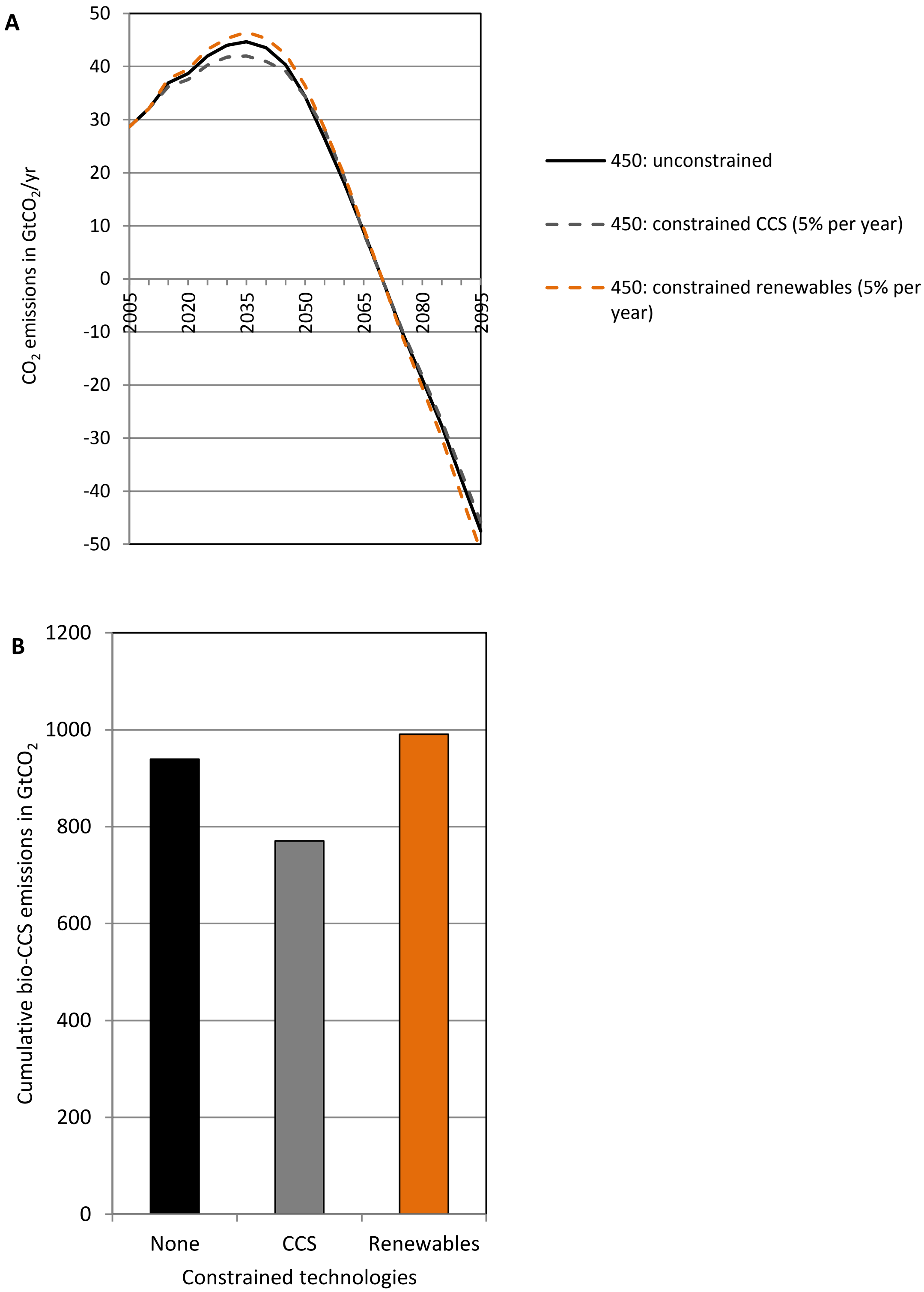

Figure 6 a.) CO2emissions pathways and b.) Cumulative CO2 removal (2020-2095) based on bio-CCS under constrained expansions of CCS and renewables

