ABSTRACT

Title of Document:	LOW-CARBON TECHNOLOGIES AND CLIMATE CHANGE MITIGATION POLICY IN AN IMPERFECT WORLD.
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It is widely acknowledged that an important element of climate change mitigation policy will be the development and diffusion of low-carbon technologies. This dissertation uses the Global Change Assessment Model (GCAM), a global integrated assessment model to study the relationships between technology and policy in the context of global climate change mitigation under three "imperfect" circumstances, namely, constraints on the rate of diffusion of low-carbon technologies, countries promoting the deployment of low-carbon technologies based on national priorities and preferences and variation in investment risks across technologies and regions. These conditions deviate from conventional idealized assumptions and thus represent an "imperfect" world.

The first essay shows that factors including social, behavioral and institutional that might constrain the rate of diffusion of low-carbon technologies even in the presence of favorable climate policies have sizeable impacts on the costs and feasibility of achieving

stringent climate targets. Such impacts are greatly amplified with major delays in serious climate policies.

The second essay illustrates the divergence between domestic and global outcomes when countries promote the deployment of specific low-carbon technologies in the near-term. In this essay, I show that a globally cost-effective, near-term international technology investment strategy to achieve a long-term climate goal is a diversified international technology investment portfolio across countries. This essay also explores the degree to which independent national technology deployment policies align with collaboratively determined regimes. I show that conditions exist under which there are substantial gains to international cooperation in the development and deployment of diverse low-carbon technologies but also circumstances in which domestic outcomes align with the global outcome.

The third essay focuses on the variation of investment risks across technologies and regions in the electricity generation sector. I find that by taking into account such variation, achieving an emissions mitigation goal is up to 40% higher than it would be in a world with uniform investment risks. Additionally, industrialized countries mitigate more and developing countries mitigate less.

The three essays together underscore the importance of policies aimed at developing capabilities and fostering international cooperation in the development and diffusion of low-carbon technologies to achieve climate change mitigation cost-effectively.

LOW-CARBON TECHNOLOGIES AND CLIMATE CHANGE MITIGATION POLICY IN AN IMPERFECT WORLD

By

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To my loving grandparents, M.S. Ramanathan, Jayalakshmi Ramanathan, D.A.S. Mani and Bhagavathi Mani

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I owe a huge debt of gratitude to Leon Clarke from the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI) for introducing me to the GCAM model that I have used throughout this dissertation and advising me on research strategy. Among the many things that I would like to thank Leon for, is his constant encouragement to develop a knack for a style of research that juxtaposes intellectual rigor with simplicity in perspective. I am also indebted to him for his guidance in improving the framing of the research presented in this dissertation.

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Chapter 1 Introduction

Climate change is one of the pressing challenges facing the world today. Mitigating climate change will require substantial reductions in greenhouse gas (GHG) emissions, in all sectors of the global economy (IPCC, 2014). The inter-relationships between technology and policy in the context of decadal-scale environmental policy issues such as climate change mitigation have received wide attention in the literature (see for example, Popp et al. (2010), Gillingham et al. (2008) and Jaffe et al. (2003)). An important lesson emerging out of this literature is that efforts to advance the development and diffusion of low-carbon technologies will be extremely important. In many cases, long-term environmental problems cannot be addressed, or can only be addressed at increased costs, using existing technologies (see for example, Clarke et al. (2007)).

Traditional analyses exploring the relationships between technology and policy in the context of global climate change mitigation have largely relied on idealized assumptions about technology availability and deployment, regional mitigation efforts and capacities to undertake those efforts. For example, most studies that assess the potential of accelerated deployment of low-carbon technologies to reduce costs of climate change mitigation typically assume that the final portfolio of technologies that gets deployed is dependent largely on relative prices. Another frequently made assumption is that countries will achieve near-term emissions reductions by employing carbon-price based mechanisms. Such assumptions have been very useful to understand the costs and patterns of climate change mitigation. However, more recently, a branch of literature that aims to understand these relationships under non-idealized or imperfect circumstances has sprung up (see, for example, Clarke et al. (2009) and Edmonds et al. (2008)). This dissertation opens up a dialogue with this relatively new branch of literature and aims to better understand the relationships between low-carbon technologies and climate change mitigation policy under conditions that deviate from conventional assumptions – in other words, under "imperfect" circumstances. The dissertation comprises of three essays, each of which focuses on a deviation from commonly made assumptions in assessments of emissions mitigation (Table 1-1).[1]

Table 1-1 Outline of dissertation

	Traditional assumptions	**Deviation considered in this dissertation**
Essay 1: Low-carbon technology diffusion rates	Technology deployment depends largely on relative prices	Technology diffusion may be slowed down by market failures and institutional, social and behavioral factors
Essay 2: Near-term low-carbon deployment policies	Emissions reductions in the near-term are achieved by means of carbon-price based mechanisms	Countries promote the deployment of low-carbon technologies based on national priorities and preferences
Essay 3: Nonuniform investment risks	Capacity to undertake investment is uniform throughout the economy	Investment risks are non-uniform across technologies, sectors and regions

The first essay (Chapter 2) deals with rates of diffusion of low-carbon technologies. Low-carbon technologies tend to face several economic as well as non-economic constraints to their diffusion. Economic constraints are a virtue of the cost of such technologies relative to fossil-fuel technologies – low-carbon technologies such as renewables, nuclear and carbon capture and storage (CCS) are more expensive compared to their fossil-fuel counterparts – and that limits the diffusion of such technologies. There are other

[1] The three essays that form this dissertation resulted in publications as co-authored journal articles. For more details on the contributions of individual authors in each of the essays, see Appendix A.

constraints that tend to influence diffusion - for example, market failures. Market failures in technology diffusion are similar to those related to innovation- because the benefits of adopting a new technology accrues to society at large, incentives for the adoption of new technologies are limited. Likewise, non-market constraints to the adoption of low-carbon technologies such as institutional, behavioral, and social factors also influence their rate of diffusion (Hultman et al., 2012). In this essay, I review the literature on the sources of such diffusion rate constraints, and explore the potential implications of such constraints using the Global Change Assessment Model (GCAM), a global integrated assessment model. I find that such constraints may not be critically important without major delays in policy action. However, if political action is delayed by a few decades, these constraints have greater influence on the costs and feasibility of achieving stringent long-term climate targets. The results of this analysis suggest that policies to encourage technology deployment and address diffusion constraints, especially in the near-term would play an important role in cost-effective climate change mitigation.

The second essay (Chapter 3) focuses on deployment policies to promote low-carbon technologies in the near-term and their relationship with long-term domestic and global outcomes. Because climate change is a global problem, there is consensus in the international community that efforts to address it must entail some international coordination. Indeed, most scholars conclude that a global, economy-wide and long-term approach is the most cost-effective method for stabilizing the climate (Jacoby et al., 2008; Nordhaus, 2005). Previous work has also shown that the economic benefits of such an approach are particularly large if stringent climate targets are to be met (Clarke et al., 2009; Edmonds et al., 2008). While the conventionally idealized world of GHG control is one of seamless regulation that spans all sectors globally, the real world comprises of non-uniform, bottom-up efforts. Recent climate change negotiations show that such efforts are increasingly being undertaken at regional and national levels based on national priorities and preferences. And many countries view promoting the deployment, via policy, of low-carbon technologies as an alternative to idealized economy-wide carbon prices. For example, China's recent commitment was to increase the share of non-fossil technologies in the energy mix to 20% by 2030 (The White House, 2014). Among several motivations for such policies are emissions reductions, energy security, technological change and early-mover advantages. This raises the following important question from the point of view of the global social planner. What is the most effective mix of near country-level deployment policies? Should all countries pursue the same technologies? Or, is a diversified approach more effective? The answers to these questions are compounded by the fact that technologies have public goods characteristics. For instance, technological change that might occur due to domestic deployment policies could spill over to firms globally. Therefore, what is cost-effective from the global perspective may not be so, from the perspective of the investor countries investing in the deployment policies. This essay explores the implications for domestic and global outcomes in the long-term when countries promote the deployment of low-carbon technologies in the near-term. I show that the globally cost-effective, near-term international technology investment strategy to achieve a long-term climate goal is a diversified international technology investment portfolio across countries. In addition, my analysis illustrates that conditions exist under which there are substantial gains to international cooperation in the development and deployment of different low-carbon technologies but also circumstances in which domestic outcomes align with the global outcome. The results of this essay argue for a solid assessment of technologies in question and the scope and nature of technological change in policy collaborations aimed at undertaking stringent mitigation in the future.

The third and final essay (Chapter 4) investigates the issue of non-uniform investment risks and how such differences affect the costs and geography of emissions mitigation. Low-carbon technologies are capital intensive, implying that a transformation to a low-carbon energy system will require large amounts of capital. A number of factors such as national policy environments, quality of public and private institutions, sector and technology specific risks, and firm-level characteristics can affect investors' assessments of risks, leading to a wide variation in the business climate for investment. Such variation can influence where, how and at what costs firms deploy capital. In this essay, I investigate how national institutions affect investment risks and thus the cost of financing (Acemoglu and Zilibotti, 1997; Faria and Mauro, 2009; North, 1990). Specifically, I investigate the implications of non-uniform investment risks for the costs and patterns of mitigation. Using a modified representation of investment risks in the GCAM model, I find that emissions mitigation is more expensive in a world with non-uniform investment risks than it would be in a world with uniform investment risks. In addition, industrialized countries mitigate more, and developing countries mitigate less. This essay introduces a new front in the research on how real-world factors influence climate mitigation and suggests that institutional reforms aimed at lowering investment risks could be an important element of cost-effective climate mitigation strategies.

The final chapter (Chapter 5) concludes with a summary of the dissertation, policy implications of the research and future research directions. Not only do the three essays together have methodological contributions in providing solid frameworks to incorporate real-world factors and policies in assessments related to low-carbon technologies and climate change mitigation policy, they also provide valuable insights for domestic and international policy. Collectively, the three essays underscore the importance of policies aimed at developing capabilities and fostering international cooperation in the development and diffusion of low-carbon technologies to achieve climate change mitigation cost-effectively.

Chapter 2 Diffusion of low-carbon technologies and the feasibility of long-term climate targets [2]

2.1. Introduction

Addressing the problem of climate change will 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 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. In this essay, I 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?*

Previous studies employing integrated assessment models (IAMs) to explore the role of low-carbon technologies have made simple assumptions regarding the availability of

[2] This chapter is based on Iyer et al. (2015a)

specific technologies.[3] 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 essay contributes to the existing literature on limited technology availability by assessing the implications of diffusion constraints for achieving stringent mitigation targets. I also add a temporal dimension to the study by investigating the implications of constrained diffusion when there are major delays in globally coordinated mitigation efforts to address climate change.

The structure of the chapter is as follows. I first review the factors that constrain the diffusion of low-carbon technologies. Following this, I review the historical diffusion rates of technologies in order to provide a background on the notion of "slow" and "fast" diffusion. Next, I provide a description of the method and then present the results and findings of this study. The final section of this chapter concludes with a summary of the findings and scope for future work.

2.2. 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

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[3] In this essay, and throughout the dissertation, I use a global IAM used for climate policy analysis, namely, GCAM. Features of the model are described in Section 2.4.

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 (Box 2-1). 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.

2.2.1. Factors in the presence of favorable climate change policies

Several characteristics of the energy 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).

Box 2-1 Summary of factors constraining the deployment of low-carbon technologies

Factors in the presence of favorable climate policies

Lack of information about performance of new technologies
Lack of financial support for capital intensive technologies
Preference of risk-averse investors to existing technologies
Public perceptions
Lack of adequate institutional frameworks
Lack of adequate regulations, for e.g. absence of regulations for transport and storage of CO_2
Firm-specific characteristics such as size, ownership
Technology-specific characteristics such as resource availability and intermittency

Factors due to uncertainty in climate change policy

Option value in the presence of uncertainty in carbon prices
High discount rates by investors

One source of increasing returns is the existence of learning economies. 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). Another 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., 2008).

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). Among other sources of lock-ins and path dependencies in the energy system are substitutability in the energy sector and institutional path dependencies. Substitutability in the energy sector increase lock-in effects. As technologies in the energy sector are perfect substitutes, new low-carbon technologies can only compete on price and not on “quality”, with fossil-fuel technologies (Kalkuhl et al., 2012; Lehmann and Gawel, 2013). In addition, lock-in effects are reinforced by co-evolving institutions and regulatory frameworks that form what is called the *techno-institutional complex* (Unruh, 2000).

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) 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).[4] 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

[4] For a detailed discussion on issues surrounding nuclear technologies, see (Iyer et al., 2014)

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).

2.2.2. 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) or pessimistic expectations about policy signals. Another incentive to delay adoption under policy uncertainty occurs when the firm is large enough to meaningfully affect policy via coalition building (Jacobsson and Lauber, 2006).

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, I compile historical diffusion rates of various technologies to provide a background on the notion of "slow" and "fast" diffusion.

2.3. 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.

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). I compile the diffusion rates for different technological transformations from these studies in Table 2-1. The above 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 diffusion 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, I use the first metric, namely, the one used by (Hook et al., 2012). As I will explain in the following section, this enables me to specify future growth trajectories, simply, in terms of various annual growth percentages from existing levels of output. In order to express the findings of Grübler et al. (1999), Wilson and Grübler (2011) and Wilson et al. (2012) in terms of annual percentage growth, I 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 diffusion rate provided by (Hook et al., 2012), the average annual diffusion rate in percentage during this period can be shown to be equal to $219.7/\Delta t$ (see Appendix B for a derivation of this result).

A look at the historical diffusion rates compiled in Table 2-1 shows that most technological transitions have happened at low rates. Fossil fuel energy has grown at less than 10% per year. Even during the oil boom and the dramatic rise in global oil use, annual average diffusion rates of energy output from petroleum were about 7%. In contrast, 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. Note that most of the annual average diffusion rates presented in Table 2-1 are based on long time horizons, as high as 100 years for some cases and reflect growth during the "pervasive diffusion" phase explained earlier - they indicate, in most cases, the average diffusion rates at which technologies grew from 10% to 90% of their market shares. Not only did diffusion rates vary widely during these periods, they were very different during the market introduction and saturation phases. For example, nuclear energy grew at high rates over 25% per year until the Chernobyl accident in 1985, after which diffusion rates diminished significantly to as low as 1-2% during the 2000's (Hook et al., 2012; Wilson et al., 2012). In the case of fossil fuels, high diffusion rates of 20–30% occurred in the nineteenth century when the fossil energy industry was young. The two World Wars and the Great Depression of the 1930s reduced growth for some time. During the post-World War economic boom, fossil fuel energy production grew at over 5% annually but this decreased to about 2% by the 1980s. Diffusion rates of fossil fuel energy diminished in spite of technological breakthroughs in petroleum exploration and extraction, coal mining and similar disciplines because of a number of reasons including emergence of substitutes and a social disinclination toward dependence on fossil fuels (Hook et al., 2012).

In addition to the technologies reviewed in Table 2-1, 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.

Table 2-1 Historical diffusion rates of various technologies surveyed in literature

Range of annual growth rate	Technology transitions	Regional scope	Average annual growth rate	Source
≤ 5%	Bioenergy	Global	2%	(Hook et al., 2012)
	Coal (as a substitute for traditional energy)	Global	2%	(Grübler et al., 1999)
	Coal (as a substitute for traditional energy)	USA	3%	(Grübler et al., 1999)
	Open-hearth steelmaking	Global	3%	(Grübler et al., 1999)
	Cars	Global	3%	(Wilson et al., 2012)
	Railways	Global	4%	(Grübler et al., 1999)
	Aircrafts	Global	4%	(Wilson et al., 2012)
	Steam ships (as substitutes for sail ships)	Global	4%	(Grübler et al., 1999)
	Open-hearth steelmaking	USA	4%	(Grübler et al., 1999)
	Railways	France	5%	(Grübler et al., 1999)
	Electrification of homes	USA	5%	(Grübler et al., 1999)
	Coal power	Global	5%	(Wilson et al., 2012)
6-10%	Oil refineries	Global	6%	(Wilson et al., 2012)
	Oil energy	Global	7%	(Hook et al., 2012)
	Natural gas power	Global	7%	(Wilson et al., 2012)
	Hydropower	Global	<8%	(Hook et al., 2012)
	Mechanization in coal mining	Russia	8%	(Grübler et al., 1999)
	Railway track electrification	Russia	8%	(Grübler et al., 1999)
	Air in intercity travel (as a substitute for rail)	USA	8%	(Grübler et al., 1999)
	Chemical preservation of railway ties	USA	8%	(Grübler et al., 1999)
	Percentage of households with radio	USA	9%	(Grübler et al., 1999)
	Basic oxygen furnace	Global	9%	(Grübler et al., 1999)
	Coal and Gas energy	Global	5-10%	(Hook et al., 2012)
11-15%	Basic oxygen steel furnace	USA	11%	(Grübler et al., 1999)
	Nuclear energy	Global	11%	(Wilson et al., 2012)
	Air conditioners in homes	Japan	12%	(Grübler et al., 1999)
	Car air conditioners	USA	12%	(Grübler et al., 1999)
	Automobiles (as a substitute for carriages)	UK	14%	(Grübler et al., 1999)
	Cars (as a substitute for horses)	UK and France	14%	(Grübler et al., 1999)
	Cars (as a substitute for horses)	France	15%	(Grübler et al., 1999)
	Transistors in radios (as a substitute for vacuum tubes)	USA	15%	(Grübler et al., 1999)
	Color TV (as a substitute for Black and white TV)	USA	15%	(Grübler et al., 1999)
	Flue gas Desulfurization	USA	15%	(Taylor et al., 2005)
	Compact fluorescent lamps	Japan	15%	(Wilson et al., 2012)
> 15%	Cars (as a substitute for horses)	USA	18%	(Grübler et al., 1999)
	Locomotives	USA, Russia and UK	18%	(Grübler et al., 1999)
	Wind energy	Denmark	20%	(Wilson et al., 2012)
	Washing detergent (as a substitute for soap)	USA	24%	(Grübler et al., 1999)

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 rapid 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.

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

2.4. Methodology

2.4.1. The GCAM integrated assessment model

In this and the following essays, I use the Global Change Assessment Model (GCAM) to answer the research questions. 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).

2.4.2. Representation of diffusion constraints

In this essay, I employ a version of GCAM that imposes explicit diffusion rate constraints on top of the current technology choice framework. The constraints take the following simple form:

$$x_i(t) = x_i(t_0) \times (1+\beta)^{(t-t_0)}$$

where $x_i(t)$ represents the deployment of a technology *i* at time *t*, β is the rate of diffusion of technology *i* in percentage points per year and $x_i(t_0)$ is the deployment of technology *i* in the initial period t_0. As I explain later, the constraint may be binding or non-binding. If the constraint is non-binding, the deployment in time period *t* is assumed to be equal to the value without constraints. GCAM solves the above constraint by introducing an “adjustment cost” to the cost of the technology. The adjustment cost is changed iteratively until the constraint is satisfied. Adjustment costs can be understood as a proxy for the all the factors that constrain the diffusion of the technology in question.

The above stylized representation of technology diffusion serves two purposes. First, it is simple and enables me to treat technology diffusion as an input-output process. The assumption here is that a number of factors constrain technology diffusion and β represents the sum total of those effects. Second, by changing just one parameter, namely, β, I can explore the implications of slow diffusion rates for the costs and feasibilities of achieving stringent climate targets. As I explain in the following section, I specify low, medium and high diffusion rate constraints based on the review in Table 2-1. 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 essay, I use historical diffusion rates only as guidance or reference points to understand “slow” and “fast” diffusion in a much broader sense.

2.4.3. Scenario setting

To help answer my questions, I explore a number of scenarios using GCAM. 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, diffusion rates for the constrained technologies and the length of delays in globally coordinated mitigation action. I 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). Diffusion constraints are specified for major low-carbon technologies—nuclear, CCS, renewables (solar and wind) and bioenergy in the electricity sector.[5] These low-carbon technologies still need to be economically attractive relative to other technologies, but the diffusion constraints limit how quickly they enter the energy system. The diffusion of these technologies are constrained individually as well as jointly (renewables and bioenergy; nuclear and CCS; nuclear, CCS, renewables and bioenergy). Constraints on the diffusion of the low-carbon technologies are represented as fixed

[5] In this essay, I restrict the analysis to supply-side electricity generation technologies.

annual rates of growth of net technology deployment. While constraints on the diffusion of nuclear, CCS and renewables are imposed at the regional level, those for bioenergy are specified at the global level. I specify three levels of diffusion rate constraints at 5% (low), 10% (medium), and 15% (high) per year. The review of diffusion rates in Table 2-1 can be used as reference points to help understand how to think of these numbers. For instance, the low diffusion rate of 5% per year is similar to the historical diffusion rates of coal power (1959-1999) and oil refineries (1950-1984) (Wilson et al., 2012). Likewise, the medium diffusion rate of 10% per year is comparable to the historical growths of nuclear energy (1974-1992). And finally the high diffusion 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). Finally, I 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 2-2 for the scenario layout).

2.5. Results and discussion

2.5.1. Pathways toward 450 and 550ppm CO_2e without explicit constraints on technology diffusion

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 2-1 A). Delays in policy action extend the period of growing CO_2 emissions, followed by more dramatic emissions mitigation, 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 mitigation after the delays takes place within about 10 years. The relative degrees of mitigation effort can be seen in terms of carbon price paths, which rise exponentially following the Hotelling-Peck-Wan rule (Peck and Wan, 1996). The 450 ppm target demands higher carbon price than the 550 ppm target (Figure 2-1 B). The rapid catch-up in emissions mitigation with delays lead to increases in carbon prices as soon as the policy regime starts.

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

		550 ppm CO_2e target				450 ppm CO_2e target			
Technologies constrained	Nature of diffusion 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.

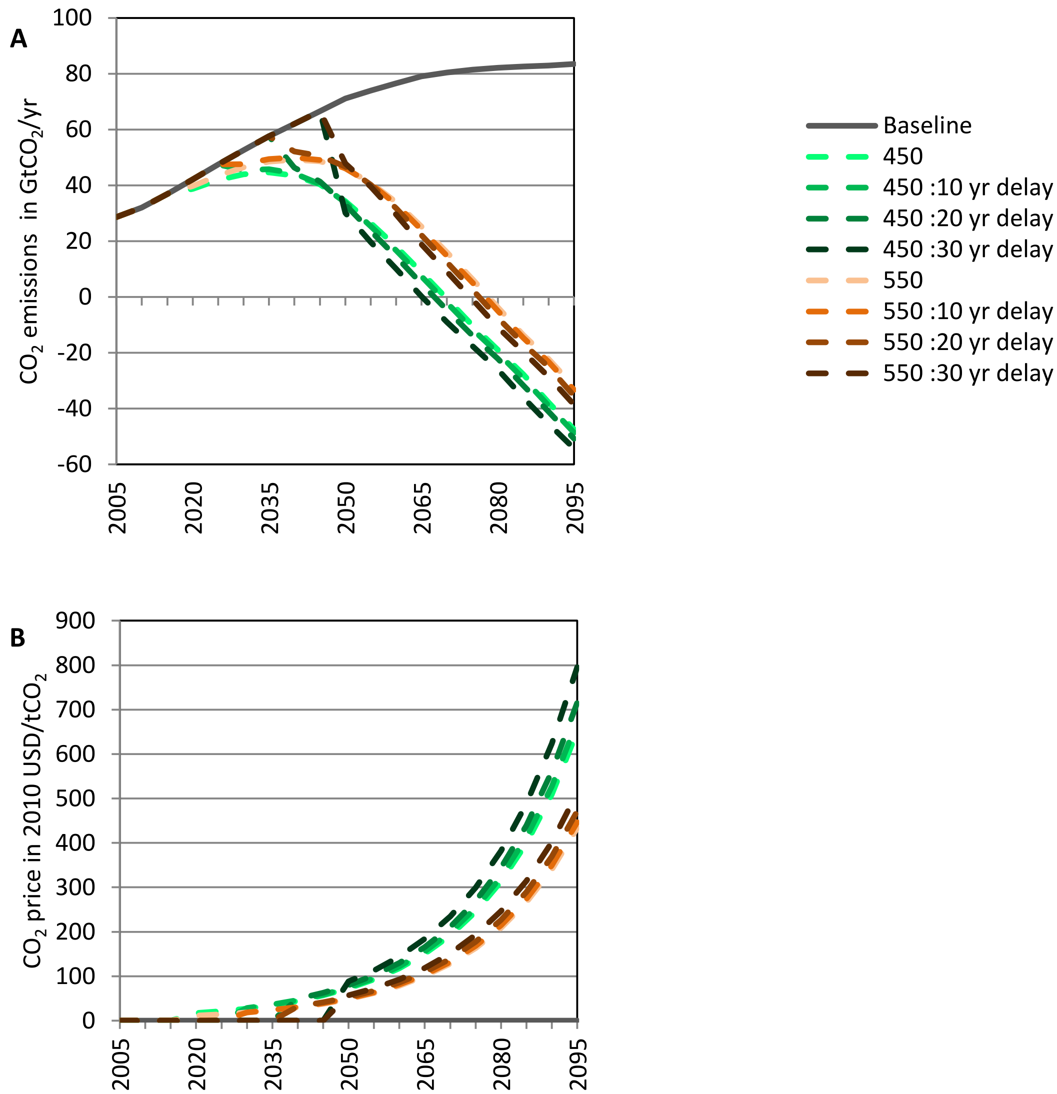


Figure 2-1 A.) Fossil fuel and industry emissions and B.) CO_2 prices in scenarios under unconstrained diffusion of low-carbon technologies. Under stringent climate targets, CO_2 emissions peak in the medium-term and then start to decline, exhibiting substantial negative emissions by the end of the century. In the presence of delays in globally coordinated action, there are more negative emissions in the long-term. In addition, carbon prices in the cases with delays are higher.

Due to higher carbon prices, the net present value (NPV) of mitigation costs (throughout this essay, I 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 2-2).[6] In addition, delayed action requires faster emissions mitigation after the peak and that is costly. This is consistent with findings of previous studies on the effects of delayed action (Bosetti et al., 2009a; 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.

The general behavior of modest near-term mitigation followed by dramatic long-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 2-3). 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 long-term.

[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 et al. (2009))

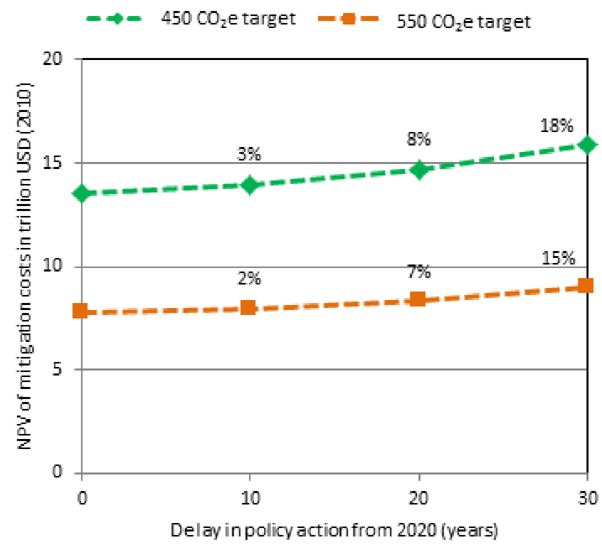


Figure 2-2 NPV of mitigation costs under unconstrained diffusion but with delays in policy action. The numbers above each data point show the percentage increase with respect to the no delay case. Mitigation costs with delays in globally coordinated action are higher.

Technology diffusion rates decrease with time, as the size of deployment increases because of increasing market competition to satisfy a finite demand (Figure 2-4). The scenarios without explicit technology diffusion constraints indicate that the low, medium and high diffusion rate constraints (5%, 10% and 15% per year) that are imposed on the low-carbon technologies may or may not be binding. Without any delays, nuclear power and bioenergy diffusion rates are modest, and hence the constraints would be binding only for brief periods of time. This is because, nuclear power is relatively mature in its stage of development and the development of bioenergy is limited by competition of land use with crop lands and forests that becomes increasingly intense under a carbon price regime. In contrast, the constraints could limit the diffusion 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 will be limited by both the medium (10% per year) and the low constraints (5% per year) until the middle of the century. However, the high constraint (15% per year) will remain non-binding throughout the century. Solar power shows rapid near-term diffusion, making even the high constraint (15% per year) binding through 2025, followed by a continued decrease in its diffusion 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 diffusion rate with less than 5% growth after 2065.

With delays in climate policy action and no diffusion constraints, low-carbon technologies grow at the same rates as the baseline case until the globally harmonized carbon price is imposed (Figure 2-4). In this year these technologies are introduced on a large scale, exhibiting major spikes in diffusion rates. Interestingly, the accelerated deployment due to delays in policy action spans over the 5-10 year time frame. The varying degrees to which diffusion 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.