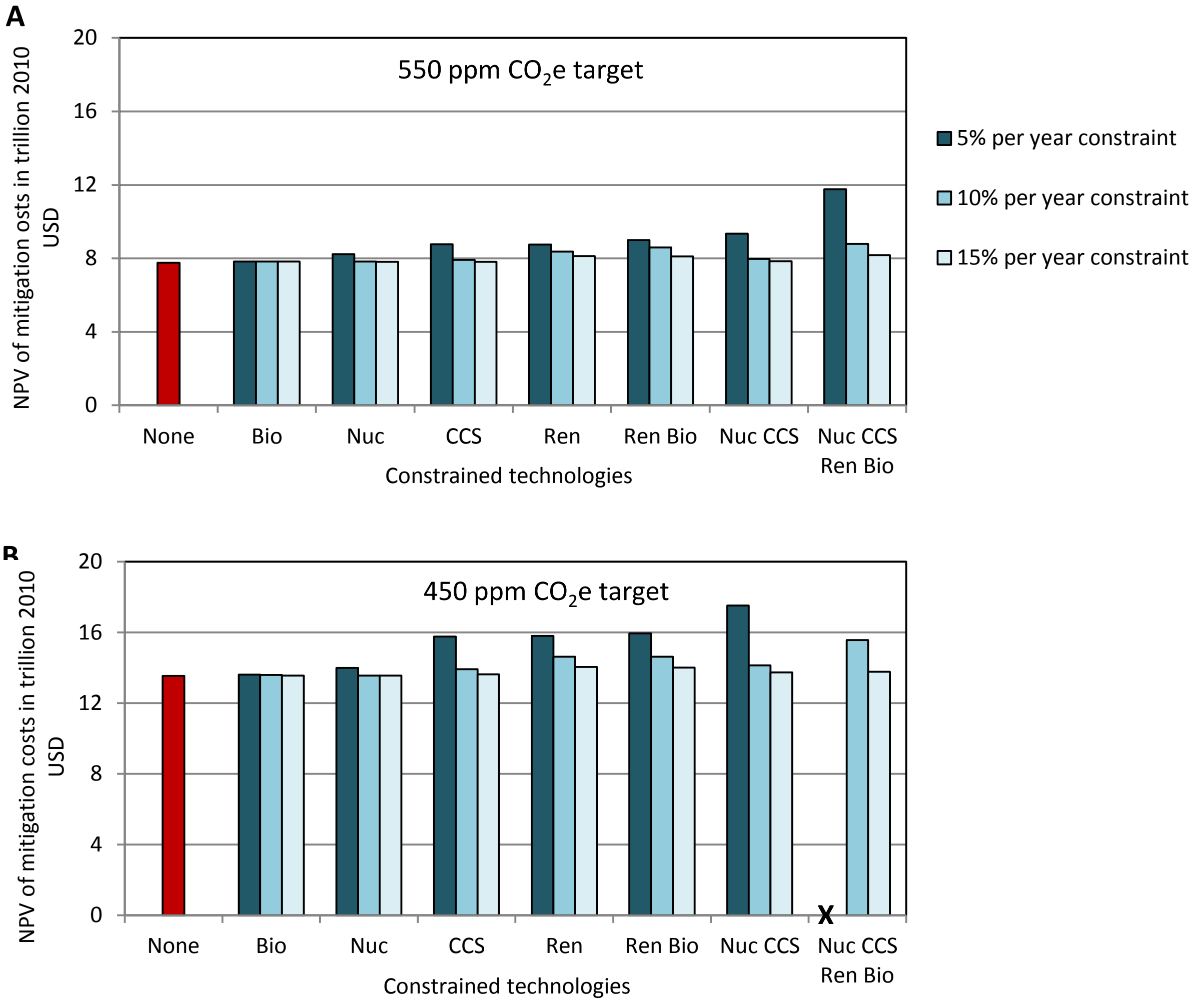

Figure 7NPV of 2020-2095 mitigation costs under expansion constraints on low-carbon technologies and no delay in action for a.) 550 ppm CO2e target and b.) 450 CO2e target An "X" indicates an infeasible scenario.

The upscalability of the global energy system also influences feasibilities. Both the stabilization targets can be achieved even when the deployments of nuclear and CCS or renewables and bioenergy are jointly constrained at any level. When all of the technologies are constrained at the 5% per year rate, however, achieving the 450 ppm target becomes infeasible. Infeasibility can be thought of as excessively high mitigation costs, where a large part of the mitigation needs to come from immediate and drastic reductions in energy demand rather than from supply-side transformation.