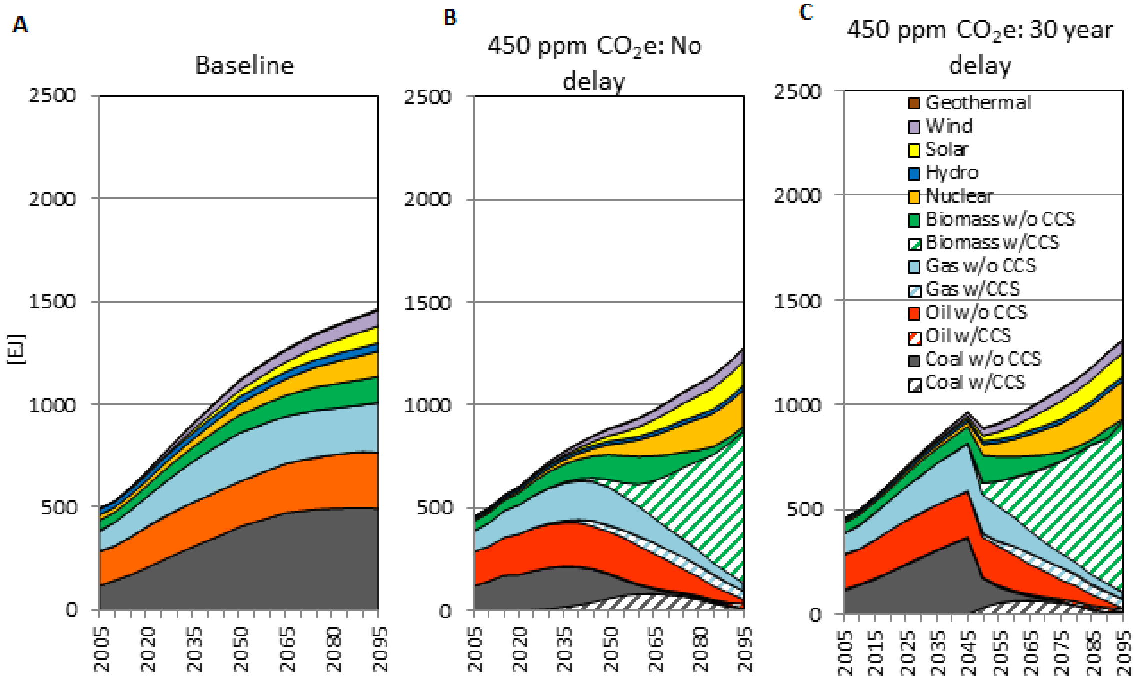


Figure 2-3 Primary energy by fuel under unconstrained diffusion of low-carbon technologies. Low-carbon technologies, such as renewables, nuclear, and bioenergy in combination with CCS technologies (bio-CCS), are deployed on a large scale over the second half of the century, especially when globally coordinated action is delayed by several decades.

2.5.2. The effect of diffusion constraints

Constraints on the diffusion 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 2-5). In the first half of the century, diffusion constraints limit the optimal deployment of renewables and CCS technologies, leading to reduction in energy consumption. During this period, conventional fossil fuel and bioenergy, which remain non-binding, continue to get deployed. In the latter half of the century, CCS technologies are rapidly installed, as diffusion constraints are no longer binding in most regions, especially for the production of electricity from biomass, the diffusion 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. Such changes in the energy system result in higher carbon prices and mitigation costs in scenarios with diffusion constraints compared to the case without 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 prices. 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 2-6 A). In this case, greater and cheaper mitigation can be done later in the century using bio-CCS (Figure 2-6 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 2-6 A).

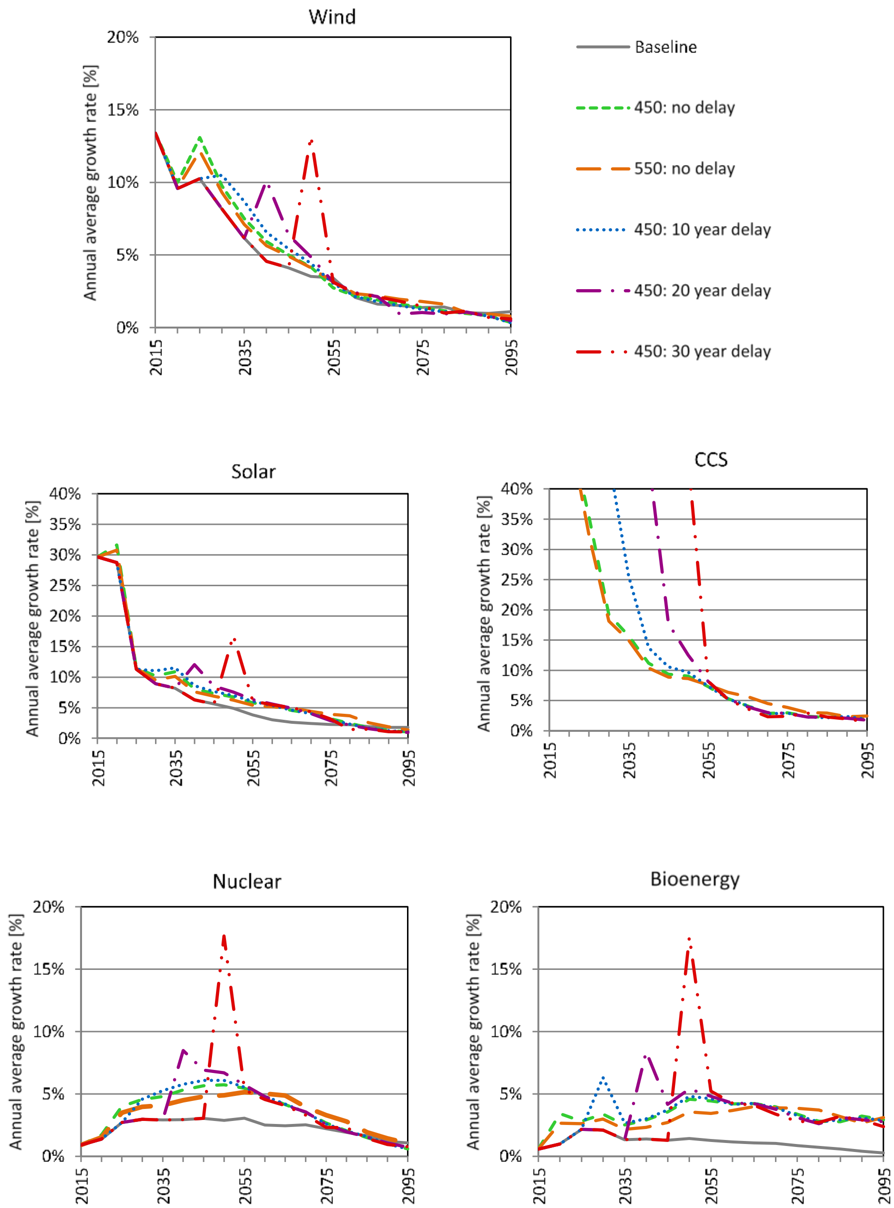


Figure 2-4 Annual diffusion rates of low-carbon technologies under different long-term stabilization targets (450 ppm with and without delays in policy action and 550 ppm without delays) and unconstrained diffusion of low-carbon technologies. With delays in climate policy action, low-carbon technologies grow at the same rates as the baseline case until the globally harmonized carbon price is imposed. In this year these technologies are introduced on a large scale, exhibiting major spikes in diffusion rates.

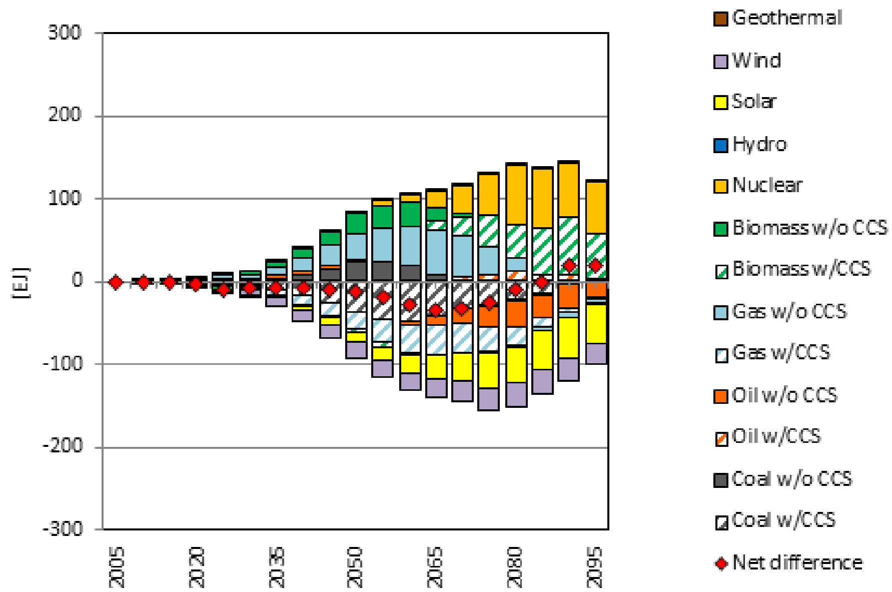


Figure 2-5 Change in primary energy consumption by fuel for the 450 ppm target with constraints on the diffusion of nuclear, bioenergy, renewables and CCS at medium rates (10% per year), without delay in policy action, relative to the case without diffusion constraints. In the presence of diffusion constraints, the deployments of renewables and CCS are slowed down until the mid-century. Thereafter, the deployments of bio-CCS and nuclear power are sped up.

The departure from the optimal schedule of technology deployment due to factors that constrain their diffusion has the effect of raising mitigation costs (Figure 2-7). 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. Diffusion 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. Diffusion 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 diffusion rates varies across the type of technologies that are constrained. For example, the costs of achieving the 450 ppm target with the low diffusion rate constraint (5% per year) for CCS or renewables are 16% and 13% higher, respectively, than the cases with the high diffusion rate constraint (15% per year). In comparison, the cost of achieving the same target with the low diffusion 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 diffusion rate is 28% higher than the case with the high rate, as these technologies no longer serve as substitutes. Note that diffusion constraints themselves could have impacts on the mitigation cost as large as several decades of delays in mitigation action (Figure 2-2).

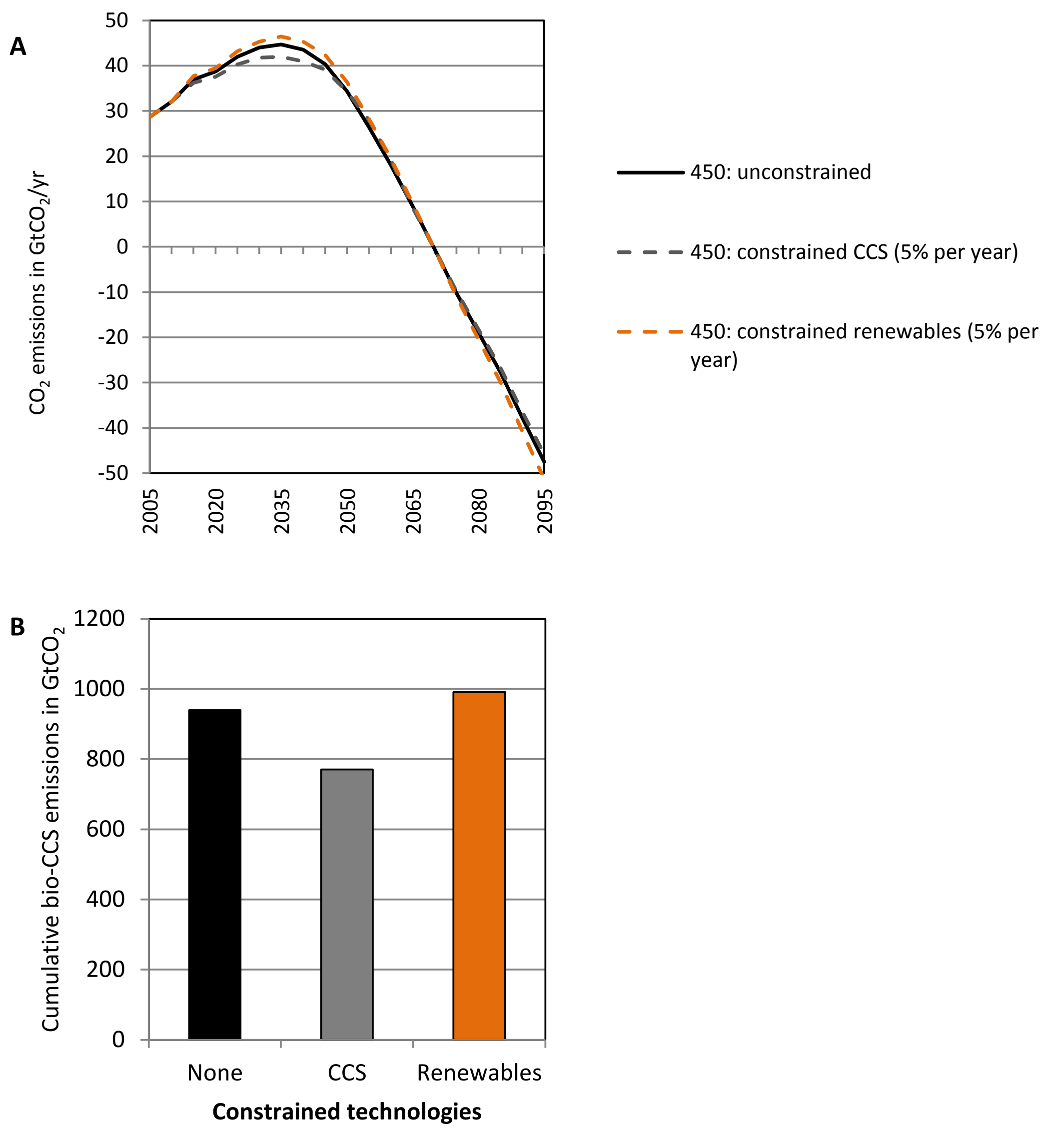


Figure 2-6 A.) CO_2 emissions pathways and B.) Cumulative CO_2 removal (2020-2095) based on bio-CCS under constrained diffusion of CCS and renewables. Constraining the diffusion of renewables would delay emissions mitigation. In this case, more bio-CCS would get deployed in the latter half of the century. On the other hand, if the diffusion of CCS is constrained, greater mitigation in the near term would be required.

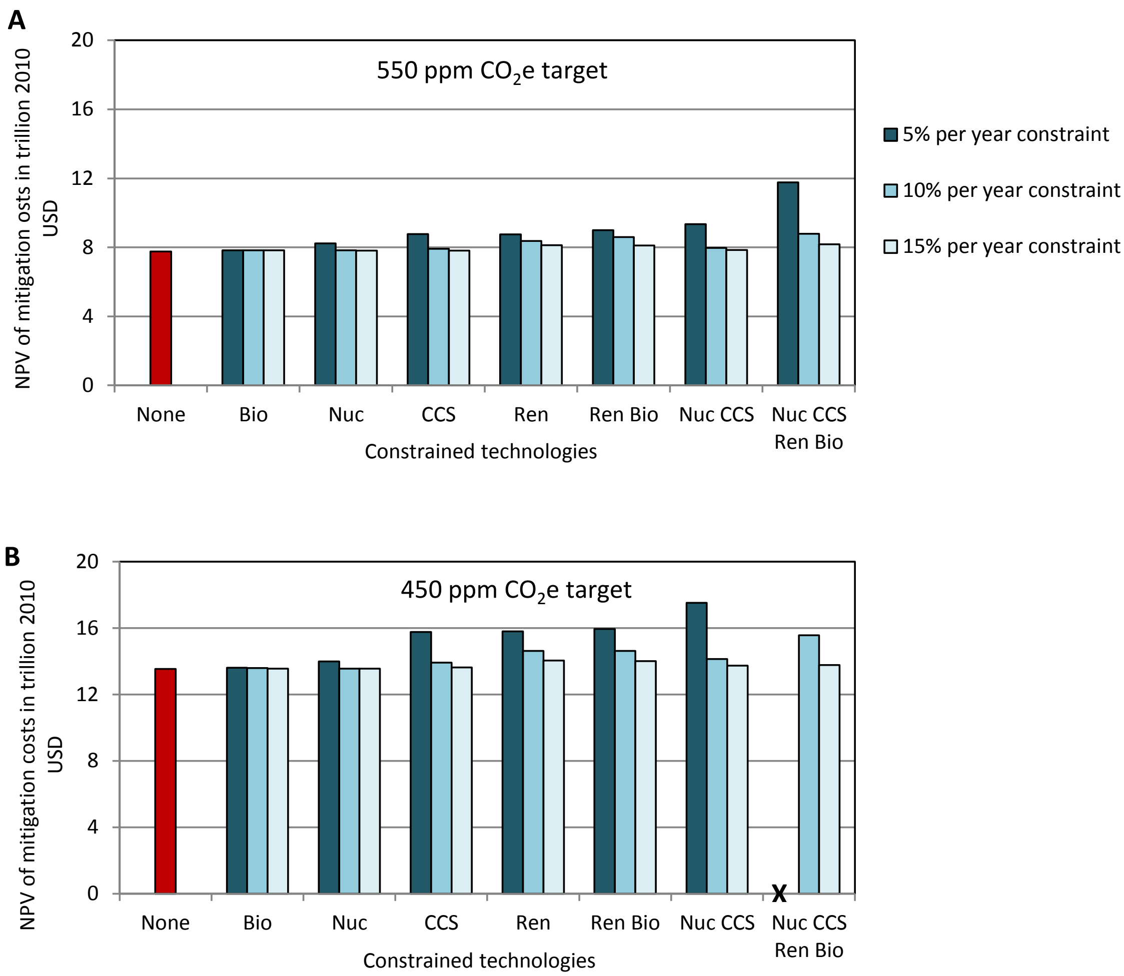


Figure 2-7 NPV of 2020-2095 mitigation costs under diffusion constraints on low-carbon technologies and no delay in action for A.) 550 ppm CO_2e target and B.) 450 CO_2e target. An "X" indicates an infeasible scenario. In the presence of constraints to the diffusion of low-carbon technologies, mitigation costs of achieving stringent climate goals are higher. When all low-carbon technologies are jointly constrained at the 5% per year level, achieving the 450 ppm target is infeasible.

Constraints on the diffusion of low-carbon technologies also influence 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.

2.5.3. The effect of diffusion 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 we expect to see higher mitigation costs and even infeasibilities with diffusion constraints on top of delays. Delays in policy action in addition to diffusion 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 2-8 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.

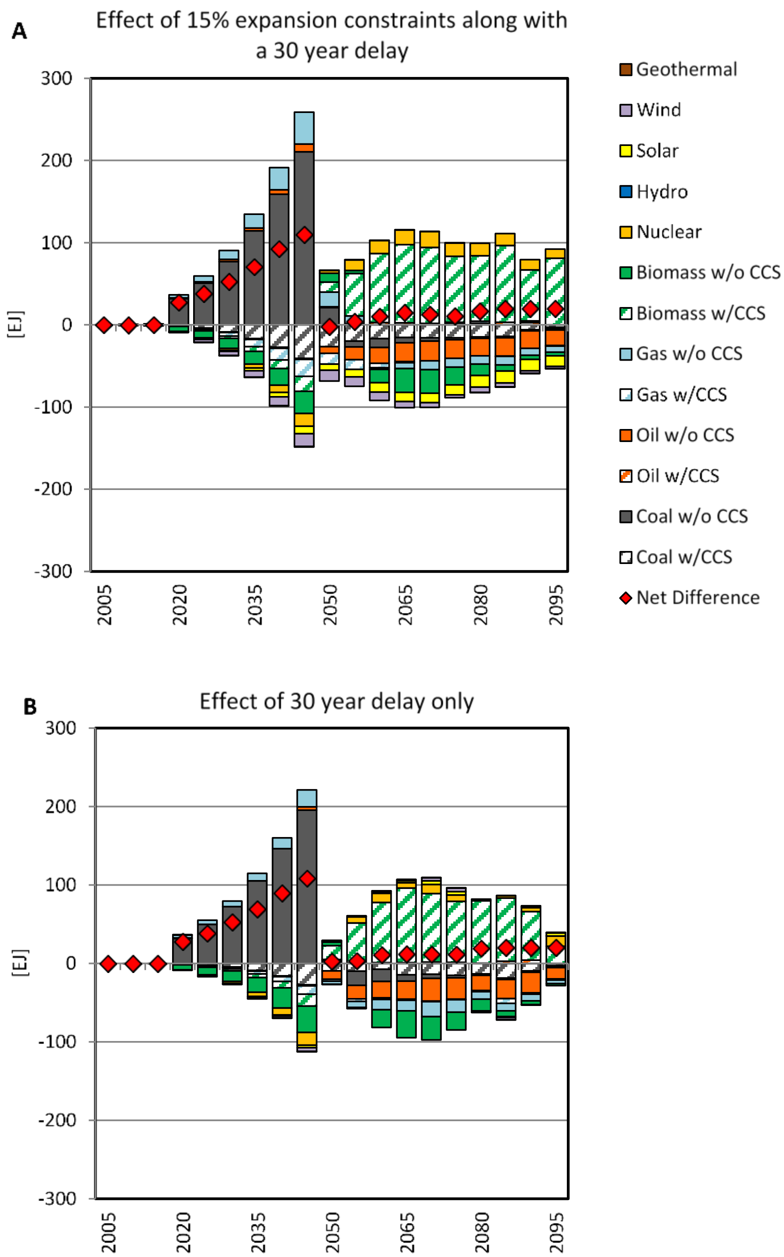


Figure 2-8 Change in primary energy consumption by fuel for a 450 ppm CO_2e target with constraints on the diffusion of nuclear, bioenergy, renewables and CCS at the high diffusion rate (15% per year) along with a 30 year delay in policy action, relative to A.) the unconstrained case without delay and B.) the case with the same constraints in place but no delay.

Also, as the diffusion 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 diffusion 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 2-8 B).

Mitigation costs increase convexly with number of years of delay in policy action as in the case without diffusion constraints (Figures 2-2 & 2-9). However, the relative increase in costs with delay (in other words, the responsiveness of the costs to delays in policy action) increases in the scenarios with diffusion 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 2-2). In contrast, when the diffusion of bioenergy, nuclear, or renewables are constrained at the medium diffusion rate, a delay of 30 years increases the mitigation costs by 14-18%. Likewise, under the same climate target, when the diffusion 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.

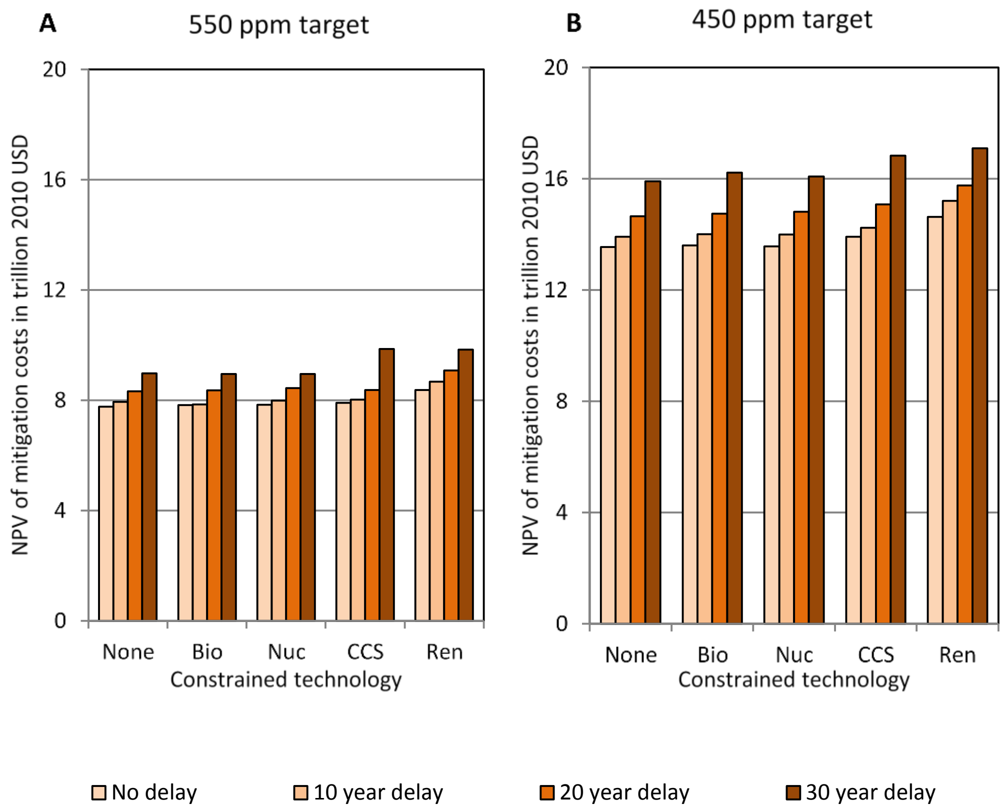
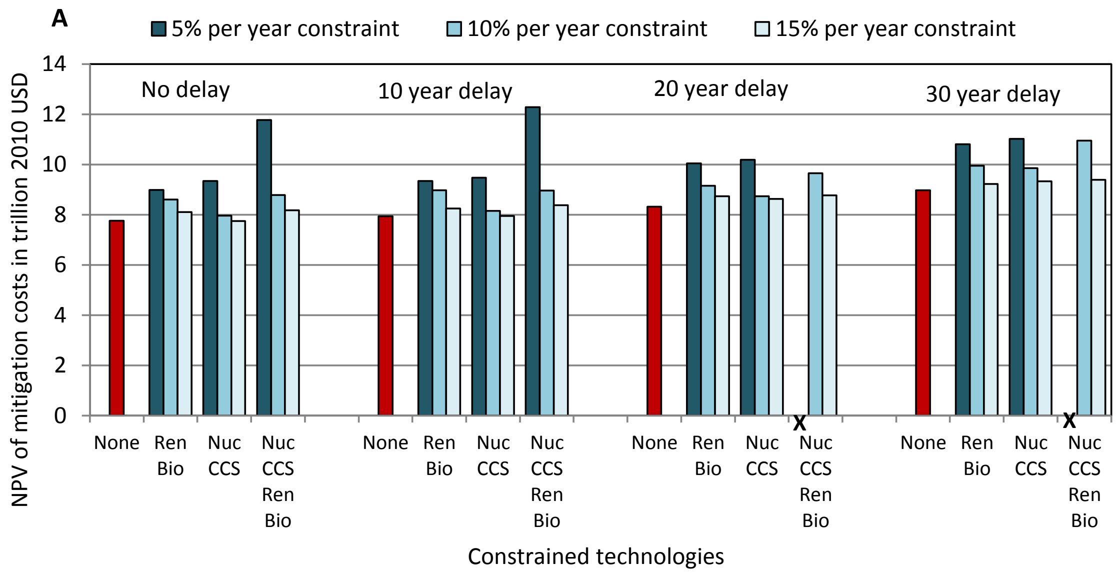


Figure 2-9 NPV of mitigation costs up to 2095 under the medium diffusion rate constraint on the diffusion of individual low-carbon technologies and delays in policy action for A.) 550 ppm CO_2e and B.) 450 ppm CO_2e targets. In the presence of delays, mitigation costs are higher.

Delays in policy action influence the effect of diffusion constraints on mitigation costs substantially especially when low-carbon technologies are jointly constrained (Figure 2-10). For example, the mitigation cost for the 550 ppm target under the low diffusion rate constraint on the diffusion 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 diffusion constraints. For example, with no delay, the mitigation cost of achieving the 550 ppm target with the low diffusion rate on renewables and bioenergy is 11% higher than the case with the high diffusion rate constraint. However, with a 30 year delay, this increases to 17%.

Achieving stringent climate targets under diffusion constraints becomes challenging with delays in policy action. When the diffusion of CCS or renewables is constrained at the low diffusion 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 diffusion rate constraint, 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 diffusion 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.



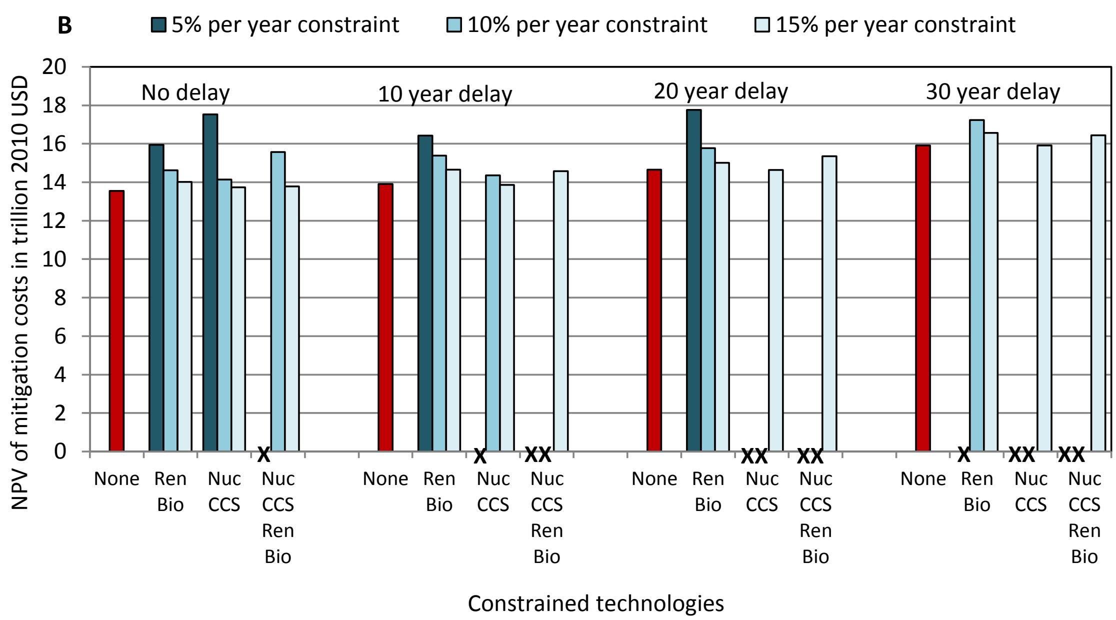


Figure 2-10 NPV of mitigation costs up to 2095 for A.) 550 ppm CO_2e and B.) 450 ppm CO_2e targets under different constraints on the diffusion of multiple low-carbon technologies on top of delays in policy action from 2020. An "X" indicates an infeasible scenario. When mitigation action is delayed, achieving stringent climate goals may be infeasible, especially when low-carbon technologies are jointly constrained

2.6. 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 essay, I review the literature on the sources of such factors and have highlighted potential implications of technology diffusion constraints. I also study 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 I impose exogenous diffusion constraints that aim to capture the effects of various factors that influence the rate of low-carbon technology diffusion.

The analysis in this essay provides several 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 diffusion 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. Likewise, this analysis shows that delayed action itself may not matter a lot in a world with no diffusion constraints. However, delayed action becomes extremely important with diffusion constraints on major low-carbon technologies. For example, without any diffusion constraints, a 450 ppm target with a 30-year delay can be achieved at higher costs. However, under severe constraints on the diffusion of low-carbon technologies, achieving this target becomes infeasible even with a 10-year delay in policy action.

Third, constraints on the diffusion 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. The presence of factors serving to slow down the diffusion of low-carbon technologies in the real world implies that achieving long-term policy targets may require particular focus on near-term policy for technology deployment.

This analysis is not without limitations. First, the diffusion constraints specified in this analysis are constant over time. Thus, I 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 ease some of the constraints and potentially speed up diffusion. Nevertheless, I believe that insights that would have been obtained by modeling this endogeneity are captured, at least in part, by specifying different levels of diffusion rates. Second, it may be likely that the diffusion rates are not constrained as severely as this chapter assumes, particularly for technologies such as wind and photovoltaics. For example, among other factors, economies of scale and ease of installation might ease the stringency of diffusion rate constraints for photovoltaic technologies. It is important to note that this chapter explored a range of scenarios in which not only were different levels of diffusion rate constraints imposed, but these were also imposed on different sets of low-carbon technologies. Also, the constraints considered in this chapter are meant to capture among others, institutional, behavioral and social factors that might limit diffusion rates even in the presence of favorable technology characteristics and policies (Hultman et al., 2012). The results of these scenarios should, therefore, not be seen as only showing the increasing difficulty of mitigation in the presence of diffusion rate constraints, but also viewed as highlighting the importance of addressing them.

Third, I 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, I believe that the broad qualitative insights from this analysis would remain unchanged. Fourth, it is important to bear in mind that the scale of negative emissions in the second half of the century might influence the costs and feasibilities of the scenarios explored in this essay. Finally, future studies must investigate the implications under less than perfect international cooperation in terms of climate policy and technology transfers.

Chapter 3 Long-term payoffs of near-term low-carbon deployment policies

3.1. Introduction

Recent climate change negotiations indicate that near-term actions to address climate change are likely to occur on the basis of national priorities and preferences. Countries are likely to employ a range of different policy options, not just idealized economy-wide carbon price based mechanisms. One common option under consideration is promoting the deployment of specific low-carbon technologies in the near-term through policies such as renewable portfolio standards, feed-in-tariffs, subsidies, etc. For example, in the recent US-China climate deal, China's commitments focused on increasing the share of non-fossil energy sources in the near-term (The White House, 2014). Although promoting the deployment of low-carbon technologies through policies such as subsidies involves a cost in the near-term, these policies can pay off in the future, through reduced costs of long-term emissions abatement, improved competitiveness of domestic industries leading to expanded exports and improved energy security.

This essay focuses on reduced costs of long-term emissions abatement. There are two avenues for reducing long-term abatement costs (Figure 3-1). First, there is a *near-term abatement* effect. Promoting the deployment of low-carbon technologies may avoid lock-in into carbon-intensive technologies, leading to emissions abatement in the near-term. If, in the long-term, there is globally coordinated action against climate change to achieve a climate target by the end of the century, abatement in the near-term would result in lower abatement in the long-term because, the more abatement that occurs in the near-term, the less that needs to occur in the long-term for a given long-term climate goal; resulting in reduced long-term abatement costs. Second, there is a *technological change* effect - promoting the deployment of low-carbon technologies could lead to improvements in technology costs, reducing long-term abatement costs (Grubb, 1997; Grübler and Messner, 1998; Schneider and Goulder, 1997). An important question in this context is, how do these interact and what does this mean for the most effective mix of near country-level deployment policies? Should all countries pursue the same technologies? Is a diversified approach more effective?

The potential answers to these questions are complicated by the fact that what is cost-effective globally may not be so from the domestic perspective. This difference between domestic and global outcomes is due to the public goods characteristics of both near-term abatement and technological change. Emissions abatement is a public good because greenhouse gases are well-mixed. Likewise, technological change that occurs domestically due to a domestic deployment policy may spill over to firms globally, also representing a public good (Clarke and Weyant, 2002).

In this essay, I examine the divergence between long-term domestic and global outcomes in the context of an international approach to climate change, in which countries promote low-carbon technologies in the near-term by means of deployment policies. As I will show, the nature of this divergence depends critically on a range of factors, including the nature of technological change, technology spillovers, and domestic mitigation potentials. For the purpose of illustrating the potential implications of these various factors, I conduct a series of examples in which China and USA have the option to promote wind or solar technologies in the near-term. I use the Global Change Assessment Model

(GCAM), to produce results for this example under a range of different conditions. It is important to note that the aim of the analysis is not to represent any particular real-world policy, but rather to illustrate, by means of an example, the various forces at work, how they interact, and the implications for international collaborations on climate change mitigation and technology.

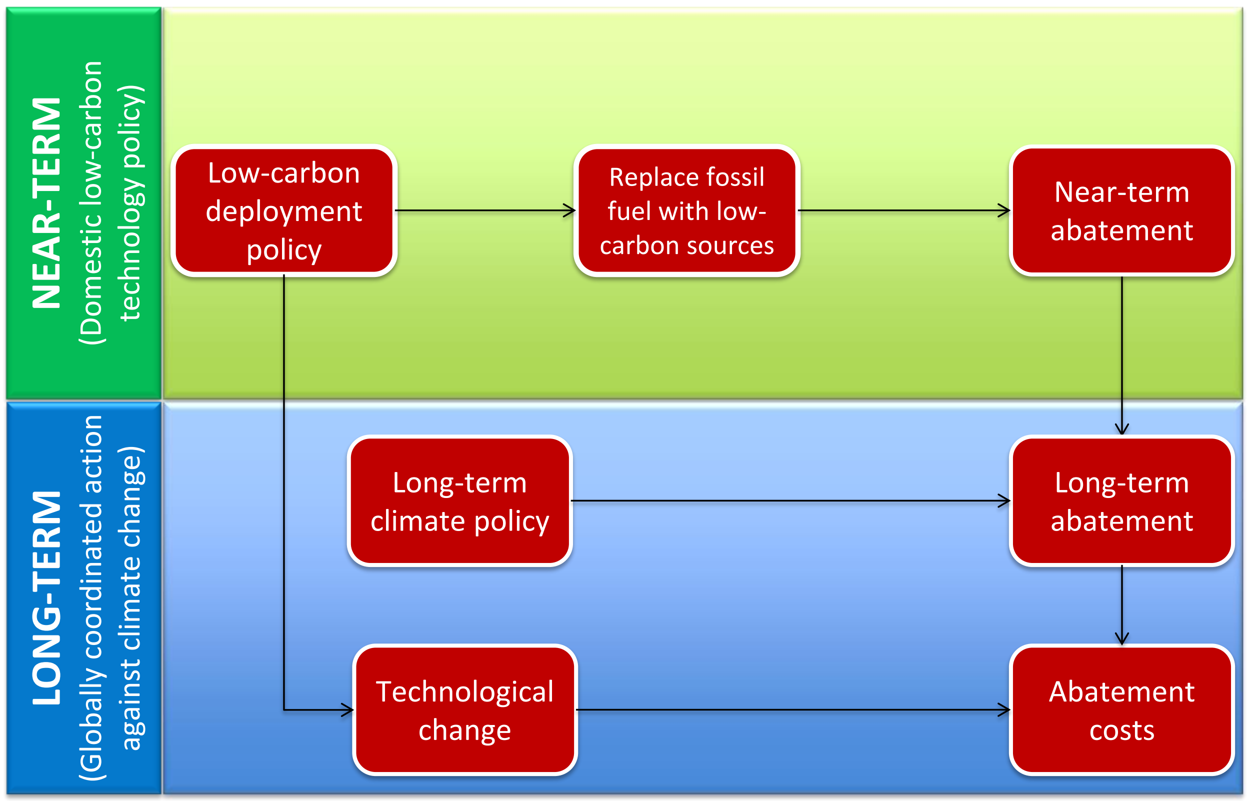


Figure 3-1 An example of the long-term payoffs of near-term low-carbon deployment policies. Promoting the deployment of low-carbon technologies by means of a deployment policy (such as subsidy or standard) would lead to reduced abatement costs in the long-term through two effects: the near-term abatement effect and technological change effect.

The paradox that individually rational strategies lead to collectively irrational outcomes has been discussed at length (see for example, Olson (1965)) and illustrated for a broad range of issues such as supply chain management (Cachon, 2001; Cachon and Netessine, 2004) and even international climate change negotiations (Barrett, 2003). The principal contribution of this essay is to illustrate these effects in the context of low-carbon technology deployment policies and international climate change mitigation. Another key contribution of this essay is that it extends existing analyses based on energy-economic models that have explored the economics of "sub-optimal" near-term policies. Although several studies in the past have dealt with benefits of near-term mitigation actions and their implications for the long-term, they do not address the issue of near-term action from the perspective of technology policies or more specifically, deployment policies. Near-term policy in such studies is typically assumed to be the application of a carbon price. Example of such studies include Bosetti et al. (2009a) and Jakob et al. (2012). Studies that do consider technology policies explicitly have either assessed different policy options for promoting low-carbon technologies (which approach is the best?) or focused on the interaction effects of carbon-price based and technology policies. As an example of the first type, Fischer and Newell (2008) used a theoretical model and found that in terms of achieving emissions reductions in the U.S. electricity sector, an emissions price policy ranked highest while subsidies for adopting renewables and R&D subsidies ranked lowest. Studies such as Fischer (2008) and Fischer and Preonas (2010) use theoretical models to make the argument that technology policies are effective only with emissions pricing and serve as complements to rather than substitutes for the latter. Examples of the second type include studies from the EU that are based on the interaction between the EU-ETS and renewable support schemes. Such studies use large-scale quantitative energy-economic models to conclude that the renewable support schemes do not help in achieving any additional emissions reduction on a global level over and above the ETS and that they also tend to increase the overall mitigation costs (Böhringer et al., 2009; Böhringer and Rosendahl, 2010; del Río, 2009; Fankhauser et al., 2010; Pethig and Wittlich, 2009).

In contrast to the above analyses, Clarke et al. (2010) explored the role of advanced technologies being available only in the United States versus globally and found that domestic and global benefits of achieving a stringent climate goal in these cases are vastly different. For example, if advanced technologies are made available everywhere but the United States, global abatement costs are lower than if advanced technologies are available only in the United States. On the other hand, if advanced technologies are made available in the United States alone, abatement costs to the United States are higher. This essay builds off the Clarke et al. (2010) study by introducing elements of heterogeneity in near-term technology choice and analyzing long-term implications from the perspectives of both, the globe as well as the individual countries undertaking deployment policies in the near-term.

This chapter is organized as follows. First, I provide a background on the long-term payoffs of promoting the deployment of low-carbon technologies in the near-term. The next section describes the construction of the analysis in which I consider the example of China and USA promoting wind and solar in the near-term. Following this, I use the Global Change Assessment Model (GCAM) to understand how different configurations of near-term deployment policies impact domestic and global outcomes for the long-term. The final section of the paper concludes with a discussion of the broader implications of the results.

3.2. Review of long-term payoffs of near-term deployment policies

Policy makers make use of a number of policy instruments to promote the deployment low-carbon technologies. Examples include renewable portfolio standards (which is prevalent in many US states and some European countries), feed-in-tariffs (common in majority of European countries, Australia, Canada and some developing countries), exempting energy taxes on low-carbon technologies, production tax credits and subsidies (for example for nuclear power in the US). Although such policies involve a cost in the near-term, they could pay off in the long-term. In this section, I review some of the long-term payoffs of promoting the deployment of low-carbon technologies through near-country level deployment policies in the near-term.

3.2.1. Reduced long-term abatement costs

An important long-term payoff of promoting the deployment of low-carbon technologies is that it could lead to reduced costs of emissions abatement in the long-term. Two main effects lead to this. The first is the *near-term abatement effect*. 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 low-carbon technologies, leading to a “carbon lock-in” (Arthur, 1989; Grübler et al., 1999; Unruh, 2000). Deployment policies to promote the deployment of low-carbon technologies help in avoiding carbon lock-in – they displace carbon-intensive fossil fuel technologies and add low-carbon energy to the energy system, leading to emissions abatement.

Near-term abatement is a public good because greenhouse gases are well mixed. Consequently, any abatement achieved by the investor country also applies to the globe. Hence, if, in the long-term, there is global action against climate change to achieve a climate target by the end of the century, abatement in the near-term would result in lower global abatement in the long-term, because, the more abatement that occurs in the near-term, the less that needs to occur globally in the long-term. This would lead to reduced global abatement costs in the long-term. In addition, reduced global abatement in the long-term also implies reduced abatement by the investor country, resulting in reduced long-term abatement costs for the investor country as well.

The second effect is the *technological change effect*. The literature on induced technological change suggests that promoting the development and deployment of technologies could lead to improvements in technology costs (Clarke et al., 2006; Clarke and Weyant, 2002; Jaffe et al., 2003; Popp et al., 2010). For example, the performance of a technology could improve as experience with the technology accumulates. This concept, widely known as learning-by-doing occurs as repetitive manufacturing tasks result in an improvement in the production process, which can also be supported by a number of forces such as increases in labor efficiency, new processes and changes in production methods, changes in the administrative structure, etc. Other avenues through which such improvements occur include users' experience and feedback effects as sources of learning and further R&D and tacit learning through increase in the stock of knowledge arising out of exchange of information about product characteristics and user requirements between various actors such as research laboratories, industry, end-users and policy makers (see Kahouli-Brahmi (2008) for a detailed taxonomy and description of such mechanisms). Promoting the deployment of low-carbon technologies could thus generate cheaper technological options and emissions can be reduced at lower costs in the future, potentially leading to substantial economic benefits to the investor countries.

The technological change effect also has public goods characteristics. Technological change that occurs domestically due to a domestic deployment policy may spill over to firms globally. A number of studies have confirmed the presence of such spillovers in the manufacturing sector (Argote et al., 1990; Barrios and Strobl, 2004), semiconductor industry (Irwin and Klenow, 1994), chemical processing industry (Lieberman, 1984) and the nuclear power industry (Lester and McCabe, 1993; Zimmerman, 1982). In a more recent study, Nemet (2012) analyzed a panel of electricity output from wind turbines in California, and found that firms not only learned from their own experience but from the experience of others as well. In the case of low-carbon technologies such as wind, it might also be reasonable to assume that spillovers exist on a global scale – because the global wind market is dominated by few turbine manufacturers, especially the Danish ones and because these big manufacturing companies deliver turbines all over the world and basically use the same technology concepts (Junginger et al., 2005).

The public goods characteristics of the technological change effect described above could influence long-term abatement costs for the globe as well as the investor country. First, as explained earlier, since an emissions abatement technology is cheaper, the investor country would benefit from it for its own emissions abatement. In addition, if the cheaper technology becomes widely available through spillovers, it lowers the cost of emissions abatement in general. This effect would help the investor country even were it never able to utilize the technology itself, since the technology lowers the cost to all parties leading to greater emissions reductions by other parties, and thereby reducing the level of effort needed in the investor country itself, further reducing abatement costs for the investor country.

The above discussion suggests that the near-term abatement and technological change effects are rather complicated and deserve careful analysis. While examining these effects on the global and domestic long-term abatement costs is the focus of this paper, it is important to look at other avenues through which near-term low-carbon deployment policies could pay off in the future. In the following subsections, I review some such payoffs.

3.2.2. Early-mover advantages

Deployment policies targeted at specific technologies could create early-mover advantages for domestic firms. From the perspective of a firm, an important source of early-mover advantages is technological leadership. Cheaper technological options may arise due to the technological change effect explained earlier; and if those options can be kept proprietary through mechanisms such as patents, it could create barriers to entry for late entrants, creating opportunities for technological leadership. In this case, the returns garnered by the early moving firm are pure economic rents (Lieberman and Montgomery, 1988).

In addition to advantages at the firm level, expansion of a low-carbon industry could lead to increases in overall macro-economic growth through the expansion of export industries and associated increases in wages. A classic example in the energy industry is that of Denmark. Hansen et al. (2003) found that the Danish wind energy strategy not only improved the international competitiveness of the industry but also compensated for the initial welfare loss. Another example is that of the Spanish wind sector in which several hundred firms dedicated to equipment manufacturing, installation and sales, financial services, technical assistance, and maintenance services supply almost a fifth of all wind turbines installed in the world (Lund, 2009).

In addition to the above advantages, expansion of low-carbon industries could create domestic employment opportunities. In the case of renewable energy policies, proponents have argued that compared to fossil-fuel power plants, renewable energy generates more jobs per unit of installed capacity, per unit of power generated and per dollar invested (Kammen et al., 2004; UNEP, 2008; Wei et al., 2010).

3.2.3. Energy security

Many countries promote alternative technologies with the objective of energy security. Industrialized as well as developing nations have shown renewed focus on energy security because of the exceedingly tight oil market and high oil prices and also due to other drivers such as the threat of terrorism, instability in some exporting nations and geopolitical rivalries (Chester, 2010; Yergin, 2006).

To summarize, promoting the deployment of low-carbon technologies in the near-term could pay off for the investor country in several ways, making a rather strong case for specialization in particular low-carbon technologies. However, because technologies have public goods characteristics, specialization may not lead to a globally cost-effective outcome. For example, if all countries were to specialize in the same low-carbon technology, from the global perspective, long-term abatement costs (assuming long-term global action against climate change) would be greater than the case in which different countries specialize in different low-carbon technologies. This is because, in the latter scenario, technological improvements in more emissions abatement technologies could become widely available through spillovers, leading to lower global long-term abatement costs compared to the scenario in which all or most countries specialize in the same technology, in which case, spillovers could be redundant. Thus, we expect the globally cost-effective strategy to be a diversified portfolio of investments.[7]

The above discussion suggests that, if countries were to interact and negotiate with each other on technology deployment, motivated by domestic economic benefits that might accrue from specializing in particular low-carbon technologies, we would expect to see a divergence between domestic and global outcomes. In the subsequent sections, I illustrate this divergence by means of an example in which China and USA have the option to promote wind or solar technologies in the near-term through deployment policies. I use the GCAM integrated assessment model to examine long-term payoffs for the globe as well as the investor countries. While the focus of the present analysis is on payoffs from reduced long-term abatement costs to illustrate the key dynamics in play, I also consider

[7] Although I do not examine them in this study, other arguments for a diversified portfolio of investments in technology include diminishing returns to scale of experience and technological knowledge and risk management (see for example, Blanford and Clarke (2003)). Knowledge gained out of experience or R&D has been shown to exhibit diminishing returns to scale (Arrow, 1962). Hence, as marginal returns fall with increased investment, it will be optimal to invest in options that generate higher marginal returns to exploit the most productive range in each option. Likewise, diversification might also provide insurance against any single technology not advancing as fast as expected. Finally, under uncertainty about when and where unexpected technological breakthroughs might arise, diversification could provide the ability to take advantage of such opportunities. Note that the above arguments for diversification hold for individual countries as well. In this study, I do not investigate the case in which countries promote the deployment of different technologies, reserving it for future research. The focus of this essay is to understand the long-term implications when countries are motivated by interests to specialize in particular technologies.

payoffs from early-mover advantages to understand how including such payoffs influences the key insights.

3.3. Methodology

3.3.1. The GCAM integrated assessment model

This analysis uses the Global Change Assessment Model (GCAM) described in Section 2.4. Features of the model that are relevant to this chapter are as follows. Outcomes of GCAM are driven by assumptions about population growth, labor participation rates and labor productivity in fourteen geo-political regions, along with representations of resources and technologies (Edmonds et al., 2004; Kim et al., 2006). Deployment of technologies in GCAM depends on relative costs and is achieved using a logit-choice formulation in which not all decision makers choose a technology option just because it is cheaper; higher-priced options may also get some market share (McFadden, 1980). Costs of solar and wind technologies include exogenous capital and O&M costs; resource costs based on exogenous supply curves, representative of costs that are expected to increase with deployment as least-cost sites are used first (such as long-distance transmission line costs that would be required to produce power from remote wind resources) and endogenous resource intermittency costs (Clarke et al., 2008).

3.3.2. Example of China and USA promoting wind or solar technologies in the near-term

In this essay, I consider an example of China and USA having the option to promote wind or solar technologies in the near-term and use GCAM to analyze long-term payoffs. Throughout the analysis, I assume that the near-term refers to the period between 2016 and 2030 and the long-term refers to the period between 2031 and 2100. The selection of countries for the example is based not only on relevance to recent policy discussions, but also differences in expected near-term energy system characteristics in the absence of any targeted deployment policy. For example, China's energy system is dominated by coal and is expected to grow in the near-term (Figure 3-2 A). In contrast, gas and oil account for a significant share in the energy mix of USA, in addition to coal and the energy system is expected to remain stable. The selection of technologies is based on differences in expected near-term market maturities of the technologies in domestic as well as global markets. In the example, the relatively cheaper and mature technology is wind.

Near-term low-carbon deployment policies are modeled as renewable portfolio standards to achieve an installed capacity of 500 GW by 2030 (roughly consistent with an extrapolation of China's 2017 targets for installed capacity of wind technologies) (Bloomberg, 2014).[8] Near-term costs are calculated as the change in both consumer and producer surplus due to the policy. For simplicity in illustrating the key dynamics in play, no other countries undertake mitigation during this period. These policies will lead to emissions abatement in the near-term, but they could also lead to technological change in the targeted technologies in the long-term. In the long-term, I assume that there is globally coordinated action (modeled as a global price on carbon) to achieve 550 ppm CO_2e by 2100. In the long-term, I consider payoffs from reduced in abatement costs to illustrate the key dynamics. In addition, I consider payoffs from early-mover advantages

[8] I fix the near-term installed capacities across possible deployment policy configurations to focus on the near-term abatement and technological change effects, keeping other variables fixed. Alternative assumptions about near-term installed capacities would not materially alter the insights obtained from this analysis.

to understand how these dynamics change when other payoffs are included. The above assumptions are summarized in Table 3-1.

Table 3-1 Summary of key assumptions

Variable	Near-term	Long-term
Period	2016-2030	2031-2100
Policy mechanism	Deployment policy (renewable portfolio standard)	Global carbon price
Policy stringency	500 GW cumulative installed capacity by 2030	550 ppm CO_2e by 2100
Costs	Change in consumer and producer surplus due to policy	None
Payoffs	None	Reduced long-term abatement costs* Early-mover advantages
Technological change	Deployment policies do not lead to additional technological change	Technological change scenarios**

*Abatement costs are calculated as area under the marginal abatement cost curve

** See Table 3-2

I consider four scenarios to investigate the technological change effect (Table 3-2). First is the counterfactual scenario in which deployment policies do not lead to any additional improvements in technology costs (the "No additional technological change" scenario). If deployment policies lead to improvements in technology costs, they may apply only to the country that invests in the deployment policy (the "Faster domestic improvements" scenario) or spill over to other countries. If they do spill over, they may do so after some period of delay beyond 2030 (the "Faster domestic improvements and delayed spillovers" scenario) or immediately in 2030 (the "Faster domestic improvements and immediate spillovers" scenario) (See Appendix C for a detailed description about technology costs).[9]

Table 3-2 Technological change scenarios to study the technological change effect.

Technological change scenario	**Technology costs in the long-term**	
Near-term deployment policy leading to	**Region with deployment policy**	**Region without deployment policy**
No additional technological change	Reference	Reference
Faster domestic technological improvements	Advanced	Reference
Faster technological improvements and delayed spillovers	Advanced	Delayed-Advanced
Faster technological improvements and immediate spillovers	Advanced	Advanced

Finally, in order to test the sensitivity of the results to assumptions about rates of technological improvements, I consider five sensitivity cases in which I vary the rates of technological improvements (Table 3-3). This also includes a breakthrough scenario in which promoting solar in the near-term leads to a technological breakthrough in solar technologies such that costs of solar technologies drop to one-fourth that of wind by 2050 and rapidly decrease thereafter.

[9] In this stylized representation of technological change, I do not explicitly track the sources of technological change to avoid uncertainties related to estimations of the effects of R&D and experience on technological change to influence the insights from the analysis. In other words, the analysis is largely agnostic to the specific mechanism through which technological change occurs. However, I do consider a number of sensitivity cases, including a breakthrough scenario to study the effect of the rate of technological change on the results.

Table 3-3 Sensitivity cases to study the effect of rates of technological improvements on domestic and global outcomes.

Reference technologies	Advanced technologies		
Rate of improvement of reference solar technologies relative to reference wind technologies	**Rate of improvement of advanced solar technologies relative to reference solar technologies**	**Rate of improvement of advanced wind technologies relative to reference wind technologies**	**Remarks**
2	2	2	Central Assumptions
4	2	2	
2	4	4	
4	4	4	
2	Costs of solar technologies drop to one-fourth of wind by 2050 and improve eight times as fast as reference technologies thereafter	2	Solar breakthrough

3.4. Effects of deployment policies in the near-term

To understand the implications of deployment policies, it is useful to first explore the nature of technology deployment absent any near-term policies. In this case, near-term deployment of wind in both countries is larger than solar because wind is relatively more mature and cheaper – hence more competitive – compared to solar (Table 3-4). In addition, the deployments of both technologies are greater in China compared to USA because China's energy demand grows far more rapidly. Differences in near-term deployments can also be explained by differences in resource endowments and domestic preferences.

Table 3-4 Near-term deployments of wind and solar without and with a deployment policy in China and USA.

Country	2030 Cumulative deployments				2030 additional deployment with deployment policy [GW]	
	Without deployment policies [GW]		With deployment policies [GW]			
	Wind	Solar	Wind	Solar	Wind	Solar
China	177	11	500	500	323	489
USA	62	4	500	500	438	496

Under deployment policies, fossil-fuel energy sources are replaced with low-carbon sources, leading to near-term emissions abatement (Figure 3-2 B). A solar policy leads to greater near-term abatement compared to a wind policy because a solar policy adds more low-carbon energy to the system (note that both, wind and solar policies are modeled to achieve the same cumulative capacity in the near-term and there is lesser solar to begin with, see Table 3-4). Consequently, the economic costs of a solar policy are higher (Figure 3-2 C). Near-term costs for USA and China are different because of differences in resource endowments and energy system characteristics (for example, China's energy system is dominated by coal which is cheaper to displace compared to gas and oil which account for a significant share in the energy mix of USA, in addition to coal).

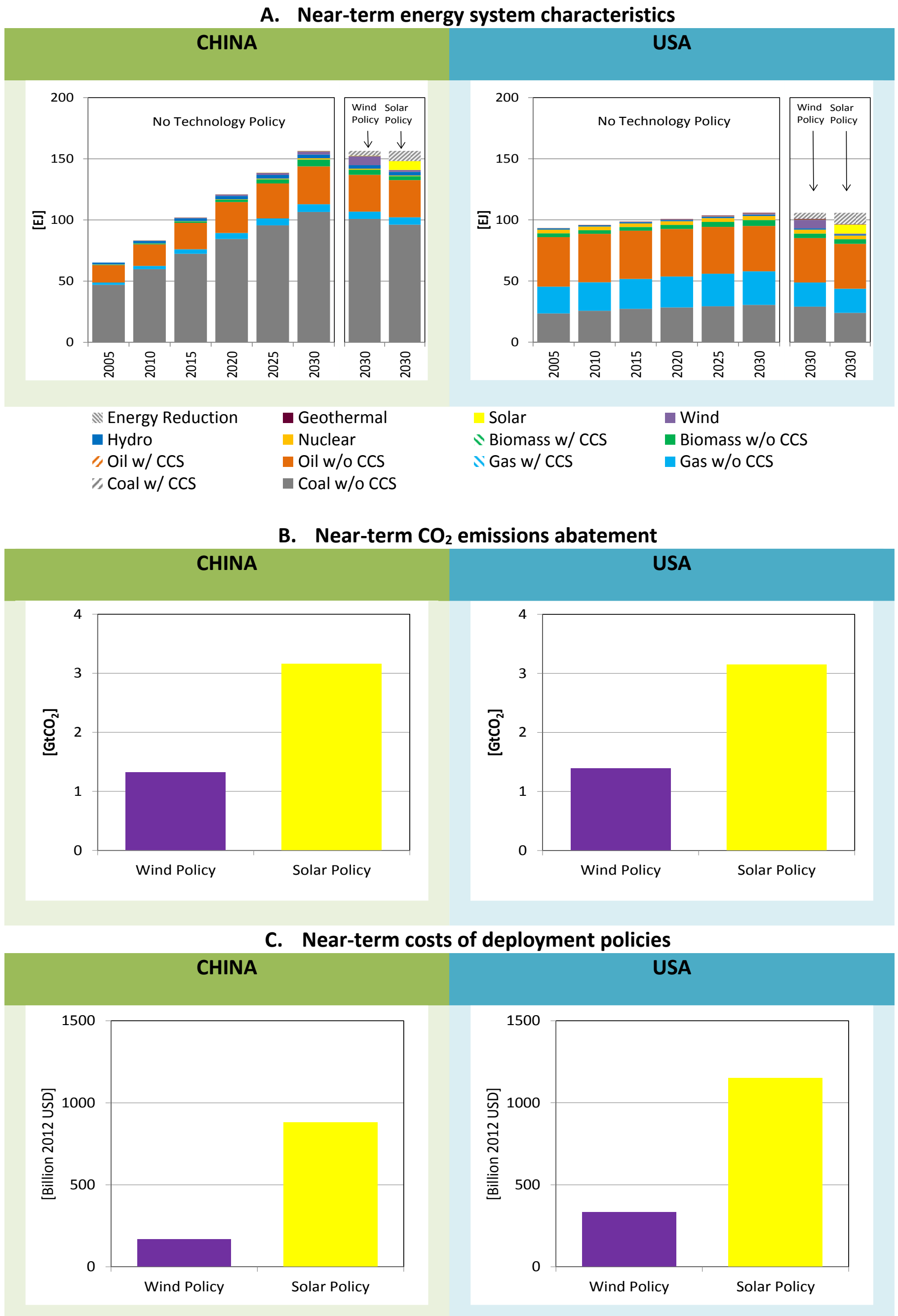


Figure 3-2 A.) Near-term primary energy consumption in China and USA without and with deployment policy B.) Near-term abatements in direct CO_2 emissions from fossil fuel and industry with respect to the case without deployment policies C.) Near-term costs of deployment policies, calculated as change in both consumer and producer surplus with respect to the case without deployment policy. Costs from 2016 to 2030 are discounted and cumulated.