5.3 The effect of expansion constraints with delayed action

Delays in policy action mean that the transition to a low-carbon energy system must be more rapid once climate policy comes into play. As a result, larger diffusion rates will be required and one would expect to see higher mitigation costs and even infeasibilities with diffusion constraints on top of delays. Delays in policy action in addition to expansion constraints exaggerate the dynamics observed earlier once the policy regime is strengthened. For example, when all low-carbon technologies are constrained at high rates (15% per year) along with a delay in policy action of 30 years, the energy system becomes more carbon intensive (more emitting sources and less renewable sources) than the unconstrained case through the year 2050 in which a price on carbon is first applied (Figure 8(a)). During this period, energy consumption becomes higher than the unconstrained case due to lower energy prices. Beyond 2050, however, there is drastic retirement of conventional fossil fuel energy over a very short period of time. Also, as the expansion constraints in this scenario are mostly non-binding, immediate ramp-up of bio-CCS (aided by a high price on carbon) and accelerated nuclear power expansion help in achieving the climate target. In addition, because of the largely non-binding constraints, most of the changes described above occur because of the delay (Figure 8 (b)).

Mitigation costs increase convexly with number of years of delay in policy action as in the case without expansion constraints (Figures 2 & 9). However, the relative increase of costs with delay (in other words, the responsiveness of the costs to delays in policy action) increases in the scenarios with expansion constraints. For example, in the unconstrained case, a delay of 30 years increases the mitigation cost of achieving the 550 ppm target by 15% (Figure 2). In contrast, when the expansions of bioenergy, nuclear, or renewables are constrained at the medium growth rate, a delay of 30 years increases the mitigation costs by 14-18%. Likewise, under the same climate target, when the expansions of CCS technologies are constrained at medium rates, a 30-year delay increases the mitigation cost by as much as 25%. This is because the large-scale availability of low-carbon technologies matters more when the time window for serious action is compressed.