3.5. Long-term payoffs from reduced abatement costs

3.5.1. Near-term abatement effect

To understand the *near-term abatement effect*, it is useful to first explore the scenario in which deployment policies do not lead to any additional technological improvements. Any reductions in long-term abatement costs would be due only to the near-term abatement effect. To compare different deployment policy configurations, I define payoff as the reduction in long-term abatement cost with near-term deployment policy relative to the case with no deployment policy divided by the near-term cost of the policy. Thus payoffs in this scenario would be proportional to the ratio of near-term abatement to near-term cost. China's payoffs are highest when China promotes wind and USA promotes solar because this configuration leads to the highest near-term abatement to cost ratio (Figure 3-3 A). In contrast, payoffs for USA are highest when USA promotes wind and China promotes solar (Figure 3-3 B). In other words, since near-term abatement is a public good, both countries benefit from a solar policy because that leads to more abatement; however, promoting solar is more expensive, creating incentives to free-ride. Each country would prefer to promote the relatively mature and cheaper technology (wind) domestically and free ride on the benefits of the other country undertaking larger and more expensive abatement. The equilibrium strategy (derived as the Nash equilibrium for a non-cooperative game with imperfect but complete information[10,11]) is

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[10] I assume, here, that the countries are monolithic, unitary and rational actors with self-interest. Self-interest means that that each country prefers a larger payoff to a smaller one. It also requires that each country does not directly care about the payoff received by the other country.

[11] In game theory, the difference between perfect and complete information is important. Perfect information refers to the case where each player knows how the other will act. Here I assume that the game is played only once and that players make their choices simultaneously, without knowing the other

for both countries to promote wind (Figure 3-4).[12] This is also the globally cost-effective configuration because it leads to the highest near-term abatement to cost ratio (Figure 3-3 C). In other words, from a global perspective, without improvements in technology, there is little reason to invest in the more expensive technology.

3.5.2. Technological change effect

When the *technological change effect* is included – that is, when deployment policies lead to faster improvements in domestic technology costs (that do not spill over to other regions)– domestic and global payoffs are higher because access to advanced wind or solar technologies results in reduced long-term abatement costs. However domestic and global rankings of the configurations are not altered. Both countries are still better off promoting wind irrespective of the other country's choice, making the China-wind-USA-wind configuration the equilibrium strategy. In the absence of spillovers, this strategy is also the globally cost-effective one (Figure 3-3 D-F).

country's choice. Thus, this is a game of imperfect information. Complete information, on the other hand, refers to the case where each player knows the choices that both parties may make, the payoffs associated with every outcome and the preferences of the other player. In addition, I assume that all of this is *common knowledge*: each player knows that the other player knows these things, each knows that the other knows that it knows these things, and so on (Barrett, 2003).

[12] This outcome is the equilibrium because neither player would be better off by deviating unilaterally from this outcome, given the choices of the other player.

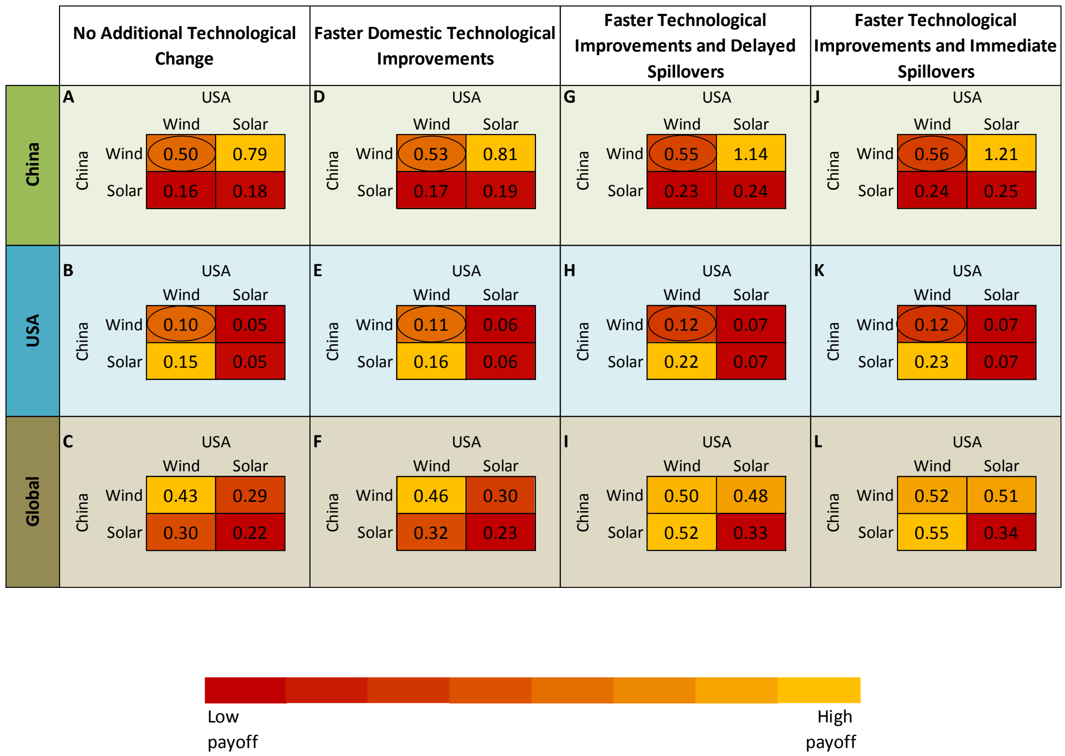

Figure 3-3 Domestic and global payoffs from reduced long-term abatement costs (reductions in long-term abatement costs relative to the case without near-term deployment policies divided by near-term costs of deployment policies) under central technology cost assumptions (see Table 3-3 for more a detailed description of the assumptions). The circled payoffs show the Nash equilibrium under a technological change scenario (see also, Figure 3-4). For both China and USA, highest payoffs are achieved by promoting wind domestically and free riding on the benefits of the other country promoting solar in all technological change scenarios. The Nash equilibrium corresponds to both countries promoting wind in all technological change scenarios. In contrast, in the presence of spillovers, global payoffs are highest when China promotes solar and USA promotes wind.

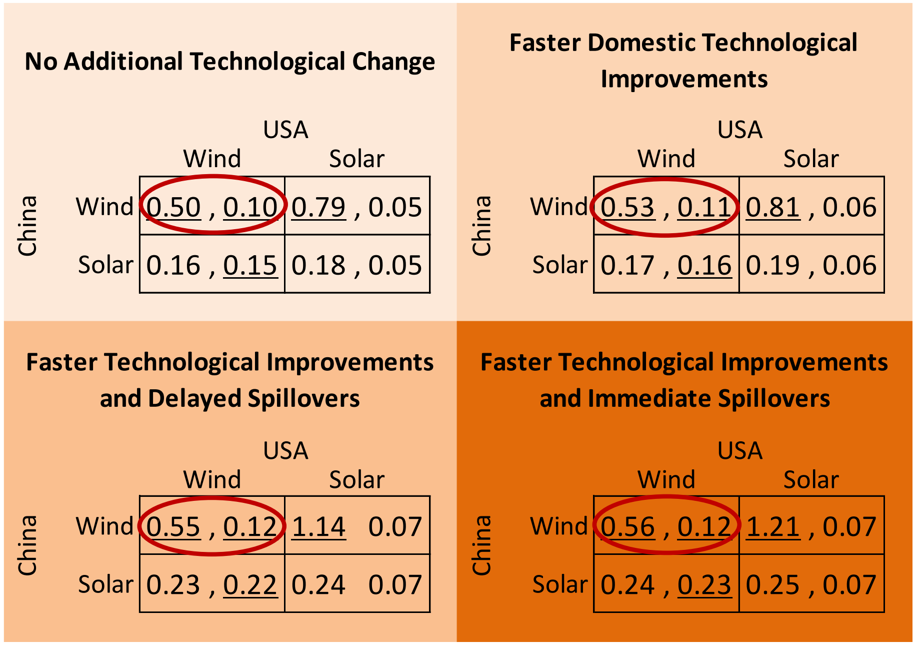

Figure 3-4 Dominant strategies in a non-cooperative game with perfect information in which China and USA chose strategies with the only payoff of reduction in long-term abatement costs. The Nash equilibrium is for both regions to promote the cheaper technology, namely wind under all technological scenarios. The payoffs presented correspond to central technology cost assumptions (see Table 3-3 for more a detailed description of the assumptions).

The technological change effect becomes important if technological improvements *spill over* to other regions (Figure 3-3 G-L). In these cases, global access to cheaper wind and solar technologies lowers marginal abatement costs throughout the globe (leading to lower carbon prices required to achieve the climate target). This effect leads to greater reductions in long-term abatement costs and so, higher payoffs for the investor region even were it never able to utilize the technology itself. This is because, lower marginal abatement costs in the rest of the world results in greater emissions reductions by other regions, thereby reducing the level of effort needed in the region itself. However, domestic rankings of the configurations and the equilibrium strategy remain unchanged.

This is because, promoting solar in the near-term is expensive and advanced solar technologies would be available irrespective of who undertakes the effort in the near-term, adding to the free-riding incentives discussed earlier. Therefore, both countries continue to remain better off promoting wind, irrespective of the other country's choice. In contrast, global payoffs are highest when China promotes solar and USA promotes wind. Not only does this configuration lead to the highest near-term abatement to cost ratio, but improvements in *both* technologies spill over to other regions. In other words, the globally cost-effective configuration corresponds to the one in which public goods characteristics of near-term abatement as well as technological change are maximized.

Domestic payoffs presented in the analysis so far could potentially be influenced by two assumptions. First, while I have considered one long-term payoff of near-term deployment policies (namely, reduction in long-term abatement costs), several others exist (see Section 3.2 for a detailed review). In the following subsection, I consider the implications of including payoffs from early-mover advantages for domestic outcomes. Second, assumptions regarding future rates of technological improvements induced by near-term deployment policies depend on a number of factors. For example, technological change in the rest of the world might spill over to China and USA inducing faster rates of technological improvements. In the subsequent subsection, I consider a number of sensitivity cases with a range of assumptions about rates of technological improvements (Table 3-3).

3.5.3. Long-term payoffs from early-mover advantages

It is important to note that in the analysis so far, I have considered only one long-term payoff of near-term deployment policies, namely, reduced long-term abatement costs. As discussed in Section 3.2, promoting low-carbon technologies in the near-term could lead to other domestic payoffs in the long-term, with the potential of influencing the results observed earlier. While a detailed examination of all the payoffs reviewed in Section 3.2 is beyond the scope of the present analysis, I explore how the inclusion of one other payoff, namely, early-mover advantages influences domestic long-term outcomes.

The existence and magnitude of such advantages have been debated. Some scholars are skeptical about early-mover advantages in adopting new technologies. Fudenberg and Tirole (1985), for example, showed that potential early-mover advantages may get completely dissipated under preemptive adoption. By including uncertainty about the profitability of new technology, Hoppe (2000) showed that there may be second mover advantages if spillovers are assumed to be present. In addition, technological, scientific and policy uncertainties (especially in the context of climate change) create an option value for delaying the adoption of a technology (Dixit, 1994).

Likewise, the "green jobs" and "green growth" arguments are also controversial. Creation of "green jobs" could be offset by job losses that result from the crowding out of cheaper forms of conventional energy generation, along with indirect impacts on upstream industries (Frondel et al., 2008; Frondel et al., 2010; Michaels and Murphy, 2009). Subsidies based policies often translate into higher electricity prices for the consumer resulting in lower profits for electric utilities (Traber and Kemfert, 2009). In addition, higher electricity prices could impact economic activity and lead to additional job losses (Frondel et al., 2010). Michaels and Murphy (2009) also argued that because renewables require higher labor input per unit of output compared to fossil fuels, they bring down the overall productivity of the economy. The society thus sacrifices the outputs that those workers could have produced had they been employed elsewhere. Further, Frondel et al. (2010) argued that "green jobs" created by renewable energy promotion would vanish as soon as government support is terminated, leaving only the export sector to benefit from the possible continuation of renewables support in other countries. Indeed, in 2008, Spain accounted for the largest share of solar generation in the world, but its manufacturing and installation of new capacity virtually disappeared in 2009 when subsidies were cut off (Borenstein, 2012) (Note that this is not inherent in any specific technology. If firms are dependent on subsidies, when those revenue streams dry up, firms would reduce output. A similar effect is plausible, for example, in the defense industry which is dependent on government contracts). In addition to the above counter-arguments, there are several challenges to determining the employment effects of renewable energy - for example, an often ignored aspect of employment effects is job quality and job skills (Lambert and Silva, 2012).

In this analysis, early-mover advantages are assumed to represent not only economic rents earned by firms in early-moving countries but also broader impacts on the economy such as job creation reviewed earlier. I approximate early-mover advantages to be equal to a fraction of global market revenue. Since the existence and magnitude of such advantages have been debated, I consider a range of fractions. In addition, I consider market revenues only until 2050, keeping in mind that early-mover advantages get dissipated under competition and preemptive adoption (Fudenberg and Tirole, 1985; Hoppe, 2000).

As explained previously, under central technology cost assumptions (corresponding to the analyses presented in Figure 3-3, see Table 3-3 for detailed assumptions), if countries were to promote low-carbon technologies in the near-term, the globally cost-effective strategy in terms of abatement costs of achieving a stringent long-term climate goal is a diversified approach in which different countries invest in different technologies. In contrast, the cost-effective strategy from the perspective of individual countries is to invest in currently mature and cheaper technologies. The question relevant to the present analysis is whether including early-mover advantages affects this outcome and align it with the globally cost-effective strategy.

In this case, solar technologies are more expensive than wind even if deployment policies are assumed to lead to faster technological improvements in the long-term. Hence, in all technological change scenarios, global demand for solar technologies is lower than wind and the future global revenue from the solar market is smaller (Figure 3-5). As a result, even under optimistic assumptions about the presence and magnitude of early-mover advantages (which are proportional to the future global revenue), both countries continue to remain better off promoting wind irrespective of the other country's choice and the equilibrium strategy remains unchanged (Figure 3-6).

The results suggest that if countries interact with each other and make decisions on low-carbon technology deployment driven by domestic advantage alone, such decisions will favor currently cheaper alternatives – even if domestic incentives other than reduced long-term abatement costs are taken into account – primarily because such incentives might be closely tied with each other. This is because, technological change influences payoffs from long-term abatement costs as well as early-mover advantages in similar ways. Under central assumptions about rates of technological change (Table 3-3), solar technologies are more expensive than wind in the long-term in all technological change scenarios. Thus, long-term payoffs from reduced abatement costs with a near-term solar policy are lower than wind in all technological change scenarios.

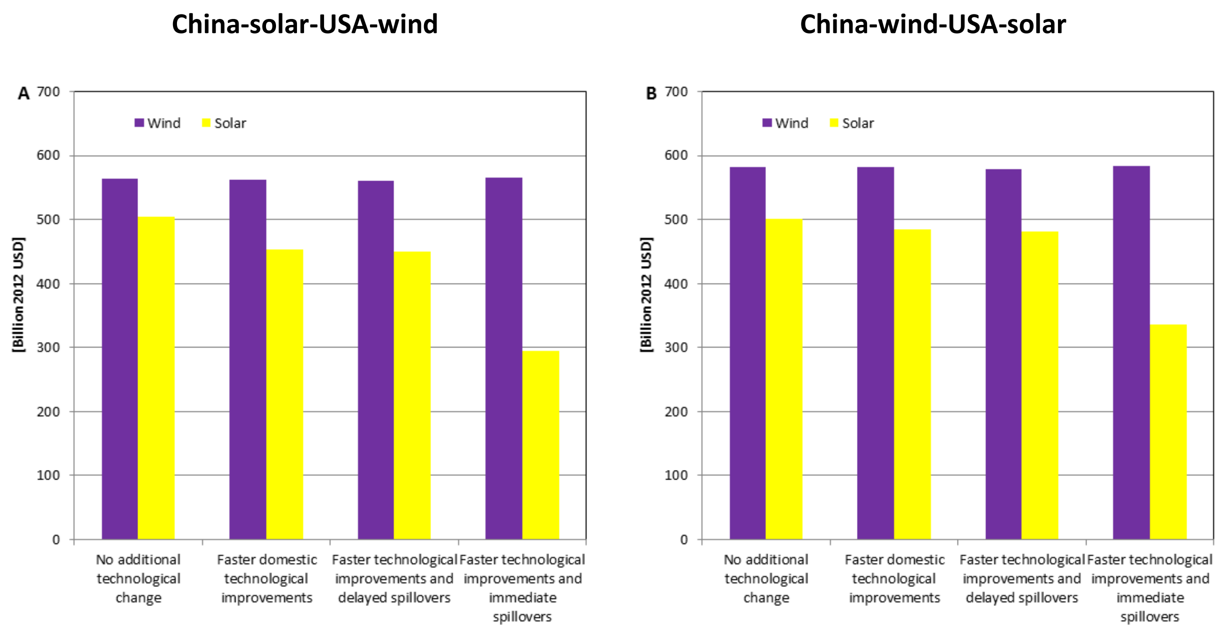

Figure 3-5 Global revenues (2031-2050) from the wind and solar markets in configurations with diversified approaches in which China and USA promote different technologies in the near-term. Revenues from 2031 to 2050 are cumulated and discounted. The cases presented here correspond to central assumptions about technology costs (see Table 3-3 for detailed assumptions).

A. Payoffs for China

Rows: China's strategy; columns: USA's strategy. Fraction of global market revenue captured as early-mover advantages:

Fraction	China	No Additional Technological Change: USA Wind	USA Solar	Faster Domestic Technological Improvements: USA Wind	USA Solar	Faster Technological Improvements and Delayed Spillovers: USA Wind	USA Solar	Faster Technological Improvements and Immediate Spillovers: USA Wind	USA Solar
0%	Wind	0.5	0.8	0.5	0.8	0.6	1.1	0.6	1.2
	Solar	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
20%	Wind	1.0	1.5	1.1	1.5	1.1	1.8	1.1	1.9
	Solar	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
30%	Wind	1.3	1.8	1.3	1.9	1.3	2.2	1.4	2.3
	Solar	0.3	0.4	0.3	0.3	0.4	0.4	0.3	0.3
50%	Wind	1.8	2.5	1.9	2.5	1.9	2.9	1.9	2.9
	Solar	0.4	0.5	0.4	0.4	0.5	0.5	0.4	0.4

B. Payoffs for USA

Fraction	China	No Additional Technological Change: USA Wind	USA Solar	Faster Domestic Technological Improvements: USA Wind	USA Solar	Faster Technological Improvements and Delayed Spillovers: USA Wind	USA Solar	Faster Technological Improvements and Immediate Spillovers: USA Wind	USA Solar
0%	Wind	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1
	Solar	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.1
20%	Wind	0.4	0.1	0.4	0.1	0.4	0.2	0.4	0.1
	Solar	0.5	0.1	0.5	0.1	0.6	0.1	0.6	0.1
30%	Wind	0.5	0.2	0.5	0.2	0.5	0.2	0.5	0.2
	Solar	0.7	0.2	0.7	0.2	0.7	0.2	0.7	0.1
50%	Wind	0.8	0.3	0.8	0.3	0.8	0.3	0.8	0.2
	Solar	1.0	0.3	1.0	0.2	1.1	0.3	1.1	0.2

Low payoff — High payoff

Figure 3-6 Domestic payoffs from reduced long-term abatement costs and early-mover advantages under central technology cost assumptions (corresponding to analyses presented in Figure 3-3, see Table 3-3 for detailed assumptions). Early-mover advantages are calculated as a fraction of global market revenue. The circled payoffs show the Nash equilibria under a technological change scenario for a given fraction of global market.

In addition, global solar revenue in all policy configurations and technological scenarios is lower than global revenue from wind. As a result, long-term payoffs from early-mover advantages with a near-term solar policy are also lower than a wind policy, even under optimistic assumptions about the magnitude of early-mover advantages in all technological change scenarios. Therefore, wind remains the dominant strategy even in terms of total payoffs from reduced abatement costs and early-mover advantages.

Of course, the above treatment of early-mover advantages is rather simplistic and does not represent feedbacks to the economy. In spite of this drawback, it is useful, as a first approximation, to check whether including early-mover advantages will have any influence on domestic outcomes. As I show in the following section, if deployment policies lead to sufficiently rapid technological improvements, domestic outcomes may align with the global outcome even without considering early-mover advantages.

3.5.4. Sensitivity of results to rate of technological change

Assumptions regarding future rates of technological improvements induced by near-term deployment policies depend on a number of factors. For example, technological change in the rest of the world might spill over to China and USA inducing faster rates of technological improvements. In this section, I consider a number of sensitivity cases with a range of assumptions about rates of technological improvements (Table 3-3, Appendix D).

Of particular interest is a scenario in which promoting solar in the near-term leads to a breakthrough in solar technologies since recent experience with photovoltaic technologies has shown that such technologies have potential for rapid technological change (REN21, 2013). In the solar breakthrough scenario, costs of (advanced) solar technologies drop to one-fourth that of wind by 2050. In this case, access to advanced solar technologies in the long-term leads to greater reductions in long-term abatement costs compared to wind. Consequently, in the absence of spillovers, both countries are better off promoting solar irrespective of the other country's choice even though promoting solar is expensive in the near-term. Therefore, the equilibrium strategy shifts to both countries promoting solar (Figure 3-7 D-F).

In the presence of spillovers, if USA were to promote solar, China is better off promoting wind. As explained previously, promoting wind is cheaper. Also, this choice would make advanced wind technologies in addition to solar available to the rest of the world, reducing global carbon prices required to achieve the climate target and consequently increasing China's payoffs. However, if USA were to promote wind, China is better off promoting solar rather than wind (even though promoting solar is expensive in the near-term) because that would make the "breakthrough" solar technologies available to the rest of the world. Since "breakthrough" solar technologies are very cheap in the long-term, global access to those technologies would have a greater influence on global carbon prices compared to wind technologies, which are more expensive in the long-term. Consequently, this choice results in higher payoffs for China. Likewise, if China were to promote solar, USA is better off promoting wind and if China were to promote wind, USA is better off promoting solar. Therefore, the equilibrium strategies shift to China-solar-USA-wind and China-wind-USA-solar configurations (Figure 3-7 G-L). These configurations are respectively, the highest and second highest in terms global payoffs. Thus, if deployment policies lead to sufficiently rapid technological improvements, domestic outcomes may align with what is cost-effective globally. These results underline the importance of the rate of technological change and spillovers in influencing domestic outcomes and potentially aligning them with the global outcome.

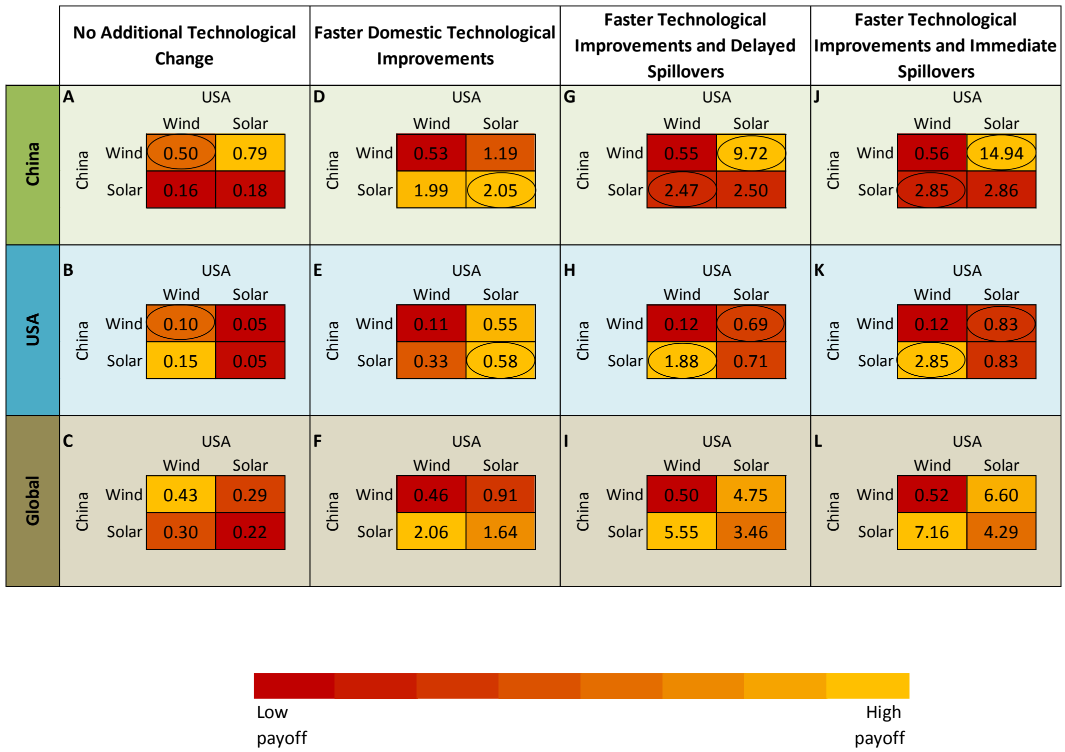

Figure 3-7 Domestic and global payoffs from reduced long-term abatement costs (reductions in long-term abatement costs relative to the case without near-term deployment policies divided by near-term costs of deployment policies) assuming that promoting solar technologies leads to a breakthrough in solar technologies (see Table 3-3 for more a detailed description of the assumptions). The circled payoffs show the Nash equilibrium under a technological change scenario. The Nash equilibrium assuming that deployment policies lead to faster technological improvements that do not spill over is for both countries to promote solar. In the presence of spillovers, the Nash equilibria are China-solar-USA-wind and China-wind-USA-solar configurations. These configurations are the highest and second-highest respectively in terms of global payoffs.

The result on multiple equilibria obtained above for the solar breakthrough scenario requires further discussion. The games presented in the last two columns of Figure 3-7 are similar to what are called "chicken" games.[13] Throughout the analysis in this chapter, I have assumed that all games are played simultaneously.[14] If we were to relax this assumption and assume that the games presented in the last two columns of Figure 3-7 are played sequentially, the outcome would depend on who goes first. If China makes the first choice, China would prefer to promote wind – because, in that case, USA would promote solar and China would receive the highest payoff among the possible configurations. Likewise, if USA makes the first choice, USA would prefer to promote wind – because, in that case, China would promote solar and USA would receive the highest payoff among the possible configurations.

Since the countries can gain by moving first, there might be scope for pre-emptive behavior. For example, if China's payoffs are not known with certainty by USA, then China might be able to take actions that made USA believe that China would chose to promote wind, irrespective of USA's choice (and USA would have similar incentives if China's payoffs were not known with certainty by USA). And incentives for pre-emptive action could be large. For instance, in the delayed spillovers scenario, if China moved first and the outcome were China-wind-USA-solar, China's payoff would be about 4 times the payoff for the China-solar-USA-wind configuration which is the outcome that would result if USA moved first instead (Figure 3-7 G). Likewise, in the same scenario, if

[13] The name "chicken" has its origins in a game in which two drivers drive towards each other along city streets that are too narrow for the cars to pass safely unless one driver slows down. But if one driver slows down and the other does not, the one who slowed down will be called a "chicken," meaning a coward.

[14] It can be verified that even if the games presented in Figure 3-3 and Figure 3-6 are played sequentially, domestic outcomes do not change.

USA moved first and the outcome were China-solar-USA-wind, USA's payoff would be about 3 times the payoff for the China-wind-USA-solar configuration which is the outcome that would result if China moved first instead (Figure 3-7 H). However, from the global perspective, it does not really matter who goes first. For example, in the delayed spillovers scenario, global payoff for the China-wind-USA-solar configuration is only 14% lower than the China-solar-USA-wind configuration (Figure 3-7 I). Therefore, in the absence of some kind of cooperative agreement or third party enforcement, the presence of such advantages could result in both countries promoting wind – which would lead to the least payoffs from the global perspective.