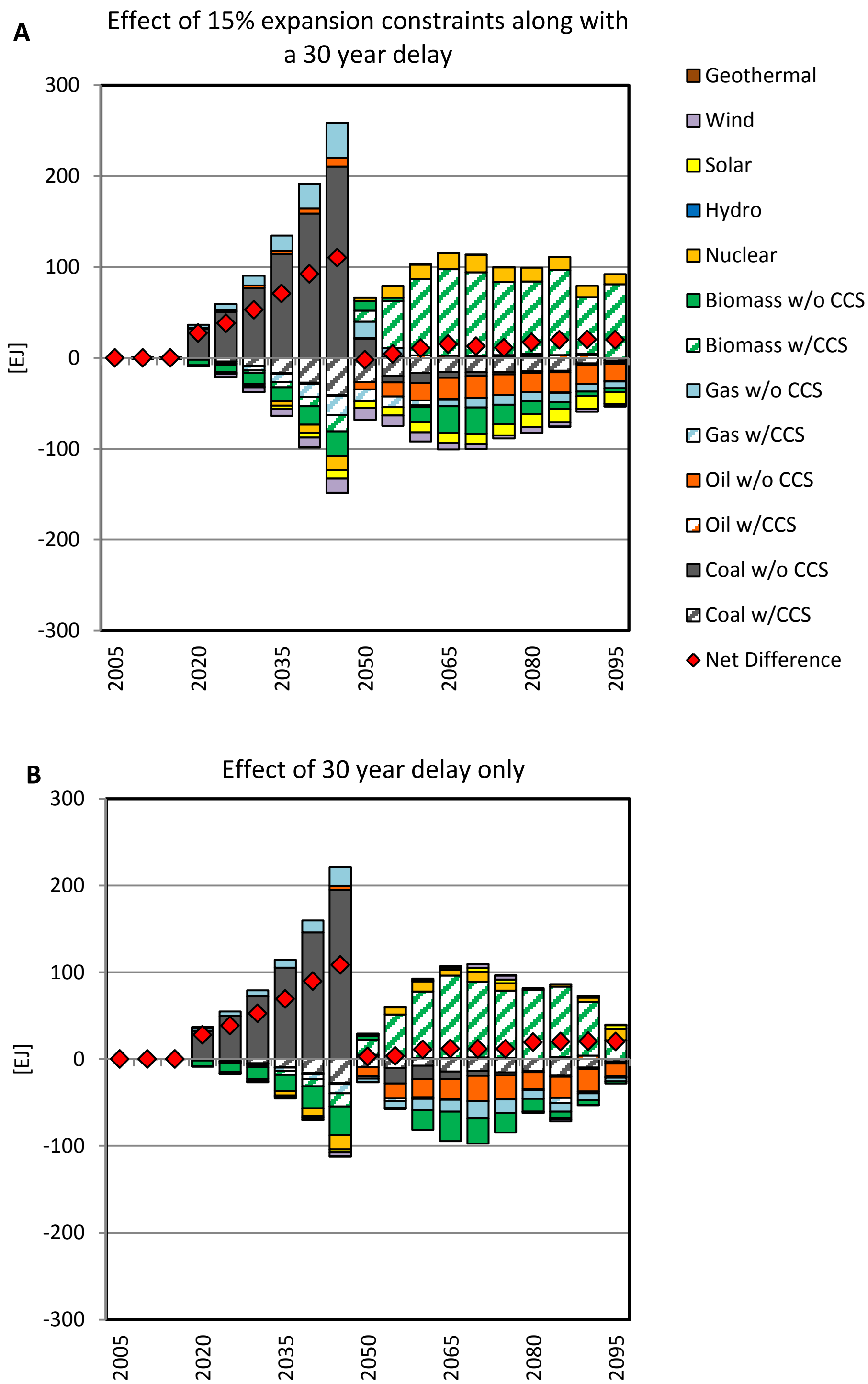

Figure 8Change in primary energy consumption by fuel for a 450 ppm CO2e target with constraints on the expansion of nuclear, bioenergy, renewables and CCS at the high growth rate (15% per year) along with a 30 year delay in policy action, relative to a.) the unconstrained case without delay and b.) the case with the same constraints in place but no delay

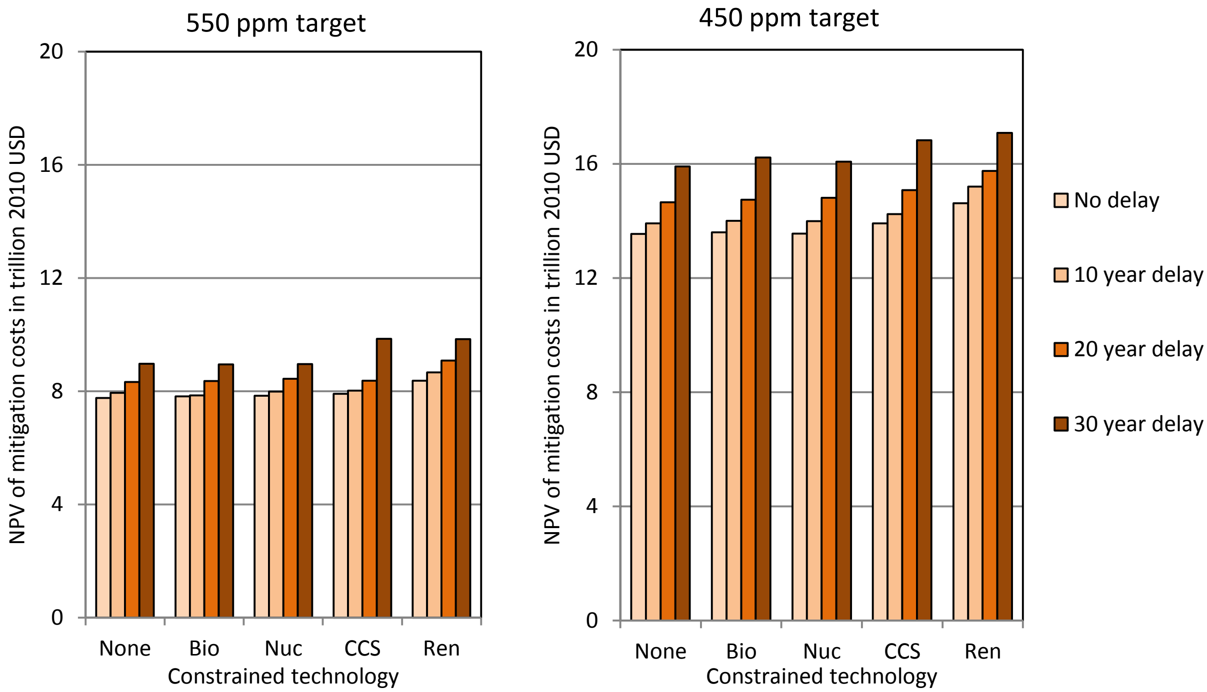

Figure 9NPV of mitigation costs up to 2095 under medium expansion constraints on the expansion of individual low-carbon technologies and delays in policy action

Delays in policy action influence the effect of expansion constraints on mitigation costs substantially especially when low-carbon technologies are jointly constrained (Figure10). For example, the mitigation cost for the 550 ppm target under the low growth rate constraint on the expansions of renewables and bioenergy is 16% higher than the unconstrained case. On the other hand, with a 30 year delay, the mitigation cost is 21% higher compared to the unconstrained case with the same delay. Delays also influence the responsiveness of costs to different levels of expansion constraints. For example, with no delay, the mitigation cost of achieving the 550 ppm target with the low expansion rate on renewables and bioenergy is 11% higher than the case with the high expansion rate constraint. However, with a 30 year delay, this increases to 17%.

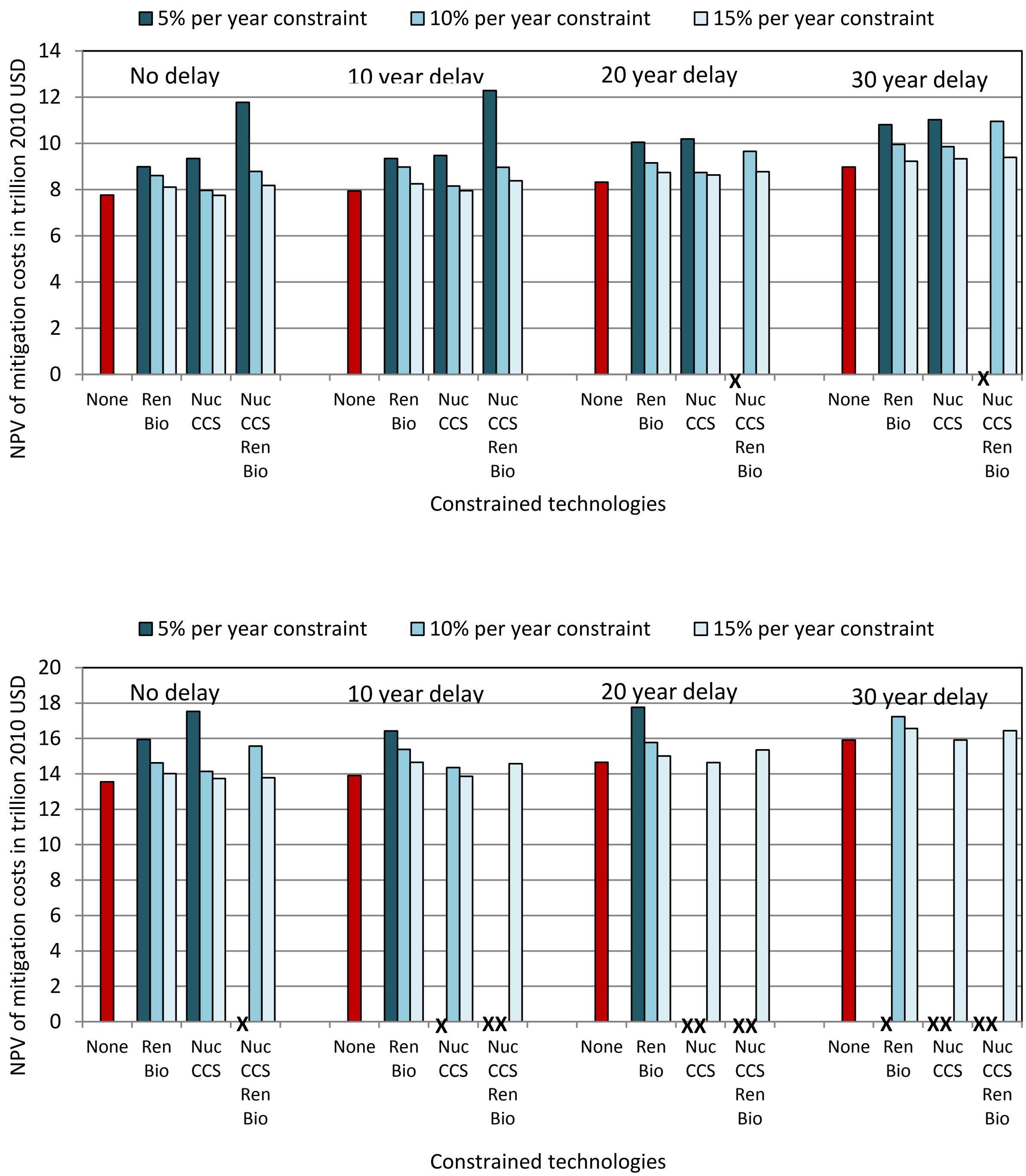

Figure 10NPV of mitigation costs up to 2095 for a.) 550 ppm CO_2e and b.) 450 ppm CO_2e targets under different constraints on the expansion of sets of low-carbon technologies on top of delays in policy action from 2020. An "X" indicates an infeasible scenario.