The results presented in this section suggest a role for international cooperation in the diffusion of different low-carbon technologies – not only because such cooperation could induce faster technological change, but also because cooperation could avoid globally inefficient outcomes that may potentially arise out of pre-emptive actions.

3.6. Conclusions

Steps to mitigate climate change are increasingly moving toward a bottom-up approach wherein countries take actions based on national priorities and preferences. One popular near-term action under consideration is to promote low-carbon technologies in the near-term because that can pay off in the long-term. In this chapter, I consider a hypothetical example of China and USA having the option to promote wind or solar technologies in the near-term and investigate the implications for long-term payoffs from reduced costs of future abatement under a range of assumptions about the rates of technological change and spillovers. This example illustrates that under certain assumptions about technological change, domestic and global outcomes are divergent. This divergence occurs because public goods characteristics of technologies combined with differences in near-term costs of promoting different technologies create incentives to free-ride. If countries make decisions on low-carbon technology deployments driven by domestic economic benefits alone, such free-riding incentives might tilt investments toward currently dominant or mature alternatives. On the other hand, to the degree that the international community is looking toward achieving a long-term climate goal cost-effectively, the findings of this essay argue for the need for broader development and deployment of a diverse portfolio of low-carbon technologies—not just the current dominant alternatives. This suggests a role for international cooperation in the broader development and diffusion of diverse low-carbon technologies. For example, left to themselves, developing countries might not be interested to undertake investments in currently expensive technologies such as CCS. The results of this chapter argue that there are global benefits to encourage and facilitate such investments through some form of cooperative or collaborative mechanisms that are more subtle than relatively stale calls for simple “technology transfer”. Instead, the cooperation would focus on developing markets and institutions beyond those explicitly related to climate, including those for trade, development, and intellectual property (Newell, 2010).

The analysis in this chapter also underlines the importance of the rate of technological change in influencing long-term domestic payoffs of near-term deployment policies - domestic and global outcomes may align if deployment policies can induce sufficiently rapid technological change in currently expensive technologies. This finding further supports the argument for international cooperation in the development and diffusion of diverse low-carbon technologies. This is because, such cooperation will foster technological change and increase spillovers which will be instrumental in aligning domestic policy objectives with international goals and avoid globally ineffective outcomes.

It is important to note that the results in this chapter are dependent on one particular formulation of technological change and others are quite possible. First, I assume that increasing the deployment of low-carbon technologies leads to faster reductions in technology costs. However, in the case of energy technologies such as nuclear, increase in deployment has often led to an increase rather than a decrease in technology costs. Scholars have argued that increased construction times due to increased size and complexity of reactors coupled with new environmental, health and safety regulations and increased difficulty in standardization due to the site-specific nature of deployment have led to escalating capital as well as operating and maintenance costs in the nuclear industry (Cantor and Hewlett, 1988; Cooper, 2010; Grübler, 2010; Hewlett, 1996; Hultman and Koomey, 2007; Hultman et al., 2007; Joskow and Rose, 1985). Such cost escalations have been found in other manufacturing industries in addition to nuclear – For example, Argote and Epple (1990) found that the unit production costs of the Lockheed L-1011 TriStar aircraft fell as production increased from 1972–1975, but escalated after a production cut in late 1975. They argued that “organizational forgetting” or depreciation of knowledge due to factors such as individual employees forgetting to perform their tasks or individuals leaving the organization and being replaced by others with less experience were responsible.

Second, the results are dependent not only on assumptions about the rates and direction of technological change, but also spillovers. While the existence of spillovers is nearly undisputed in the literature, the nature of spillovers across regional boundaries is unclear. It is plausible that spillovers from abroad cannot be appropriated by domestic firms or such appropriation might be costly and limited by institutional, political and even cultural factors (Braun et al., 2010; Clarke and Weyant, 2002). For example, in a recent econometric estimation, Braun et al. (2010) used patent data for 21 OECD countries to show that innovation in wind and solar technologies is strongly driven by knowledge spillovers. However, the study concluded that spillovers are domestic in nature and international spillovers are insignificant. One explanation for this is that the pool of knowledge available domestically may be large enough that acquiring foreign knowledge is redundant. Another more plausible explanation could be that appropriation of foreign knowledge is expensive compared to domestic knowledge. The above discussion highlights that results presented in this chapter for scenarios assuming no additional technological change and different levels of spillovers might be equally important and merit attention.

Finally, the formulation in this analysis does not consider diversity within countries, that is, the option of countries promoting different technologies domestically in order to retain focus on demonstrating the effects of different technology choices on domestic and global outcomes. The above caveats notwithstanding, the analysis presented in this chapter calls for a solid assessment of the technologies in question, their potential for improvement and the nature of spillovers in policy collaborations aimed at undertaking stringent mitigation in the future.

Chapter 4 Non-uniform investment risks and patterns of climate change mitigation[15]

4.1. Introduction

The international community has established a target of keeping global mean temperature rise below 2^0C in order to prevent dangerous anthropogenic interference with the climate system (UNFCCC, 2010). Achieving such a stringent target will require a dramatic transformation of the energy system; a transformation which in turn involves large scale investments (McCollum et al., 2013). Investment depends not only on the supply or availability of funds but also on the capacity to carry out the physical investment. Because decisions on investments involve multiple institutions that respond to various criteria in different regions differently, this capacity is non-uniform across the globe. Previous assessments of emissions mitigation patterns have largely ignored the huge variation in real-world factors—in particular, institutions—that affect where, how and at what costs firms deploy capital (Calvin et al., 2012; Clarke et al., 2009; Kriegler et al., 2014; McCollum et al., 2013; Riahi et al., 2015). There are strong reasons to believe that the risk of investment varies across countries, sectors and technologies. In this essay, I review the literature on these reasons and answer the following question: *How do differences in investment risks affect the costs and geography of climate change mitigation?*

[15] This chapter is based on (Iyer et al., 2015b)

This essay contributes to the growing literature on climate policy analysis under imperfect circumstances. Examples of such studies include limits on the availability or growth of technologies (see for example, Tavoni et al. (2012)), delays in establishing international climate policy regimes (see for example Jakob et al. (2012), Bosetti et al. (2009a) and Calvin et al. (2009)) and labor market imperfections (see for example Guivarch et al. (2011)). Among previous studies that attempt to address similar issues, Bosetti and Victor (2011) showed that due to lack of regulatory credibility, agents become myopic and are unable to make optimal investments in energy technologies. This increases the costs of achieving stringent climate goals. Along similar lines, Ekholm et al. (2013) studied the effects of financial constraints in Sub-Saharan Africa by including capital supply curves in a linear cost optimization model with perfect foresight and concluded that limited capital supply decreases investments to capital-intensive low-carbon technologies especially in the near term. They also found that because emissions are higher in the near term, the emissions price required to meet a given long-term emissions target is higher. While the above studies tackle either the issue of credibility or availability of funds, I address the question of differences in capacities to undertake physical investments. Effects of such non-uniformities have not been studied sufficiently and there are reasons to believe that they might be substantial in their effects on eventual low-carbon deployment. The central contribution of this essay is to demonstrate how imperfections in the process of investment—which arise from a “mosaic” of actors, institutions, regional and national objectives that vary in their ability to attract and deploy investment—affect the cost and geography of mitigation (Edmonds et al., 2012; Flannery, 2009).

This chapter is organized as follows. I first review the literature on the factors affecting socially optimal levels of investment and the reasons for the variation of investment risks across regions, sectors and technologies. Following this, I use the GCAM integrated assessment model and incorporate decisions on investments based on risks along two dimensions (Table 4-2). Along the first dimension, I vary perceived risks associated with particular technologies. To do so, investment in low-carbon technologies are assigned a higher cost of capital as these involve intrinsically higher levels of regulatory and market risk. The second dimension uses a proxy to vary investment risks across regions, based on an institutional quality metric published by the World Economic Forum (Schwab, 2013). In addition to these two dimensions of variation in investment risks, I consider scenarios with and without a climate target. I restrict the analysis to investments in the electricity generation sector, which are expected to account for a significant share of future investments in the context of climate change mitigation (McCollum et al., 2013).

4.2. Factors affecting investment

Many hard-to-model factors have the potential to affect investment in low-carbon energy. At the macro-level, several factors affect saving rates and economy-wide capital formation. For example, the quality of institutions in a country may affect regulatory credibility and discourage investment in general. At the sector-level, idiosyncrasies related to specific sectors could lower returns to capital in such sectors thereby affecting investment. The electricity sector is a classic example of a sector in which returns to capital can be influenced by government regulations. Likewise, at the technology-level, particular technologies face special risks. For instance, regulatory challenges make investment in nuclear technologies more risky in many countries. Finally, factors at the level of the firm such as ownership structure and individual decision-makers such as information asymmetry between lenders and borrowers also affect investment. In this section, I review the literature on such factors.

4.2.1. Macro-level factors: Investment from an institutional economics perspective

The vast literature on institutional economics discusses how the quality of institutions affects investment. Institutions are the formal and informal rules that constrain individual behavior and shape human interaction. Institutions are devised to create order and reduce uncertainty in exchange. A solid institutional framework is necessary to encourage private investment. Investors will be reluctant to risk their capital when property rights are weak and poorly protected, and if, as a result, they fear that their returns may be appropriated by others (North, 1990). Empirical studies on the link between institutions and investment have confirmed this theory. For example, Knack and Keefer (1995) conducted cross-country regressions and found that security of property rights affects not only the magnitude of investment, but also the efficiency with which inputs are allocated. Likewise, Acemoglu et al. (2005) showed that institutions determine not only the aggregate economic growth potential of the economy, but also the distribution of resources (wealth, physical and human capital) in the future. In addition, Acemoglu and Zilibotti (1997) showed that in developing countries that lack large and efficient financial markets, investors tend to invest in safer projects with lower return because the presence of indivisible projects limits the degree of risk diversification. This slows down capital accumulation, and the inability to diversify idiosyncratic risk introduces a large amount of uncertainty in the growth process.

Empirical research also shows that institutional quality affects foreign direct investment. Investors considering FDI may be particularly concerned about the likely exposure to requests for bribes and the need to work through red-tape in host countries. Similarly, weak institutions in a recipient country (including lack of transparency in the corporate sector and weak corporate governance) may deter international investors from acquiring portfolio equity stakes there (Faria and Mauro, 2009). Busse and Hefeker (2007) used data from 83 developing countries between the period from 1984 to 2003 and found that government stability, the absence of internal conflict and ethnic tensions, basic democratic rights and ensuring law and order are highly significant determinants of foreign investment inflows. Along similar lines, Alfaro et al. (2008) showed that poor institutional quality is the most important reason for lack of capital flows from rich to poor countries between 1970-2000. Likewise, Wei (2001) applied a gravity model of bilateral FDI stocks and bank loan stocks to a sample of about 10 source countries and 20 recipient countries and found that weaker institutions are associated with less FDI and more bank loans.

Contract enforcement tends to be weak in countries with inferior institutions and that has adverse effects on investment. For example, Clague et al. (1999) showed that investment is adversely affected in countries that lack adequate third-party contract enforcement because in such countries, firms are usually restricted to capital that can be obtained through savings or other domestic sources. Therefore, economic gains from either capital-intensive or large-scale production are lost. On the other hand, in places where institutions increase the certainty that contracts will be honored and property protected, individuals will be more willing to specialize, invest in sunk assets, undertake complex transactions and accumulate and share knowledge (North, 1990). In addition, credible and effective regulations will be critical to facilitate investment (Levy and Spiller, 1994). For example, if the government has incentives to change taxes or regulations ex-post with the knowledge that investors cannot easily withdraw, investors can delay or forego investment, especially if they are large and irreversible.

In short, the quality of institutions will have a major influence on investment required for transformational change in the context of the energy system because that is closely tied with the magnitude of Ronald Coase's "transaction costs" (Coase, 1960). As Coase points out, the effects of high transaction costs "*are pervasive in the economy. Businessmen, in deciding on their ways of doing business and on what to produce, have to take into account transaction costs. If the costs of making an exchange are greater than the gains which that exchange would bring, that exchange would not take place..*." (Coase, 1992).

4.2.2. Sector-level factors: example of investment in the electricity sector

The electricity sector is one example of a sector which is expected to involve large investments in the future, especially in the context of climate change mitigation, and therefore presents a useful case to investigate (McCollum et al., 2013). Traditionally, due to network effects and economies of scale that create high barriers to entry, the electricity sector had remained a natural monopoly. In the last few decades, however, the electricity sector has undergone reforms all over the world. The principles of these reforms are guided by three main elements. First, the idea that generation is not intrinsically monopolistic and can be supplied by competitive private firms led to unbundling generation from transmission and distribution. On the other hand, the transmission and distribution segments of the electricity sector need to be regulated because these markets are replete with network effects and barriers to entry that make them prone to monopoly. Second, the belief that private entities, rather than the state, could better allocate capital and assure efficient operations lead to privatization of ownership of those parts of the power system that could be competitive. The final step involved creating powerful new institutions—notably, independent regulators (Heller and Victor, 2004).

In spite of these reforms, the electricity sector has some peculiar characteristics that affect investment. First, the technology involves large specific, sunk investments (note that this characteristic is generally true throughout the energy sector). Therefore, once the investment is undertaken the operator will be willing to continue operating as long as operating revenues exceed operating costs. Since operating costs do not include a return on sunk investments, the operating company will be willing to operate even if prices are below total average costs. Second, the sector is characterized by massive economies of scale and scope, implying that the number of suppliers will be small, giving rise to monopoly power, especially in the transmission and distribution sector. Third, outputs from this sector are consumed widely by households and industry. Hence, politicians and interest groups will care about the level of pricing (Bergara et al., 1998; Spiller, 1995). Therefore, governments have incentives to behave opportunistically with the investing company. Expropriation of sunk assets may be profitable for a government if the direct costs (such as loss of reputation or reduced investment in the future) are small compared to the short-term benefits of such action (such as achieving re-election by reducing electricity prices for consumers or by attacking the monopoly), and if the indirect institutional costs (such as disregard of the judiciary or not following the proper administrative procedures) are not too large (Spiller, 1995). This discourages investors by creating additional risks. Indeed, using a sample of thirty-four independent power projects in thirteen countries, Woodhouse (2006) showed that regulatory credibility in host countries is important for risk-averse investors because of the fear that unpredictable changes in regulations will lead to expropriation of fixed assets. Note that investment patterns in other sectors may be quite different than for the electricity sector. For example, at the geographical scale used in most IAMs, investments in power production are likely to be domestic; that may not be the case in the transportation sector where fuels and vehicles may be imported rather than produced domestically. Similarly, investments in some sectors may primarily be self-financed by firms rather than through commercial or development institutions.

4.2.3. Project and technology level factors

Regulatory and policy uncertainty could affect investment in particular technologies. Non-conventional technologies may face regulatory challenges (e.g. safety and environmental regulations for nuclear power plants) because of which investment is more risky due to the probability of failure or stoppage and hence losing any expected future cash-flow (Ekholm et al., 2013). Likewise, a number of scholars have argued that uncertainty in carbon price will delay investment in low-carbon technologies (e.g. Fuss et al. (2012), Laurikka and Koljonen (2006), Laurikka (2006)). Newer technologies face a special investment challenge – because investors are unaware about the performance of new technologies, they will expect higher rates of return (Jaffe et al., 2002). In addition, technologies whose cost structures are fuel-intensive face the increased risk of exposure to market uncertainties (Krohn et al., 2009). Technologies in the electricity sector face an additional risk – wholesale electricity prices are volatile due to the homogenous nature of electricity, its lack of storability, inelastic demand and the steepness of the supply curve as electricity production nears system capacity (Borenstein, 2002; Roques et al., 2005). Likewise, uncertainty in price of commodities and other inputs adds to the risks perceived by investors.

Increased penetration of intermittent technologies such as wind may affect investment in other technologies. Steggals et al. (2011) argued that in a market with high penetration of wind which is typically characterized by long periods of low prices and a short periods of high wholesale prices, investment in other low carbon technologies such as nuclear will be adversely affected because of its high capital costs and relative inflexibility. Other factors affecting investment at the technology level include unplanned plant closure, for example owing to unavailability of resources, plant damage or component failure, risk of a fall in volume of electricity produced owing to lack of wind or sunshine, etc. These factors affect investment in technologies differently and may lead to a re-ordering of the relative attractiveness of the various investment options. All else being equal, investors would prefer to invest in lower risk technologies

4.2.4. Firm and individual level factors

One of the key factors affecting investment decisions is the ownership structure of the firm. For a public utility, 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 utility which is exposed to the uncertainties of the market. Likewise, the type of financing used by the firm could imply different risks. Corporate financing uses corporate credit and general assets of a corporation, typically a utility, as the basis for credit and collateral. This is less risky compared to project financing in which lenders base credit appraisals on the estimated cash flows from the facility rather than on the assets or credit of the corporation. Apart from the above factors, several others at the level of the individual such as information asymmetry between lenders and borrowers and principal-agent problems could affect investment, especially in the demand-side of the energy sector (Jaffe and Stavins, 1994; Stiglitz and Weiss, 1981). In this essay, I focus only on the supply side in the electricity generation sector; a detailed examination of factors in the demand-side is beyond the scope of this study.

Due to the factors reviewed above, investments may not take place at the socially optimal level. However, under certain circumstances, investment risks can be mitigated and investment encouraged. In the following subsection, I consider the case of China, in which investment in energy is low-risk due to a combination of factors including favorable policy environment and state-capitalism.

4.2.5. Special case: investment in China

Among developing economies, China currently accounts for the largest share of investment across all major technologies in the electricity sector. For example, in the year 2013, Chinese investment in renewable energy was the highest, more than even the whole of Europe (Frankfurt School-UNEP Centre/BNEF, 2014). China accounts for more than a third of all proposed coal plants and more than a third of all proposed nuclear power plants worldwide (WNA, 2013). From the perspective of an investor, investing in the Chinese electricity sector is relatively low-risk because Chinese electricity demand will continue to grow and any investment in the electricity sector will provide attractive returns. In addition, China's 12th Five Year Plan lays emphasis on renewable energy and energy efficiency. This gives clear signal that investment in these areas will be encouraged (Sullivan, 2011). Also, policies such subsidies, feed-in-tariffs and income tax incentives encourage investment (Rong and Victor, 2011; Victor et al., 2012). Most importantly, China's system of "state capitalism" that tries to juxtapose the powers of the state with the powers of capitalism, allows for a different character of large-scale energy investment that bolsters capital-intensive technologies and projects with higher market risks. First, the Chinese energy sector is dominated by state-owned enterprises that are often able to manage risks by shifting them to the government. Second, financing from Chinese "policy banks" such as the Chinese Development Bank that finance the construction of new power plants including emerging technologies such as solar through extremely low interest rates reduces financial risks considerably. In addition, state support usually limits delays associated with acquiring rights of way or essential permits. Note, however, that such advantages may not be unique to China, and they often arise when state-backed firms raise debt; for example, Mexico's Pemex (Victor et al., 2012).

The factors reviewed in this section create non-uniformities in investment risks across regions, sectors and technologies. Such non-uniformities will have important implications for the large-scale investments in the energy system required to address the climate change problem because investors could respond to them by expecting higher returns to invest in a risky project; delaying or forgoing the investment or investing in existing, familiar technologies.

4.3. Methodology

As in the first two essays, I use the GCAM integrated assessment model to analyze how differences in investment risks across regions and technologies affect first-best trajectories and outcomes of achieving stringent climate targets. Among different variables affected by differences in investment risks, I focus on the cost of capital for investment.

Risk-averse investors expect risk-adjusted rate of return, raising the cost of capital for investing in projects involving greater risk. The cost of capital affects investment at the level of the technology and the macro-economy. At the technology level, the cost of capital affects the balance between capital and running costs. On the aggregate macroeconomic level, variables such as institutional quality can affect the cost of capital which in turn influence the rate and magnitudes of capital formation.

I restrict the analysis to capital investments in electricity generation, which are expected to account for a significant share of future investment in the context of climate change mitigation (McCollum et al., 2013). In addition, biomass-based technologies in sectors other than electricity, for example biofuels and biogas are included to avoid the results from being influenced by availability of biomass resources. For instance, if biomass-based technologies were to be excluded, a higher risk of investing in the electricity sector would shift investment to bioenergy (which would remain low-risk) to satisfy growing energy demand and meet a stringent climate target. Note that GCAM operates in a partial equilibrium framework. Conducting the analysis in a general equilibrium framework or including other key energy or land use sectors in the analysis will provide additional insights but will not materially affect the broad qualitative insights from the current analysis.

4.3.1. The cost of capital and Fixed Charge Rates

In GCAM, the cost of capital is represented in the fixed charge rate (FCR). In this section, I explain the different terms and concepts surrounding the cost of capital.

Typically, firms use a combination of debt and equity to finance their businesses. The cost of debt is "*the amount paid to the holders of debt securities for the use of their money*" (Short et al., 1995). The amount paid, which is the lending interest rate is set by banks. Since the interest is tax-deductible, the cost of debt is usually calculated on an after-tax basis. The cost of equity refers to the "*the earnings expected by an investor when purchasing equity shares in a company"* (Short et al., 1995). Note that equity is a riskier form of financing compared to debt and so the cost of equity is greater than the cost of debt. The expected return on any investment can be written as the sum of the risk-free rate and a premium to compensate for the risk (the risk-free rate represents the time value of money and compensates investors for placing money in any investment over a period of time). The equity risk premium, thus refers to the premium added to the risk-free rate to estimate the cost of equity. The overall cost of capital is derived from a weighted average of all capital sources, widely known as the weighted average cost of capital (WACC). The WACC is used as the discount rate, which reflects the fact that the value of a cash flow depends on the time at which the flow occurs.

Finally, the Fixed Charge rate (FCR) represents "*the before-tax revenue that a profit-maximizing firm would require annually to cover its cost and carrying charges of an* *investment and to achieve its desired after-tax return. Carrying charges include return on debt and equity, income and property tax, book depreciation, and insurance*." The FCR is a function of the discount rate and the lifetime of the capital investment and is given by the following expression: $FCR = \frac{Discount\ rate}{1-(\frac{1}{1+Discount\ rate})^{lifetime}} \times \frac{1-(T * PV_{depreciation})}{1-T}$, where T is the marginal income tax rate, $PV_{Depreciation}$ is the present value of depreciation and lifetime refers to the lifetime of the capital investment (Short et al., 1995).

4.3.2. Representing non-uniform investment risks

In this analysis, I vary FCRs across technologies and regions in the electricity generation sector (Figure 4-1).

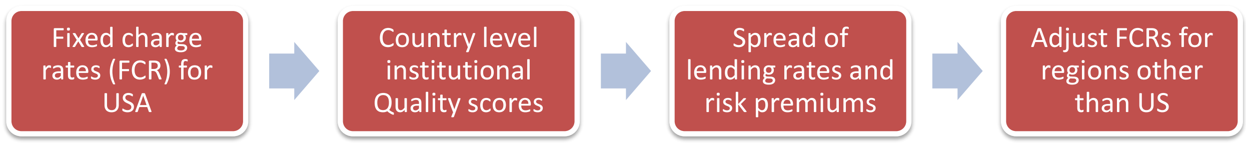

Figure 4-1 Sequence of steps followed to represent non-uniformities across technologies and regions in the electricity generation sector.

While variation across technologies affects the choice between low-carbon technologies and fossil-fuel technologies that have capital-intensive and fuel-intensive cost structures respectively, the variation across regions is represented to capture the macroeconomic effects explained above. To represent variation of investment risks across technologies, I first compile FCR values used for financial analyses of electricity generation technologies in the United States (Bunn et al., 2003; NETL, 2011; Tegen et al., 2012) (Table 4-1). I then categorize technologies into low-risk (fossil-fuel technologies) and high-risk (nuclear, renewables, bioenergy, CCS) with FCRs of 13% and 17% respectively.

To model non-uniformities across regions, I use a proxy to vary investment risks across regions, based on an institutional quality metric published by the World Economic Forum (Schwab, 2013) (Figure 4-2). I use country-level institutional scores from the World Economic Forum's Global Competitiveness Index data-set to calculate GDP-weighted scores for the fourteen GCAM regions. I then look at spreads of macroeconomic lending rates (reflecting the costs of debt) and equity risk premiums across countries (Figure 4-3). Next, I represent FCRs as a log-linear function of institutional quality and adjust the parameters of the function to be consistent with the spreads observed in Figure 4-3. Assuming that FCRs vary with institutional quality scores according to a log-linear relationship, FCRs for regions other than the U.S. are calculated using the following expression: $FCR_{i,j} = FCR_{i,USA} \times f$ where $FCR_{i,j}$ is the FCR for technology *i* in region *j* and *f* is given by: $f = \frac{\gamma_0 + \gamma_1 \ln IQ_j}{\gamma_0 + \gamma_1 \ln IQ_{USA}}$, where IQ_j refers to the GDP-weighted institutional quality score for region *j* (Benítez et al., 2007; Erb et al., 1996). γ_0 and γ_1 which are parameters of the log-linear model are chosen such that the spread in FCRs across GCAM regions is consistent with the spreads observed in lending rates and costs of equity in Figure 4-3. Not only is this representation useful to capture the macroeconomic effects explained earlier, it also reflects behavior of investors in the real world, where investors demand risk-adjusted rates of return.

Next, I explore four investment risk scenarios that vary along two dimensions (Table 4-2). Along the first dimension, I vary investment risks only across technologies and along the second, I vary investment risks along institutions. As a point of departure, I also consider a counterfactual uniform investment risk scenario. In addition to these two dimensions of variation in investment risks, I consider scenarios with and without a climate target. The climate policy scenarios all require a reduction in global CO_2 emissions from fossil fuels and industry of 50% in 2050 relative to 2005 levels (Figure 4-4) (IPCC, 2014). Table 4-3 summarizes the central assumptions across the investment risk scenarios explored in this study.

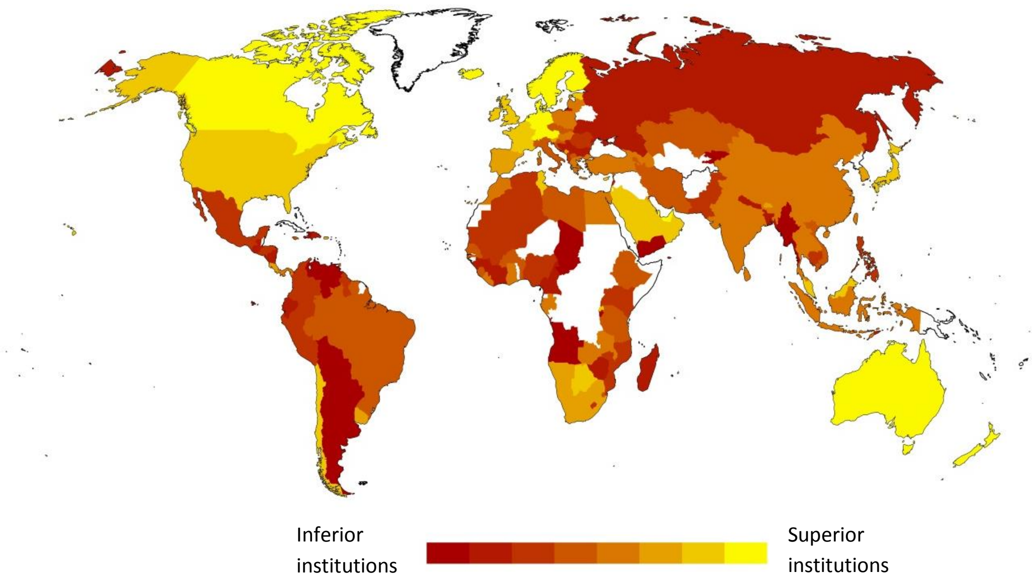

Figure 4-2 Quality of national institutions based on the World Economic Forum's Global Competitiveness Index dataset (Schwab, 2013). Assuming that non-uniformities in investment risks arise due to differences in institutional qualities, I use these data to represent costs of capital for investing in the electricity generation sector as a function of the quality of a country's institutions. This reflects behavior of investors in the real world, where investors demand risk-adjusted rates of return that are higher in regions with inferior institutions.

Table 4-1 Fixed Charge Rate assumptions in literature for financial analyses in the United States [a,b]

Technology	Categorization used in this study	FCR used in literature			Source
		Investor-owned utility	Independent power producer	Average	
Coal w/o CCS	Low-risk	11.6%	17.6%	14.6%	NETL (2011)
Gas w/o CCS	Low-risk	10.5%	14.9%	12.7%	NETL (2011)
Nuclear	High-risk	10.3%	18.8%	14.6%	Bunn et al. (2003)
Coal w/ CCS [c]	High-risk	12.4%	21.4%	16.9%	NETL (2011)
Gas w/ CCS [c]	High-risk	11.1%	17.7%	14.4%	NETL (2011)
Wind, solar, bioenergy [d]	High-risk	NA	9.5%	9.5%	Tegen et al. (2012)

[a] The Fixed Charge rate (FCR) represents "*the before-tax revenue that a profit-maximizing firm would require annually to cover its cost and carrying charges of an investment and to achieve its desired after-tax return."* The FCR is a function of the cost of capital and the lifetime of the capital investment and is given by the following expression: $FCR = \frac{Discount\ rate}{1-(\frac{1}{1+Discount\ rate})^{lifetime}} \times \frac{1-(T * PV_{depreciation})}{1-T}$, where T is the marginal income tax rate, $PV_{Depreciation}$ is the present value of depreciation and *lifetime* refers to the lifetime of the capital investment. Typically, the weighted average cost of capital (WACC) is used as the discount rate (Short et al., 1995).