Achieving stringent climate targets under expansion constraints becomes challenging with delays in policy action (Table 2). When the expansion of CCS or renewables is constrained at the low growth rate constraint, achieving the 450 ppm target with a 30 year delay becomes infeasible. Infeasibilities increase when a particular set of technologies are jointly constrained. When the diffusion of all low-carbon technologies are constrained at the medium growth rate, achieving a 450 ppm target with a delay of only 10 years or more becomes infeasible. While achieving the 550 ppm target under the low growth rate constraint is feasible up to a delay in action of 10 years, achieving the 450 ppm target becomes infeasible even with no delay. The infeasibilities, which indicate excessively high mitigation costs, suggest that constraining major low carbon technologies in unison will be much more costly with delayed action than without.

6 Conclusions

Even in a world with aggressive climate policies, factors other than relative prices of technologies including institutional, behavioral and social factors can slow the diffusion of low-carbon technologies. In this paper, we have reviewed the literature on the sources of such factors and have highlighted potential implications of technology diffusion constraints. we have also studied the implications of such constraints in the presence of major delays in climate policy action. This study differs from previous work on technology availability in that we impose exogenous diffusion constraints that aim to capture the effects of various drivers on the rate of technology up-scaling that are not well represented in IAMs.

The analysis in this paper provides several interesting insights. First, such factors may not be critically important without major delays in policy action. However, if political action is delayed by a few decades, these factors have greater influence on the feasibility (or, alternately, on the mitigation costs) of achieving stringent climate stabilization targets. Second, diffusion constraints become particularly important under delays when multiple technologies are jointly constrained. In the case of the GCAM integrated assessment model, for example, with no delay in globally coordinated mitigation action against climate change, when the expansions of nuclear, renewables, CCS and bioenergy are all severely constrained, the 450 ppm CO_2e target is achieved at higher mitigation costs. On the other hand, if these technologies are constrained with a 30 year delay, achieving the same target is infeasible.

Third, as we have modeled it, constraints on the expansion of CCS and renewables matter more than those on nuclear and bioenergy (with and without delays) mainly because the baselines in the latter cases are larger to begin with. In this context, the availability of low-carbon technologies on a large scale at the right timing is critically important if stringent climate stabilization goals are to be achieved. For instance, if the diffusion of low-carbon technologies that would play a major role in the longer term (e.g., CCS) is severely constrained, greater mitigation in the near term is required resulting in higher mitigation cost compared to the case in which the diffusion of technologies that play a major role in the near term (e.g., renewables) is severely constrained, in which case, greater opportunities for mitigation in the longer term using negative emissions technologies (bio-CCS) exist. Under delays in policy action, these dynamics become further amplified, at times making some scenarios infeasible.

Finally, our analysis also shows that delayed action itself may not matter a lot in a world with no diffusion constraints —rather unlike the real world. However, delayed action becomes extremely important with diffusion constraints on major low-carbon technologies. For example, without any expansion constraints, a 450 ppm target with a 30-year delay can be achieved at higher costs. However, under severe constraints on the expansion of low-carbon technologies, achieving this target becomes infeasible even with a 10-year delay in policy action. The presence of such factors in the real world implies that achieving long-term policy targets may require particular focus on near-term policy for technology deployment.

The analysis presented in this paper is not without limitations. First, the expansion constraints specified in this analysis are constant over time. Thus, we have not been able to capture feedbacks between policy and diffusion. In the real world, for example, not only could the presence of factors constraining diffusion lead to higher carbon prices (one of the findings of this study), but the higher carbon prices could, in turn remove some of the constraints and potentially speed up diffusion. Nevertheless, we believe that insights that would have been obtained by modeling this endogeneity are captured by specifying different levels of diffusion rates. Second, in addition to the issue of using a time-invariant expansion rate, we specify constraints in terms of net technology up-scaling rather than directly on new technology deployment. Therefore, these constraints may depend critically on the baseline technology stock profiles and the type of technologies that are constrained. Future analyses need to take into account the implications of time-varying diffusion constraints and also the dynamics of stock turnover. Nevertheless, we believe that the broad qualitative insights from this analysis would remain unchanged. In addition, we have not investigated the salient issue of diffusion of demand-side energy saving technologies, which may be more subject to institutional, behavioral, and social factors. Finally, future studies must investigate the implications under less than perfect international cooperation in terms of climate policy and technology transfers.

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