[b] FCRs in this table are based on after-tax WACC, which is used as the discount rate. The WACC depends on the debt to equity ratio, among other variables. Investor-owned utilities and independent power producers differ in debt/equity ratios (higher for the latter). The FCRs shown here do not include insurance and property taxes. In this study, I specify an FCR of 13% for low-risk technologies and 17% for high –risk technologies. FCRs of 13% and 17% correspond roughly to WACCs of 8% and 10% respectively and capital lifetime of 30 years.

[c] For CCS technologies, WACC calculations are based on lower debt/equity ratios compared to fossil-fuel technologies.

[d] The lower value of the FCR for renewables is in large part, due to 5 year Modified Accelerated Cost Recovery System (MARCS) depreciation schedule, which is used for investment in renewables in the United States. In this study, I do not consider this lower value because such subsidies affect the distribution of costs but not the total social cost (as governments take on a portion of the cost).

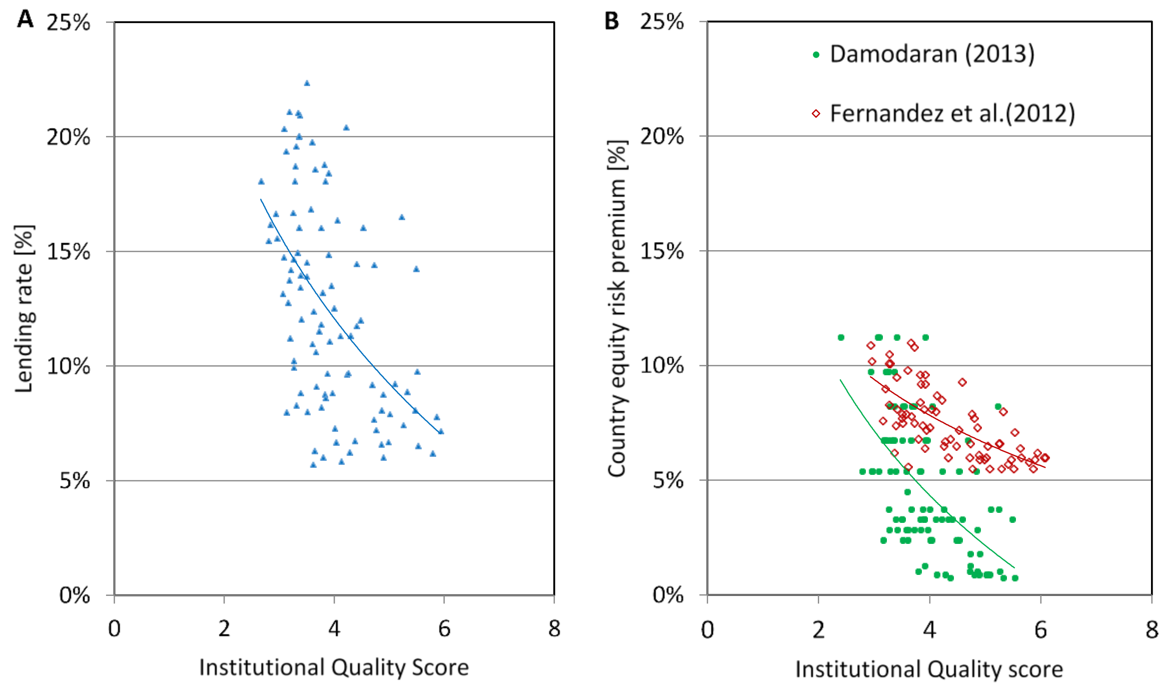

Figure 4-3 A.) Variation of average lending rates between 2000 and 2012 for private borrowers with institutional quality (The World Bank, 2013) B.) Variation of country risk premiums on the cost of equity with institutional quality(Damodaran, 2014; Fernandez et al., 2012). Data from Damodaran (2014) are based on the author's calculations and estimates using country rating data from Moody's. Data from Fernandez et al. (2012) are based on elicitations of experts. The trends in these data show that investment risks vary inversely with the quality of institutions. The wide spread in the data indicates that even countries with lower quality of institutions can have lower interest rates for a variety of reasons. See Section 4.2.5 for a review of such reasons for the case of China. See also, Section 4.3.1 for explanations of the different terms and concepts related to the cost of capital.

Table 4-2 Investment risk scenarios explored in this study

		INSTITUTIONAL INVESTMENT RISKS	
TECHNOLOGY INVESTMENT RISKS	High risk technologies ↓	No variation across regions	Investment risks vary with institutional quality
	None	Uniform Investment risks	Institutional investment risks
	Renewables, CCS, nuclear and bioenergy	Technology Investment risks	Technology and Institutional risks

Table 4-3 Fixed charge rate assumptions (central) in scenarios explored in Chapter 4

Scenario	Fossil Fuels	Nuclear	Renewables	CCS	Bioenergy
Uniform Investment risks	13%	13%	13%	13%	13%
Technology Investment risks	13%	17%	17%	17%	17%
Institutional investment risks	13%	13% X *f* [a]	13% X *f* [a]	13% X *f* [a]	13% X *f* [a]
Technology and institutional risks	13%	17% X *f* [a]	17% X *f* [a]	17% X *f* [a]	17% X *f* [a]

[a] Assuming that FCRs vary with institutional quality scores according to a log-linear relationship, FCRs for regions other than the U.S. are calculated using the following expression: $FCR_{i,j} = FCR_{i,USA} \times f$ where $FCR_{i,j}$ is the FCR for technology *i* in region *j* and *f* is given by: $f = \frac{\gamma_0 + \gamma_1 \ln IQ_j}{\gamma_0 + \gamma_1 \ln IQ_{USA}}$, where IQ_j refers to the GDP-weighted institutional quality score for region *j* (Benítez et al., 2007; Erb et al., 1996). γ_0 and γ_1 are parameters of the log-linear model are chosen such that the spread in FCRs across GCAM regions is consistent with the spreads observed in lending rates and costs of equity in Figure 4-3.

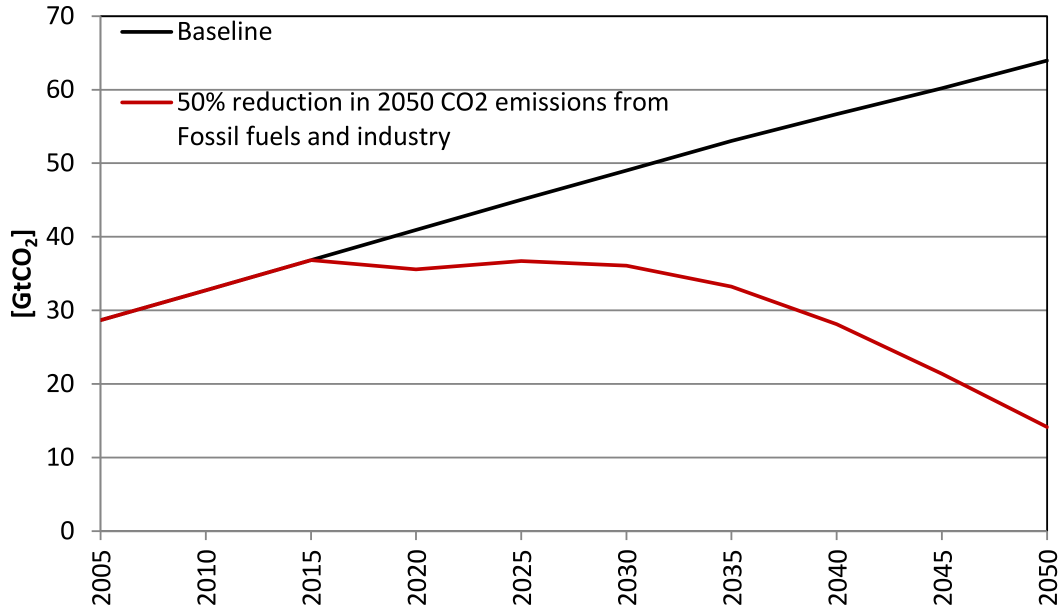

Figure 4-4 Global CO_2 emissions from fossil fuels and industry in the baseline and 50% reduction in 2050 emissions relative to 2005. The 50% pathway is achieved by means of an exponentially rising carbon tax in the uniform investment risks scenario (Peck and Wan, 1996). The 50% pathway shown here corresponds to a cumulative CO_2 emissions (from fossil fuels and industry) budget between 2011-2050 of 1260 $GtCO_2$. For comparison, the ranges of 2011-2050 cumulative CO_2 emissions budgets reported by a range of models in the EMF-27 inter-model comparison exercise are 800-1280 $GtCO_2$ for the 450 ppm CO_2e concentration target and 960-1480 $GtCO_2$ for the 550 ppm CO_2e concentration target (Kriegler et al., 2014). The same pathway is imposed on all investment risk scenarios.

Note that although I assume higher investment risks in regions with inferior institutional qualities, exceptions exist. One important exception is China. Investment risks in China are lower in spite of moderate institutional quality for a variety of reasons including favorable policies and state-backed financial institutions (Section 4.2.5). Furthermore, China accounts for a major share of global investments in the electricity sector. I therefore consider a sensitivity case in which investment risks are low only in China (Section 4.6). Finally, in order to validate the consistency of the findings, I conduct a sensitivity analysis (Section 4.7) on key assumptions in Table 4-3: i.) the global emissions target ii.) assumptions about FCRs and iii.) technologies considered high-risk.

4.4. Effects of non-uniform investment risks in the baseline

In the baseline (no climate policy) scenario with uniform investment risks, investments in the electricity generation sector[16] occur in fossil-fuel as well as low-carbon technologies (Figure 4-5, Figure 4-6). Note that sums of investments in low-carbon technologies are comparable to those in fossil-fuel technologies, although their share in total generation may be much lower because the former are both intermittent and more capital intensive; consequently, more upfront capital is required per joule of electricity generated from low-carbon technologies. When non-uniformities in investment risks across technologies are introduced, investments in low-carbon technologies decline. This is because, higher investment risks for low-carbon technologies (which are assigned higher costs of capital) raise the costs of electricity generation from them. On the other hand, costs of electricity generation from fossil-fuel technologies (which are assigned lower costs of capital), are lower. Therefore, in these scenarios, investments in fossil-fuel technologies increase more rapidly. Nevertheless, in spite of their higher generation costs, low-carbon technologies get deployed (because of the technology choice specification discussed in

[16] Investment numbers presented in this chapter do not include transmission and distribution (T&D). GCAM includes a factor for T&D losses, rather than costs under the assumption that infrastructure will not be a roadblock to investment. This helps analyze the effects of non-uniformities in investment risks keeping other variables fixed.

the Methods section), raising electricity prices. This reduces demand for electricity, reducing total investment in the electricity sector.

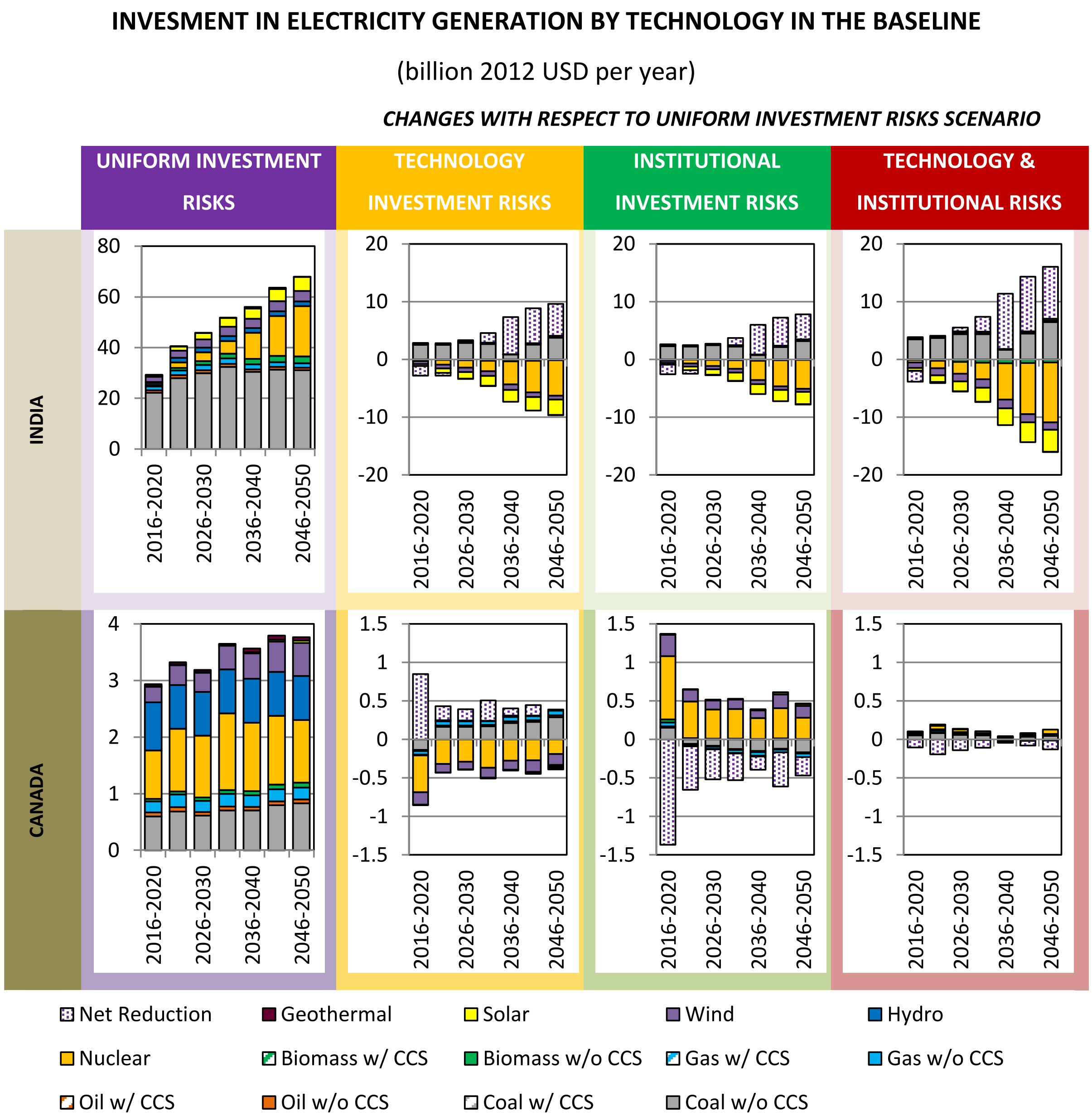

Figure 4-5 Effect of non-uniform investment risks on annual investments in electricity generation in India (lower institutional quality) and Canada (higher institutional quality) in the baseline cases. Investment numbers presented here and in other figures do not include transmission and distribution (T&D).

When non-uniformities in institutional qualities are introduced, investments in low-carbon technologies in regions with inferior institutions (where investing is more risky) decrease (Figure 4-5). On the other hand, in regions with superior institutions (where investing is less risky), investments increase. The net effect, however, is a reduction in investments in low-carbon technologies globally because most of the investments occur in developing regions such as India and China (driven by increasing demand due to growing population and income) which have relatively lower institutional qualities (Figure 4-6). The combined effect of non-uniform investment risks across technologies and regions is a reduction in investments in low-carbon technologies globally and an increase in investments in fossil-fuel technologies, leading to a net reduction in investments in electricity generation. The immediate consequence of such a shift in investment pattern is an increase in global baseline emissions (Figure 4-7).

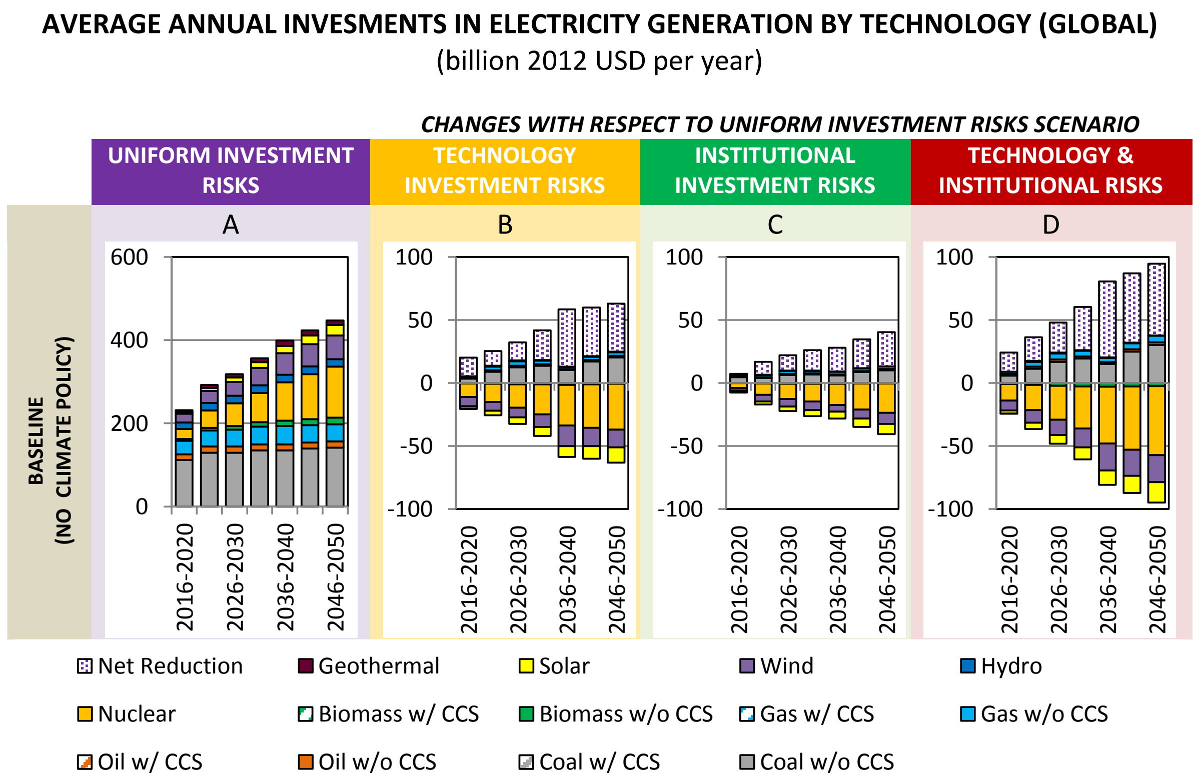

Figure 4-6 Global average annual investments in electricity generation in the baseline under the different investment risk scenarios.

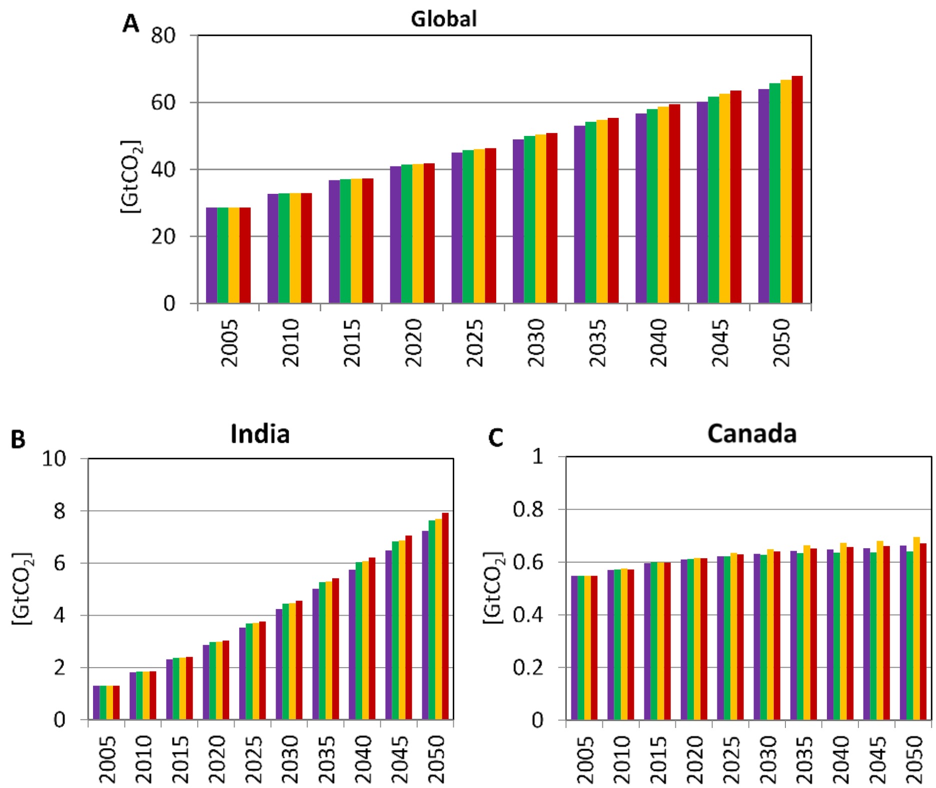

Figure 4-7 CO_2 emissions in the baseline (no-climate policy) scenarios. With non-uniform investment risks across technologies, baseline emissions are higher compared with the uniform investment risks scenario in all regions. This is because, in this scenario, deployments of low-carbon technologies are lower and those of fossil-fuel technologies are higher. When non-uniformities across regions are introduced, baseline emissions in regions with lower institutional qualities, for example, India are higher due to the effects described above. On the other hand, baseline emissions in regions with higher institutional qualities, for example, Canada, are lower. This is because, in these regions, deployments of low-carbon technologies increase and those of fossil-fuel technologies decrease (see Figure 4-5)). The combined effect of non-uniformities across technologies and regions is to increase baseline emissions in regions with inferior institutions and decrease them in regions with superior institutions. On the global level, the combined effect is an increase in baseline emissions as most of the emissions come from developing regions such as India and China with lower institutional qualities.

4.5. Effects of non-uniform investment risks under an emissions mitigation target

The 50% global emissions target is achieved through a global price on carbon. In the presence of a high enough carbon price, the modeled energy system undergoes a dramatic transformation, resulting in a realignment of investment patterns in the electricity generation sector (Figure 4-8). Low-carbon technologies become cost-competitive relative to fossil-fuel technologies, leading not only to an increase in investments in the former, but also to a net increase in investment in electricity generation relative to the baseline scenario (Chaturvedi et al., 2014). Under uniform investment risks, most of the investments occur in developing regions such as China (Figure 4-9 A). This is because, investment depends on the mitigation potential of different regions. In the baseline, fossil-fuel based electricity generation in regions such as China increases significantly due to growing population and income. Consequently, it is cheaper to invest in emissions reductions in such regions and such regions undertake more emissions mitigation.

When non-uniformities in investment risks across technologies are introduced, carbon prices required to meet the emissions target increase due to two effects (Figure 4-10). First, under non-uniform investment risks, since global baseline emissions are higher, abatement required to achieve the same target is higher. This implies a movement along the marginal abatement cost (MAC) curve, implying higher carbon prices. The second and the larger effect is that the MAC curve shifts upward because of higher costs of capital for investment in low-carbon technologies, increasing carbon prices further. When non-uniformities across regions are introduced, MAC curves for regions such as China and India with lower institutional qualities shift upward and MAC curves for regions such as Canada with higher institutional qualities shift downward (Figure 4-11, Figure 4-12). However the global MAC curve shifts further upward because most of the emissions mitigation occurs in regions such as China and India with lower institutional qualities (Figure 4-13). Therefore, global carbon prices to achieve the emissions target increase further.

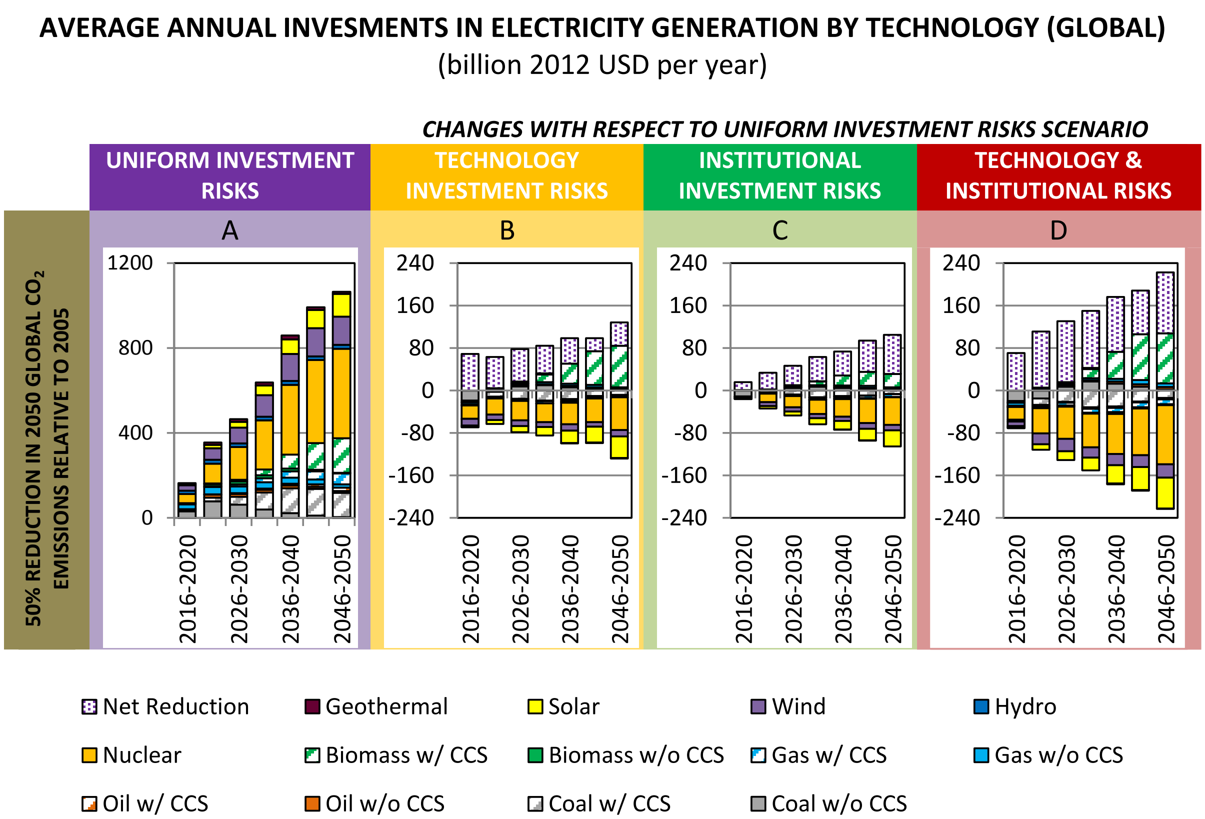

Figure 4-8 Global average annual investments in electricity generation under the 50% global emissions target and different investment risk scenarios.

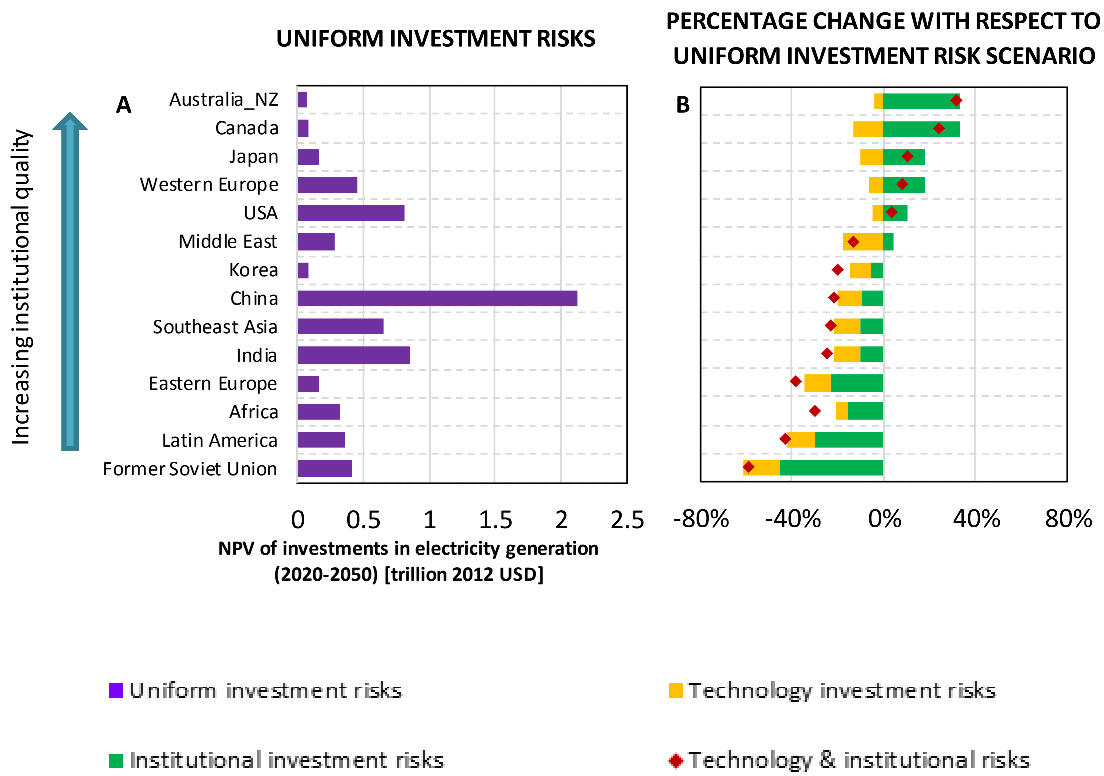

Figure 4-9 A.) Cumulative net present values of investments in electricity generation (2020-2050) under uniform investment risks by region and B.) Changes (with respect to the uniform investment risks scenario) in investments under the different investment risk scenarios considered in this study. The cases presented here correspond to the 50% global emissions target. When non-uniformities in investment risks across technologies are introduced, investments are reduced in all regions. When non-uniformities across regions are introduced, investments in regions with inferior institutions are reduced and those in regions with superior institutions are increased. Note that while the effects of non-uniformities across technologies and institutions reinforce each other in regions with inferior institutions, they act in opposite directions in regions with superior institutions.

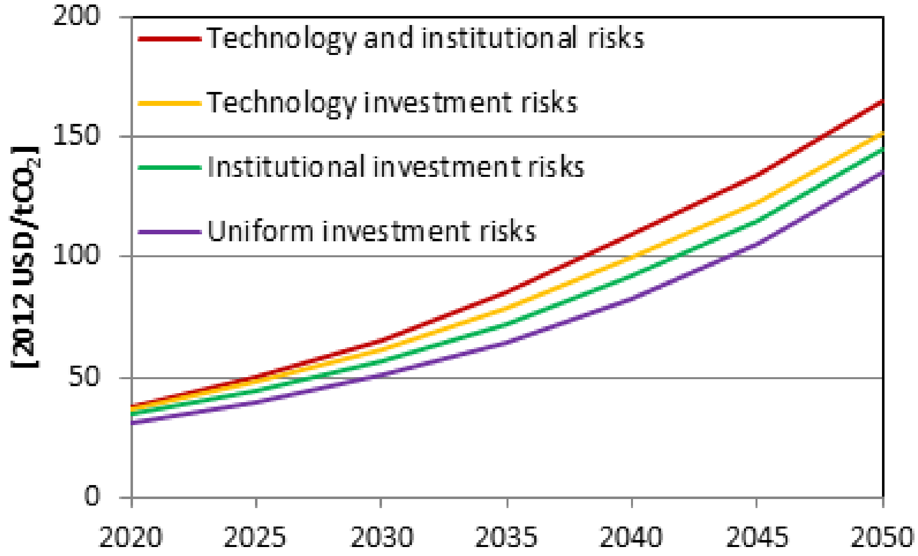

Figure 4-10 Global carbon price pathways to achieve the 50% global emissions target under the different investment risk scenarios. Under non-uniform investment risks across technologies, carbon prices to achieve the 50% global emissions target are higher.

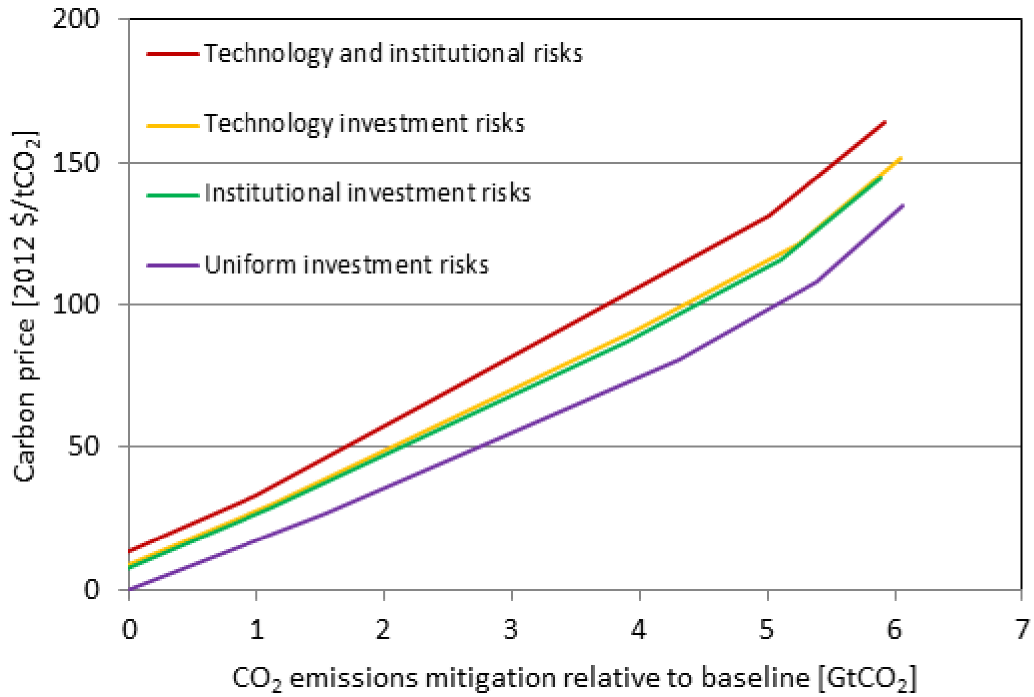

Figure 4-11 Marginal abatement cost (MAC) curves for India (lower institutional quality) in 2050 to achieve the 50% global emissions target under the different investment risk scenarios. When non-uniformities in investment risks across technologies are introduced, the MAC curve shifts upward as costs of capital for investing in low-carbon technologies in this scenario are higher. When non-uniformities in institutional qualities are introduced, the MAC curve shifts upward as investing in India is high risk and costs of capital for investing in low-carbon technologies are higher. Thus, when non-uniformities across technologies and institutional qualities are combined, technology and institutional risks reinforce each other and marginal abatement costs are higher.

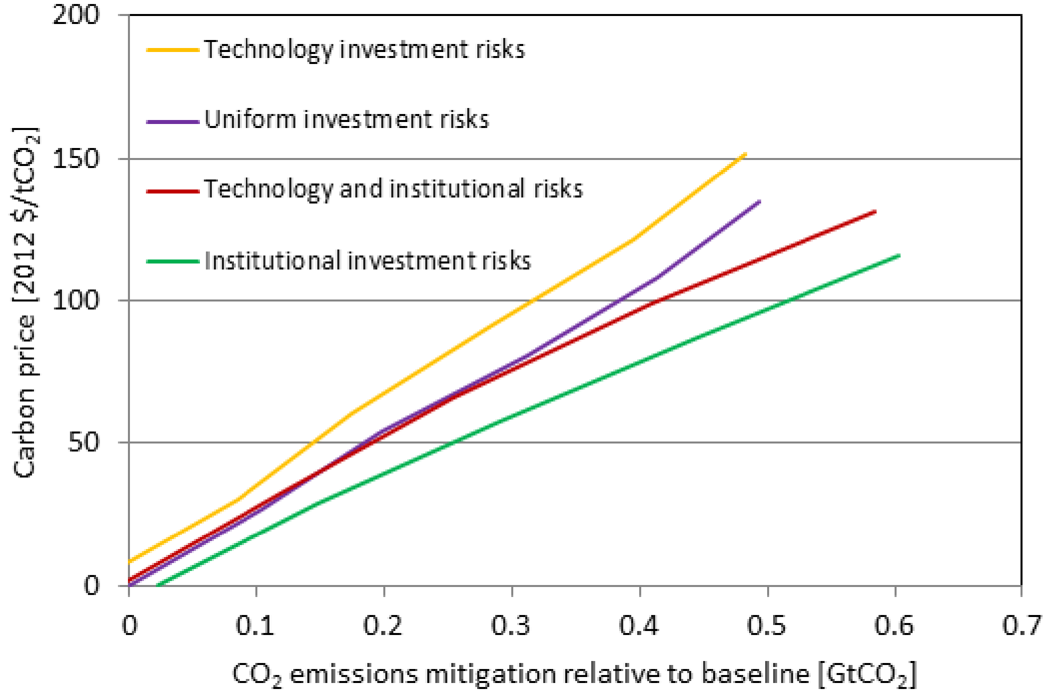

Figure 4-12 Marginal abatement cost (MAC) curves for Canada (higher institutional quality) in 2050 to achieve the 50% global emissions target under the different investment risk scenarios. When non-uniformities in investment risks across technologies are introduced, the MAC curve shifts upward as costs of capital for investing in low-carbon technologies in this scenario are higher. When non-uniformities in institutional qualities are introduced, the MAC curve shifts downward as investing in Canada is low-risk and costs of capital for investing in low-carbon technologies are lower. Thus, when non-uniformities across technologies and institutional qualities are combined, technology and institutional risks cancel each other and marginal abatement costs are lower.

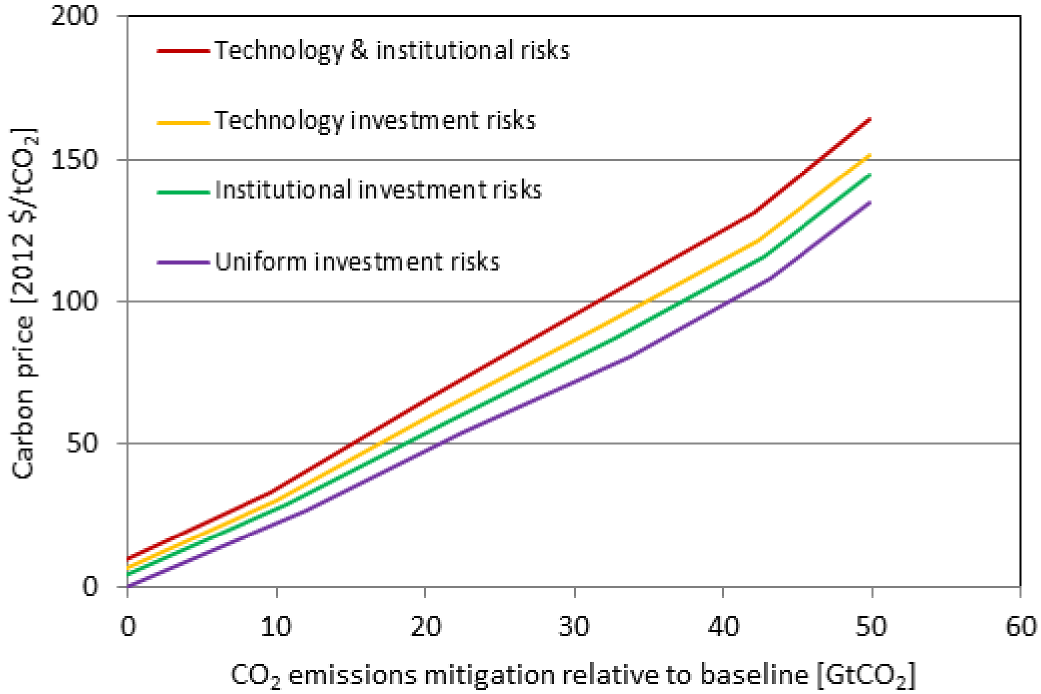

Figure 4-13 2050 global marginal abatement cost (MAC) curves to achieve the 50% global emissions target under the different investment risk scenarios. When non-uniformities in investment risks are introduced, global MAC curves shift upward.

The increased carbon prices significantly alter investment patterns (Figure 4-8 B-D). Compared with the case with uniform investment risks, investments in bio-CCS increase. This is because bio-CCS is a negative emissions technology, so higher carbon prices in these scenarios shift the economic advantage towards bio-CCS. However, similar to the baseline scenario, investments in other low-carbon technologies decrease. Nevertheless, such technologies get deployed (because of the logit technology choice specification), raising electricity prices and reducing demand for electricity by end-use sectors (Figure 4-14). As a result, overall electricity generation is lower, reducing not only investments in individual low-carbon technologies, but also total investment in the electricity sector. These effects apply to all regions, reducing power sector investments throughout the globe.

The effect of non-uniformities across regions in the climate policy scenarios is similar to the baseline scenario. Investments in regions with inferior institutions decrease and those in regions with superior institutions increase, with a net reduction in global investments (Figure 4-8). The combined effect of non-uniformities across technologies and regions is therefore a change in investment relative to the uniform investment risks scenario that is disproportionate across regions (Figure 4-9 B, Figure 4-15 A). Investments in regions with inferior institutions decrease by as much as 60% and those in regions with superior institutions increase by as much as 32%.

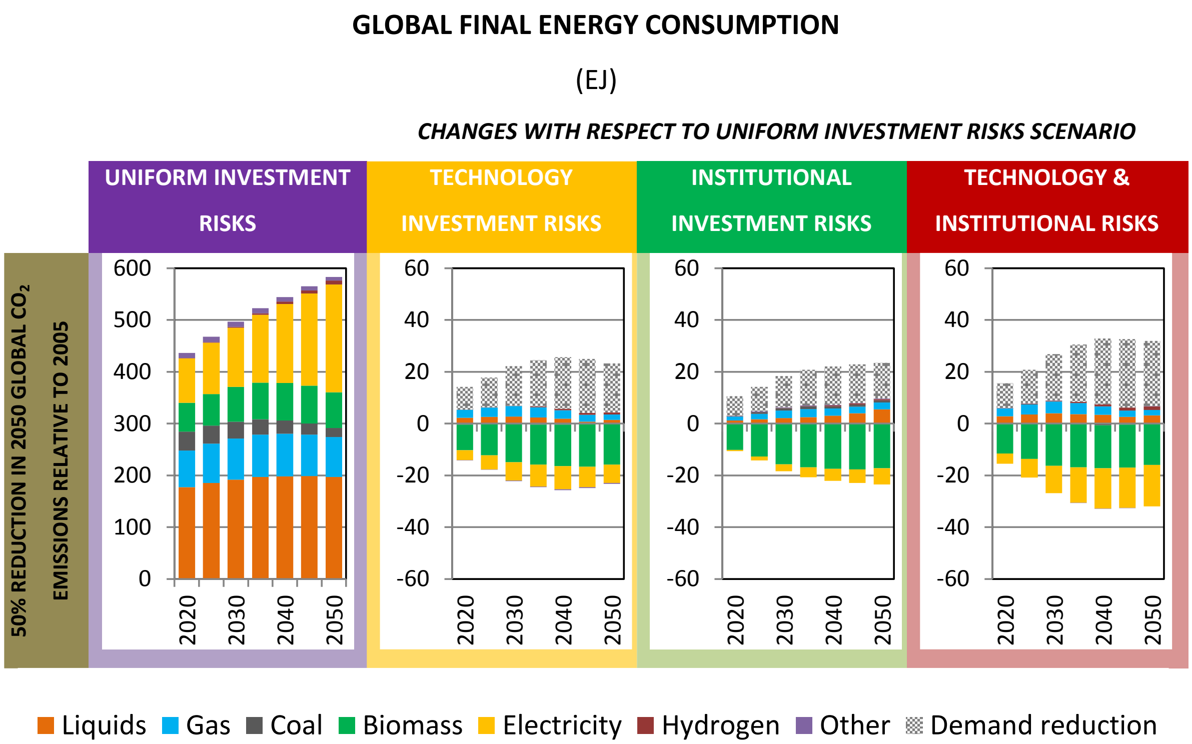

Figure 4-14 Global final energy consumption under the 50% global emissions target and the different investment risk scenarios. Under non-uniform investment risks, electricity becomes an expensive fuel, reducing demand for electricity by end-use sectors. The climate target is then achieved by reduction in energy demand and expansion of bio-CCS in the electricity sector.

As emissions mitigation is proportional to investment, regions with superior institutions mitigate more and regions with inferior institutions mitigate less compared with the uniform investment risks scenario (Figure 4-15 B). As explained earlier, the direct effect of lower investment risks in regions with superior institutions is to reduce marginal abatement costs in such regions (as costs of capital for investment in such regions are lower). Consequently, investments in regions with superior institutions increase to achieve cost-effective global mitigation and such regions undertake more mitigation compared with the uniform investment risks scenario. Because emissions mitigation is a public good, increased mitigation in regions with superior institutions results in lower mitigation in regions with inferior institutions. As a result, increases in mitigation costs (mitigation cost is calculated as the area under the marginal abatement cost curve and measures the loss in both consumer and producer surplus under a carbon policy but not the surplus gains through avoided climate damages (Calvin et al., 2009)) are higher for regions with superior institutions (Figure 4-15 C). In other words, although the global cost of achieving the stringent emissions mitigation target under non-uniform investment risks is higher compared with the uniform investment risks scenario (Figure 4-10), most of the increase is borne by regions with superior institutions.

4.6. Low investment risks in China

In the analysis presented so far, I have assumed higher investment risks in countries with inferior institutions. However, it is evident from the above discussion on China's investment climate that exceptions exist. China is an interesting case to investigate because of the large size of the market in addition to the above characteristics. I therefore consider a scenario in which investment risks are low only in China. When investment risks are low only in China, China's mitigation costs are higher compared with the uniform investment risk scenario (Figure 4-16). This is again because of the public goods effects of technologies explained previously – due to lower investment risks, marginal abatement costs in China are lower. Consequently, China undertakes more abatement relative to the uniform investment risks scenario. On the other hand, global mitigation costs remain unchanged because higher mitigation in China is offset by lower mitigation and hence, lower mitigation costs in rest of the world. An important caveat to the findings of this study in general and the China experiment in particular is that I do not account for domestic incentives such as technological leadership, comparative advantages and energy security to invest in technologies. This caveat notwithstanding, the above experiment illustrates that achieving a long-term climate goal is a global priority, international implications of domestic policies meant to encourage domestic investment- such as the financial incentives in China- will be an important driver of domestic costs.

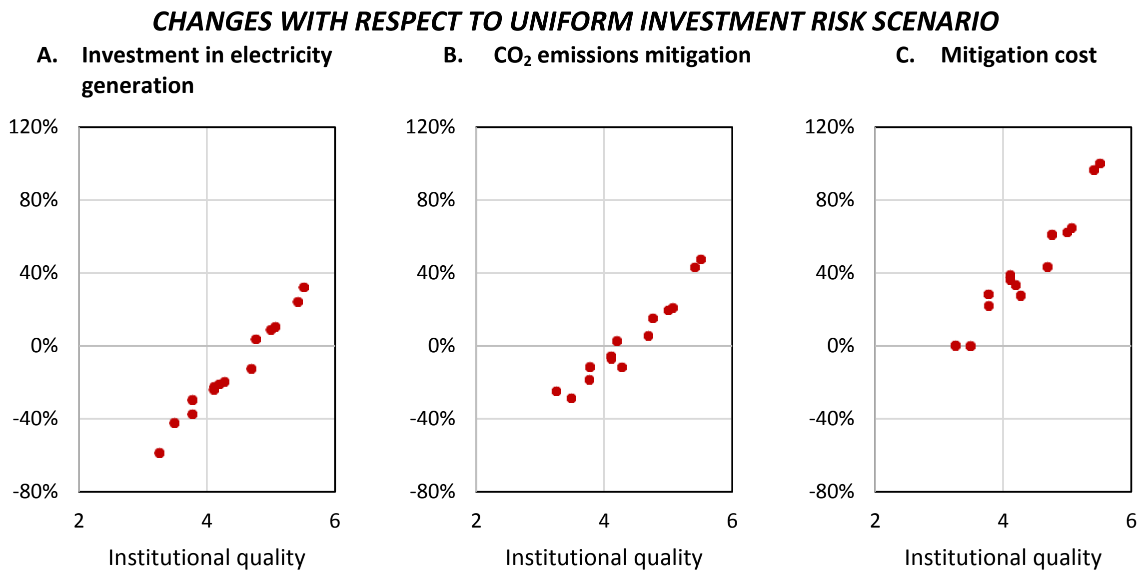

Figure 4-15 Changes (with respect to the uniform investment risks scenario) in A.) Investments (2020-2050) in electricity generation B.) Cumulative CO_2 emissions mitigation relative to the baseline (2020-2050) and C.) Mitigation costs, when investment risks vary across technologies and regions. Mitigation costs and investments between 2020 and 2050 are discounted and cumulated. CO_2 emissions are calculated only from fossil fuels and industry. The cases presented here correspond to the 50% global emissions target.

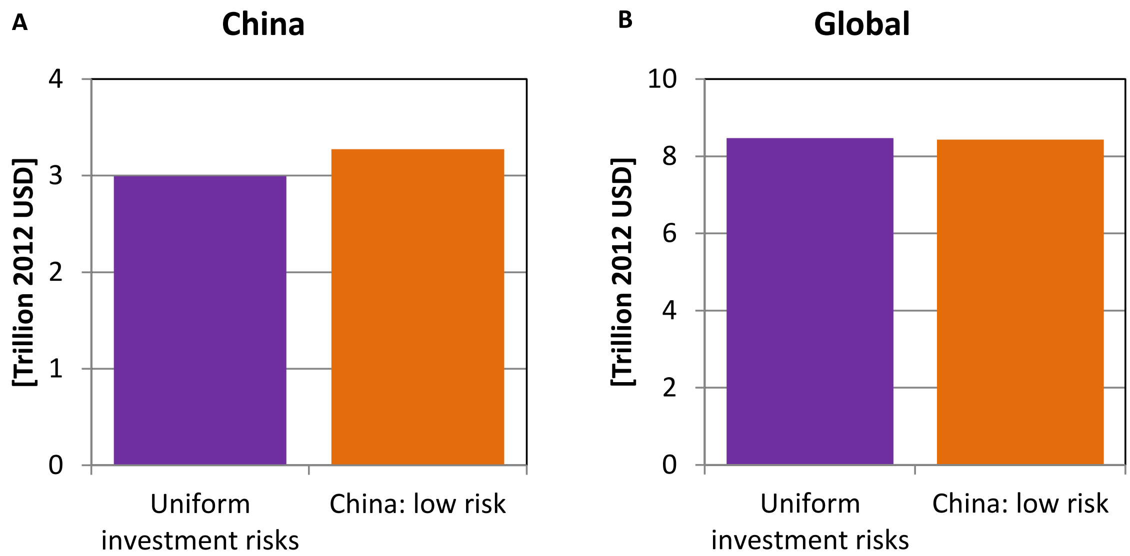

Figure 4-16 Mitigation costs for A.) China and B.) Globe under the 50% global emissions target when investment risks are lower only in China. When investment risks are lower only in China, marginal abatement costs for China decrease (as costs of capital for investment in China are lower). On the other hand, overall investment in China increases as emissions reduction is a public good. This increases mitigation costs for China in spite of lower investment risks.

4.7. Sensitivity analyses

The analysis so far leads to two key findings. First, under non-uniform investment risks, global costs of achieving a climate target are higher compared with a world with uniform investment risks (Figure 4-10). Second, compared with a world with uniform investment risks, regions with superior institutions mitigate more and regions with inferior institutions mitigate less (Figure 4-15). In order to check the consistency of these findings, I conduct sensitivity analyses on the following key assumptions (Table 4-4): i.) the global emissions target ii.) assumptions about FCRs (FCRs for low-risk technologies and risk premium for high-risk technologies) and iii.) technologies considered high-risk.

For the sake of presentation of results of the sensitivity analyses, I focus on two metrics that summarize the key findings, namely, changes in global carbon prices and cumulative CO_2 emissions mitigation (from fossil fuels and industry) under variation of investment risks across technologies and regions relative to uniform investment risks scenarios.

Table 4-4 Scenarios for sensitivity analyses

Scenario	Global emissions reduction target (2050 global CO_2 emissions from fossil fuels and industry with respect to 2005 levels)	Low-risk technologies	High-risk technologies	FCR for low-risk technologies	Risk-premium for high-risk technologies	FCR for high-risk technologies	Remarks
50% reduction target FCR:13-17 Low carbon: high risk	50%	Fossil-fuel	Low-carbon [a]	13%	4%	17% X f [b]	Central assumptions
25% reduction target	25%	Fossil-fuel	Low-carbon [a]	13%	4%	17% X f [b]	Sensitivity on global emissions reduction target
75% reduction target	75%	Fossil-fuel	Low-carbon [a]	13%	4%	17% X f [b]	
FCR:10-14	50%	Fossil-fuel	Low-carbon [a]	10%	4%	14% X f [b]	Sensitivity on low-risk FCR
FCR:16-20	50%	Fossil-fuel	Low-carbon [a]	16%	4%	20% X f [b]	
FCR:13-15	50%	Fossil-fuel	Low-carbon [a]	13%	2%	15% X f [b]	Sensitivity on risk premium for high-risk technologies
FCR:13-19	50%	Fossil-fuel	Low-carbon [a]	13%	6%	19% X f [b]	
Fossil-fuel: high risk	50%	Low-carbon [a]	Fossil-fuel	13%	4%	17% X f [b]	Sensitivity on technologies considered low/high risk

[a] Low-carbon technologies include nuclear, renewables, CCS and bioenergy

[b] Assuming that FCRs vary with institutional quality scores according to a log-linear relationship, FCRs for regions other than the U.S. are calculated using the following expression: $FCR_{i,j} = FCR_{i,USA} \times f$ where $FCR_{i,j}$ is the FCR for technology *i* in region *j* and *f* is given by: $f = \frac{\gamma_0+\gamma_1 \ln IQ_j}{\gamma_0+\gamma_1 \ln IQ_{USA}}$, where IQ_j refers to the GDP-weighted institutional quality score for region *j* (Benítez et al., 2007; Erb et al., 1996). γ_0 and γ_1 are parameters of the log-linear model are chosen such that the spread in FCRs across GCAM regions is consistent with the spreads observed in lending rates and equity risk premiums in Figure 4-3.

4.7.1. Sensitivity on global emissions target

In central analysis conducted in this chapter, I specified a 50% reduction in 2050 global CO_2 emissions from fossil fuels and industry relative to 2005 levels. For the purpose of sensitivity analysis, I consider 25% and 75% reductions. Global carbon prices under the

25% and 75% targets are lower and higher respectively, compared to the 50% target (Figure 4-17, Figure 4-18). Nevertheless, under all global emissions targets, global carbon prices are higher under non-uniform investment risks and regions with superior institutions mitigate more.

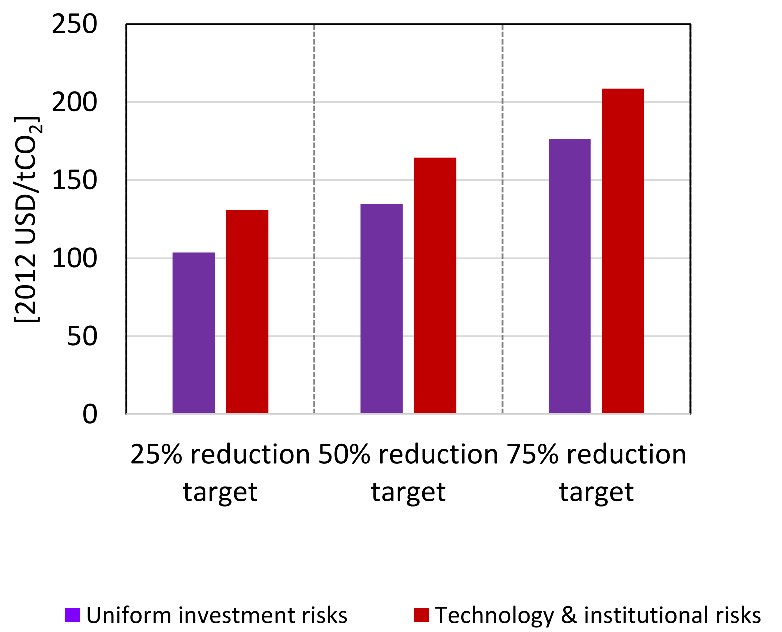

Figure 4-17 Global carbon prices in 2050 under different global emissions reductions targets (see Table 4-4 for detailed assumptions).

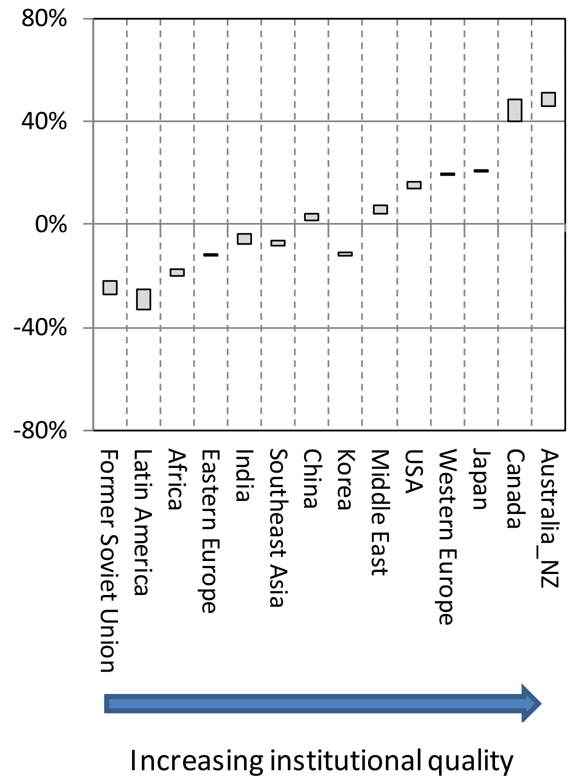

Figure 4-18 Percentage changes (relative to the uniform investment risks scenarios) in cumulative CO_2 emissions mitigation (2020-2050) relative to baseline with non-uniform investment risks across technologies and regions, under different global emissions reduction targets (see Table 4-4 for detailed assumptions). The boxes show the range across sensitivity cases. CO_2 emissions are calculated only from fossil fuels and industry.

4.7.2. Sensitivity on FCR assumptions

The findings of this study hinge on assumptions about technology costs and fixed charge rates (FCRs). Previous studies have evaluated sensitivity to technology cost assumptions in the GCAM model (Clarke et al., 2008; McJeon et al., 2011). I focus this sensitivity analysis on assumptions regarding FCRs. The main analysis of this study assumes an FCR of 13% for low-risk technologies and 17% for high-risk technologies based on a survey of FCRs used for financial analyses in the US (Table 4-1). Uncertainties in the FCRs obtained for USA can arise due to a number of reasons including assumptions about equity/debt shares, discount rates, lifespan of investments, tax rates and depreciation schedules. For the sake of sensitivity analyses, I change the FCR assumptions for low-risk technologies and the risk premium for high-risk technologies (Table 4-4).

The results indicate that changes in global and regional mitigation costs under non-uniform investment risks relative to the uniform investment risks scenarios are more sensitive to assumptions about the risk premium compared to assumptions about the FCR for low-risk technologies (Figure 4-19, Figure 4-20). For example, the spread in changes in 2050 global carbon prices under variation of investment risks with technologies and regions relative to the uniform investment risks scenarios when the FCR for low-risk technologies are varied between 10% and 16% is small (changes in carbon prices across sensitivity cases are 21%-22). In contrast, when the risk premium for high-risk technologies is varied between 2% and 6%, the spread in changes in carbon prices is greater (changes in carbon prices across sensitivity cases are 15%-28%). This is because, investments in GCAM depend on relative economics of technologies. Hence, the risk premium for high-risk technologies has a greater influence on the competitive advantage of such technologies relative to low-risk technologies compared to the FCR for low-risk technologies. Consequently, the risk premium has a greater influence on the deployments of low-carbon technologies (which are high-risk) and hence on marginal abatement costs and carbon prices. Nevertheless, in spite of changes in the magnitudes of the impacts on carbon prices and regional mitigation costs, the two key findings of this analysis are consistent across various assumptions about FCRs.

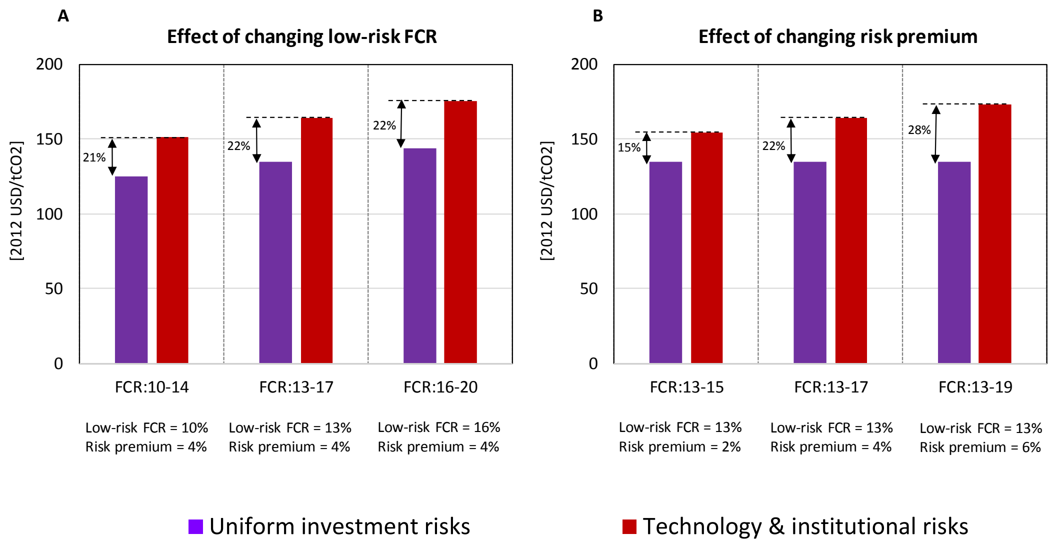

Figure 4-19 Global carbon prices in 2050 under different assumptions regarding fixed charge rates (see Table 4-4 for detailed assumptions). The cases presented here correspond to the 50% global emissions target.

4.7.3. Sensitivity on technologies considered high-risk

In the investment risk scenarios considered so far, I specified higher investment risks for low-carbon technologies and lower investment risks for fossil-fuel technologies. Here, I consider a scenario in which investment risks are higher for fossil-fuel technologies compared to low-carbon technologies. Such a scenario is conceivable in a carbon-constrained world in which a sustained and increasing price on carbon could make investments in fossil-fuel rather than low-carbon technologies more risky. Governments might adopt policies that favor low-carbon technologies—as many governments have done already—precisely with the ambition of making investors view these technologies as less risky.

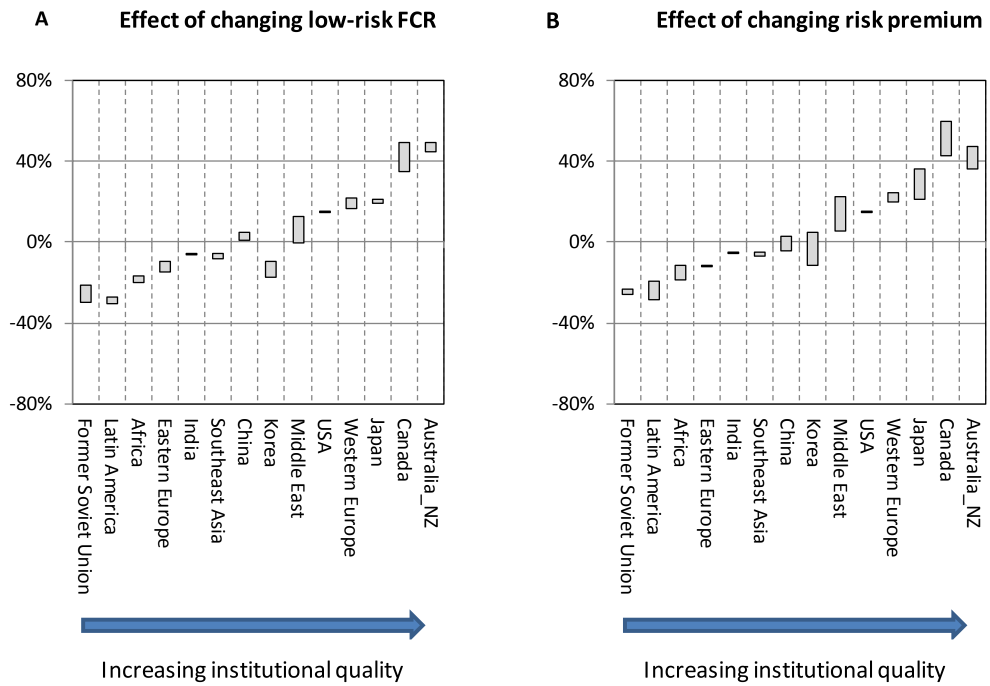

Figure 4-20 Percentage changes (relative to the uniform investment risks scenarios) in cumulative CO_2 emissions mitigation (2020-2050) relative to baseline with non-uniform investment risks across technologies and regions, under different FCR assumptions (see Table 4-4 for detailed assumptions). The boxes show the range across sensitivity cases. The cases presented here correspond to the 50% global emissions target. CO_2 emissions are calculated only from fossil fuels and industry.

The effect of higher investment risks for fossil-fuel technologies is to reduce carbon prices relative to the uniform investment risks scenario (Figure 4-21). This is because, higher investment risks for fossil-fuel technologies increase the costs of electricity generation from such technologies and improve the competitive advantage of low-carbon technologies, thus decreasing marginal abatement costs. The effect is, however, small compared to the increase in carbon prices due to higher investment risks for low-carbon technologies. For example, the global carbon price in 2050 under higher investment risks for low-carbon technologies along with variation across regions to achieve a 50% emissions target is 22% higher compared with the uniform investment risks scenario. In contrast, the carbon price under higher investment risks for fossil-fuel technologies along with variation across regions is lower by only 3%. This is because, fossil-fuel technologies are less capital-intensive compared to low-carbon technologies. Hence, a risk premium on fossil-fuel technologies will have a smaller impact on marginal abatement cost curves compared with the same risk premium on low-carbon technologies, even if the directions of the impacts will be opposite.

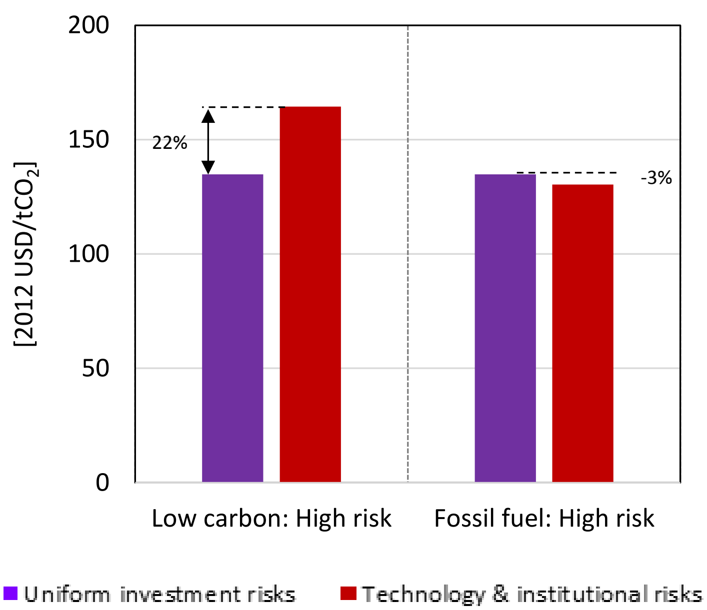

Figure 4-21 Global carbon prices in 2050 when A.) investment risks for renewables, nuclear, CCS and bioenergy are higher compared to fossil-fuel technologies and B.) investment risks for fossil-fuel technologies are higher compared to renewables, nuclear, CCS and bioenergy. The cases presented here correspond to the 50% global emissions target.

4.8. Conclusions

Achieving stringent climate targets will require a dramatic transformation of the energy system, requiring large scale investments in the energy sector. Previous assessments of emissions mitigation patterns have acknowledged the huge variation in real-world factors that affect where, how and at what costs firms deploy capital. However, most studies mention these issues in passing, and then proceeded to analyze an idealized situation that ignores these factors, even though they can be determinative in terms of outcomes (Calvin et al., 2012; Clarke et al., 2009; Kriegler et al., 2014; McCollum et al., 2013; Riahi et al., 2015). This essay reviews the factors that can affect investors' assessments of risks, leading to a wide variation in the business climate for investment and uses an integrated assessment model to analyze the implications of heterogeneity in investment risks for the costs and geography of climate change mitigation. I find that a more nuanced representation of investments in the electricity generation sector—in which perceived risks vary significantly across technologies and regions changes our understanding of emissions mitigation in two important ways. First, achieving an emissions mitigation goal is more expensive than it would be in a world with uniform investment risks- the ubiquitous assumption in modeling emissions mitigation Second, regions with inferior institutions mitigate less and regions with superior institutions mitigate more – not driven by any policy decision but because markets make emissions mitigation more difficult in regions with inferior institutions.

The above findings have implications for policy and as well as research. For policy makers, the findings of this study suggest that major efforts to improve the institutional environment for investment—and thus lower risks—need to be essential elements of a larger strategy for cutting emissions globally cost effectively. Those efforts are well known in the study of foreign investment and include improved enforcement of contracts, more transparent and reliable regulation, and more effective international rules and offshore arbitration for investors. It is plausible that institutional reforms may even be more important than technology-focused policies. And more importantly, absent such reforms, mitigation effort could be disproportionately focused on countries where investment risks are lower.

For analysts, this study provides an illustration of methods that could be used to improve how real world investment risks could be reflected in the modeling of emissions mitigation. This work, along with a suite of other studies, suggests that real-world factors affecting investments in technology are important for assessing emissions mitigation patterns (Iyer et al., 2015a). Future research might decompose each of these factors individually—to assess their relative importance and the impact of policy efforts to address them.

There are several caveats to the findings of this study. First, although many paradigms to compare mitigation efforts across regions have been put forth in the literature, I present results for equal marginal abatement cost because it provides a baseline for comparison with many previous analyses, and also because the approach internalizes the public goods characteristics of investments in technology (den Elzen et al., 2010). The actual distribution of investments would depend on the policies and mechanisms used domestically and internationally (for example, domestic policies to encourage technology deployment, offset crediting programs, etc.). Second, I assume that institutional qualities are constant over time. Competitive forces in the continuous interaction between institutions and organizations could drive institutional change. However, the process may be slow and path-dependent due to economies of scale and network externalities, or rapid because of political upheavals (North, 2008). Finally, I do not consider availability of energy efficiency options and mitigation from land-use changes to retain focus on the effects of non-uniformities in investment risks in the electricity generation sector, keeping other variables fixed. A detailed examination of the implications of non-uniform investment risks for other sectors is reserved for future work.

Chapter 5 Conclusions

5.1. Summary of the dissertation and key findings

Climate change is one of the most important challenges facing the international community today. There is wide acknowledgement by scholars that development and diffusion of low-carbon technologies will be critical elements of mitigating climate change. This dissertation aims to illuminate the relationships between low-carbon technology diffusion and climate change mitigation policy under three "imperfect" circumstances, namely, constraints on the rate of diffusion of low-carbon technologies, countries promoting the deployment of low-carbon technologies based on national priorities and preferences and variation in investment risks across technologies and regions. I call such circumstances "imperfect" in comparison to previous assessments of global climate change mitigation technology and policy issues that have relied on idealized assumptions about technology availability and deployment, regional mitigation efforts and capacities to undertake those efforts.

The three essays together contribute in two important ways. The first contribution is methodological, providing future analysts, solid frameworks to incorporate real-world factors and policies in assessments related to technology and climate change mitigation policy. The second, equally important contribution is to provide policy relevant insights. This chapter provides a summary of key findings and policy implications of the three essays and directions for future research. In short, the research presented in this dissertation asserts, along with a suite of other studies, the importance of careful considerations of processes that influence technological change, and more importantly, factors that affect technology diffusion and investment while designing domestic and international policies to mitigate climate change cost-effectively.

5.1.1. Low-carbon technology diffusion rates

The first essay focuses on the importance of diffusion rates of low-carbon technologies for the costs and feasibility of achieving stringent long-term climate goals. A number of factors including technology market failures and institutional, behavioral, and social factors constrain the diffusion of low-carbon technologies, even in the presence of favorable emissions mitigation policies. Such factors could impact the timing as well as the costs and feasibility of achieving stringent climate targets. In addition, international negotiations have a history of slow movement. And such slow movements might delay national action because international agreements are important in bolstering national action. If such delays in international action continue, global mitigation levels could continue to lag behind ideal rates. This essay reviews the factors that constrain the deployment of low-carbon technologies and addresses the following questions. First, how do these constraints impact the cost and feasibility of achieving long-term climate targets? Second, how do these impacts change in the presence of delays in global mitigation action? The analysis shows that factors constraining the diffusion of low-carbon technologies 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 of achieving stringent climate stabilization targets. In addition, diffusion constraints become particularly important under delays when multiple technologies are jointly constrained.

The first essay lays out a simple approach to understand the impacts of slow diffusion of low-carbon technologies on the costs and feasibility of achieving low-carbon technologies. This is in contrast to previous studies that have either prohibited the construction of new capacity for some technologies, such as renewables and nuclear, 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).

In addition, this essay highlights important lessons for policy. To the extent that the international community is focused on achieving stringent long-term climate goals, policies to encourage technology deployment would play an important role, especially in the near-term. For instance, the results of the analysis showed that achieving a 550 ppm CO_2e target by the end of the century with stringent diffusion rate constraints on low-carbon technologies is infeasible within the specifications of the model.[17] And such infeasibilities increase with the stringency of the climate target (for example, achieving a 450 ppm target) and under delays in political action. Under moderate diffusion rate constraints, achieving such targets might be feasible – however, costs of achieving the targets are significantly higher. Thus, if achieving stringent long-term climate targets cost-effectively is a policy goal, the results of this analysis underscore the importance of policy incentives to encourage and speed up the adoption of such technologies. Indeed, such policies exist throughout the world. Examples of such policies include renewable portfolio standards (which is prevalent in many US states and some European countries),

[17] 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.

feed-in-tariffs (common in majority of European countries, Australia, Canada and some developing countries), exempting energy taxes on low-carbon technologies, production tax credits and subsidies (for example for nuclear power in the US).

An important insight from this essay is that constraints to the diffusion of low-carbon technologies such as might exist even in the presence of favorable policies. However, it may be likely that diffusion rates are not constrained as severely as this chapter assumes, particularly for technologies such as wind and photovoltaics. For example, among other factors, economies of scale and ease of installation might ease the stringency of diffusion rate constraints for photovoltaic technologies. It is important to note that I explored a range of scenarios in which I imposed not only different levels of diffusion rate constraints but also considered constraints on different sets of low-carbon technologies. Also, the constraints considered in this chapter are meant to capture among others, institutional, behavioral and social factors that might limit diffusion rates even in the presence of favorable technology characteristics and policies (Hultman et al., 2012). The results from these scenarios should, therefore, not be seen as only showing the increasing difficulty of mitigation in the presence of diffusion rate constraints, but also viewed as highlighting the importance of addressing them.

In a broad sense, the analysis in this chapter highlights the importance of policies that are aimed at developing institutions, disseminating information, encouraging technology demonstration and developing flexible regulations intended to address broader institutional, behavioral, and social constraints that might severely limit the rate of deployment of certain low-carbon technologies.[18] Such efforts might be required on top of "demand-pull" policy instruments such as those mentioned above or other market-based policy instruments such as carbon price based mechanisms that are meant to correct only market failures and do not necessarily address other institutional, behavioral, and social issues.

5.1.2. Divergence between domestic and global long-term outcomes

The results of the first essay indicated the importance of deployment policies intended to encourage and speed up the adoption of low-carbon technologies, especially in the near-term. Indeed, many countries view promoting the deployment of specific low-carbon technologies as an alternative to economy-wide carbon price based mechanisms. Promoting the deployment of low-carbon technologies in the near-term involves a cost – but at the same time, it could pay off in the long-term. For example, promoting the deployment of low-carbon technologies in the near-term leads to additional emissions mitigation in the near-term, leading to reductions in long-term mitigation costs– simply because the more mitigation that is achieved in the near-term, the less that would have to be undertaken in the presence of a climate goal in the long-term. Promoting the deployment of low-carbon technologies in the near-term could also lead to improvements in technology costs – further reducing long-term mitigation costs. However, the near-term abatement as well as technological change effects described above have public goods characteristics. Therefore, what is cost-effective globally may not be so, from the perspective of individual countries promoting the technologies in the near-term.

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[18] While Chapter 3 did not make an attempt to separate out the effects of various factors, the analysis presented in Chapter 4 is a step in that direction.

The second essay illustrated this divergence in long-term domestic and global outcomes. I showed that under certain assumptions about technological change, the globally cost-effective strategy in terms of achieving a long-term climate goal is a diversified approach in which different countries invest in promoting different technologies. This is because, in a diversified approach, advances in more emissions abatement technologies may spill over to the globe and that leads to reduced mitigation costs globally. In contrast, under a hypothetical scenario in which all countries pursued the same technology, such spillovers would be largely redundant and the impact on global mitigation costs would be smaller. However, under the same technological change assumptions, the cost-effective strategy from the perspective of individual countries is to invest in currently mature and cheaper technologies – even if other domestic payoffs such as early-mover advantages through technological leadership, increased exports and employment benefits are taken into account. This divergence in global and domestic occurs because public goods characteristics of technologies combined with differences in near-term costs of promoting different technologies create incentives to free-ride. In other words, from the domestic perspective, countries are better off promoting the deployment of currently mature and cheaper technologies domestically and free-riding on the benefits of other countries promoting more expensive technologies. Consequently, under equilibrium, countries would prefer to invest in currently dominant alternatives and that might not lead to the globally cost-effective outcome. However, the analysis presented in the essay also showed that if deployment policies lead to sufficiently rapid technological improvements that spill over globally, domestic outcomes may align with the global outcome. That is, if technological change induced by deployment policies is sufficiently rapid, the domestic outcome could shift to a diversified approach.

An important contribution of this essay is that it lays out a framework to analyze the long-term payoffs of near-term low-carbon deployment policies. By introducing payoff matrices, the analysis illustrates the divergence in domestic and global outcomes if countries were to promote the deployment of low-carbon technologies in the near-term. The above findings also suggest implications for international and domestic policy. The analysis illustrates that if countries negotiate with each other and make decisions on low-carbon technology deployments driven by domestic economic benefits alone, such decisions are likely to tilt toward currently cheaper alternatives. On the other hand, to the extent that the international community is looking toward achieving a long-term climate goal cost-effectively, international diffusion of diverse low-carbon technologies – not just current dominant alternatives – will be required. In other words, there are substantial gains to international cooperation in the development and diffusion of diverse low-carbon technologies. More broadly, the findings of this essay argue for international cooperation mechanisms to include a diverse set of markets and institutions beyond those explicitly related to climate, including those for trade, development, and intellectual property (Newell, 2010). International cooperation in research and development of low-carbon technologies is not new (de Coninck et al., 2008). A step in that direction is the U.S.-China Clean Energy Research Center (CERC, 2015). A broader international cooperation will require reconciliation of differences in controversial issues such as international trade and intellectual property rights and careful considerations of their interactions with domestic policies. Such cooperation will be all the more important to induce faster rates of technological change and increase spillovers – which will be instrumental in aligning domestic policy objectives with international goals and also avoid globally ineffective outcomes.

5.1.3. Non-uniform investment risks

Technology-focused policies such as deployment policies and emissions-focused policies, such a carbon tax do not directly address the important issue of the huge capital investment required for the deployment of low-carbon technologies. A number of factors such as the quality of public and private institutions, sector and technology specific risks and firm-level characteristics can affect investors' perceptions of risks creating a wide variation in the business climate for investment. Such heterogeneity in investment risks can have important implications as investors respond to risks by expecting higher returns for riskier projects, delaying or forgoing investments and preferring to invest in existing, familiar technologies. The third essay answered the following question: How does heterogeneity in investment risks influence the cost and geography of climate change mitigation? This essay represented the variation in investment risks across technologies and regions in the electricity generation sector - a pivotally important sector in most assessments of climate change mitigation (Clarke et al., 2014) - and explored the impact on the magnitude and distribution of mitigation costs. This modified representation of investment risks has two major effects. First, achieving an emissions mitigation goal is more expensive than it would be in a world with uniform investment risks. Second, industrialized countries mitigate more, and developing countries mitigate less.

This essay introduced a methodology that illustrates how real world investment risks can be incorporated in models of emissions mitigation and provides evidence for the importance of such factors in assessments of the costs and distribution of emissions mitigation patterns. The results of this essay also have implications for policy. The findings of this essay suggest that major efforts to improve the institutional environment for investment—and thus lower risks—need to be essential elements of a larger strategy for cutting global emissions cost-effectively. Absent such reforms, mitigation effort could be disproportionately focused on countries where investment risks are lower.

Efforts to bring about institutional changes to encourage investment are well known in the study of foreign investment. For example, scholars have emphasized the importance of protection of investor rights in encouraging foreign investment. When investors finance firms, they typically obtain certain rights or powers that are generally protected through the enforcement of regulations and laws. Some of these rights include disclosure and accounting rules, which provide investors with the information they need to exercise other rights. Protected shareholder rights include those to vote for directors, participate in shareholders' meetings, sue directors for suspected expropriation, etc. Laws protecting creditors largely deal with bankruptcy and reorganization procedures, and include measures that enable creditors to repossess collateral, to protect their seniority, and to make it harder for firms to seek court protection in reorganization (La Porta et al., 2000). Protecting investor rights and contract enforcement through corporate governance reform would require radical changes in the legal systems of many countries, requiring amendments of securities, company, and bankruptcy laws. Such reform could lead to several benefits including the expansion of financial markets, facilitating access to foreign financing for new firms and improved efficiency of investment allocation (La Porta et al., 2000). Examples of international initiatives in these directions include Power Africa, the International Finance Corporation, Sustainable energy for All and a host of other "public-private partnerships".

The findings of this essay indicate that in the context of international climate change mitigation policy, it is plausible that institutional reforms to bring about institutional change and reduce such transaction costs may even be more important than technology-focused policies. What compounds the issue, however, is that institutional change is extremely path dependent – those who make policy and design institutions have a stake in the framework they created and resist changes that may rob them of power or property (Shirley, 2008). Sudden institutional changes may occur for example, under a revolution or a political upheaval; however, unless beliefs and norms also change, it is questionable whether such sudden changes will stick on. It is particularly important to note that due to path dependency and the stickiness of beliefs and norms, institutional change cannot be brought about by simply importing institutions that were successful in other countries (Shirley, 2008).

5.2. Important caveats

Although I discuss the caveats to the research presented in this dissertation in chapters containing the individual essays, some general assumptions merit further discussion. First, throughout the dissertation, I have used one model, namely GCAM to understand the relationships between technology and policy in the context of climate change mitigation under imperfect circumstances. While this is an important caveat, the insights from the research presented in this dissertation are fundamental and based on basic principles. Hence, the broad qualitative insights from this dissertation are solid and will remain unchanged even if other modeling frameworks are used to answer similar questions. That said, future studies exploring similar issues might perform inter-model comparisons to check the robustness of the quantitative results presented in this dissertation.

Second, I have assumed that action against climate change follows the equal marginal abatement cost rule wherein an emissions mitigation target is achieved by means of a global carbon price that is uniform across regions and various sectors of the economy. This assumption has implications, particularly in discussions surrounding long-term payoffs from reduced mitigation costs in Chapter 3 and the distribution of mitigation costs in Chapter 4. Although many paradigms to compare mitigation efforts across regions have been put forth in the literature, I consider this approach because it provides a baseline for comparison with many previous analyses, and also because the approach internalizes the public goods characteristics of investments in technology (den Elzen et al., 2010). The actual distribution of investments and mitigation costs would depend on the policies and mechanisms used domestically and internationally (for example, domestic policies to encourage technology deployment, offset crediting programs, etc.). That said, I do consider deployment policies in the near-term rather than an idealized carbon-price based mechanism for the analyses presented in Chapter 3. This is an important methodological contrast to previous studies based on energy-economic models that have explored the economics of "sub-optimal" near-term policies or "benefits of early action" – such studies have mostly represented near-term action as an economy-wide price on carbon (Bosetti et al., 2009a; Bosetti et al., 2009b; Jakob et al., 2012).

Third, all the essays in this dissertation focus on the electricity generation sector mainly because this sector has been identified as particularly critical in previous assessments of climate change mitigation policy (Clarke et al., 2014). This has implications for the impacts of diffusion rate constraints and non-uniform investment risks on mitigation costs presented in Chapters 2 and 4 respectively. All the essays are comparative static analyses and restriction of the analyses to one sector helped retain focus on the interactions between variables of interest, keeping others fixed. Future studies on related themes should consider investigating the effects of such factors on sectors other than electricity generation.

Finally, I used simple input-output representations of institutional, behavioral, and social factors in Chapter 2. The assumption is that such factors tend to slow down diffusion and I represented the effects of such factors in the form of diffusion rate constraints. Although this is an important methodological contribution in itself (compared to studies that prohibit the construction of new capacity, completely exclude technologies or cap their maximum deployment), future studies should incorporate structural representations of such factors to gain more insight on the interaction among various factors that limit diffusion and differences of their impacts across regions and sectors.

5.3. Future research directions

The above caveats lend themselves to a number of avenues for future research. First, as pointed out earlier, it would be useful for future studies to include sectors other than electricity generation in analyses intended to understand the impacts of various frictions on costs and patterns of emissions mitigation. Investment patterns in other sectors might be quite different compared to the electricity sector and might require detailed examination. For example, investments in electricity generation are mostly domestic; that may not be the case in the transportation sector where fuels and vehicles may be imported rather than produced domestically. Likewise, investments in and diffusion of energy efficient technologies in buildings and households may be influenced by a range of factors in ways that may be different from supply-side sectors (see for example, Jaffe et al. (1993) and Jaffe and Stavins (1994) that discuss principal-agent problems influencing investments in energy efficient technologies). Similarly, investments in some sectors may primarily be self-financed by firms or individuals rather than through commercial or development institutions.

Second, future studies should represent institutional, behavioral, and social factors structurally to gain more insight on their impacts on investment and technology diffusion. This will be particularly important to understand the differences of such impacts across various regions and sectors. A step in that direction is the representation of one such factor —non-uniform investment risks in Chapter 4. However, that analysis considered only one variable, namely the cost of capital that is influenced by institutional qualities. Future studies should explore the effect of institutional quality on other variables such as infrastructure, project execution times and investment approvals. Future research might also decompose each of these factors individually—to understand how they interact, assess their relative importance across regions and sectors and the impact of policy efforts to address them.

Third, the essay on the divergence between domestic and global outcomes when countries promote the deployment of low-carbon technologies in the near-term based on national priorities and preferences does not address an important question on whether such deployment policies pay off for the investor countries investing in such policies. In other words, do long-term payoffs of near-term deployment policies become greater than one? If so, under what conditions? In a companion paper, I explore these questions in detail. A broad message that emerges out of an initial analysis based on the example considered in this essay is that whether such policies will payoff for investor countries would depend on a range of factors including the type of technologies deployed in the rest of the world; presence and nature of technological change, spillovers and also other benefits such as early-mover advantages and energy security.

Finally, the research presented in this dissertation raises an important question on what issues countries should focus on, in the near-term. Chapter 3 recognizes that countries are increasingly approaching climate change mitigation from a bottom-up perspective, at least in the near-term. That chapter provides a framework to think about long-term payoffs of one particular type of near-term "bottom-up" effort, namely policies to promote the deployment of low-carbon technologies. In contrast, the analyses presented in Chapters 2 and 4 (along with previous studies) highlight the importance of market failures in technology markets as well as non-market barriers (such as institutional, behavioral, and social factors) that tend to limit investments in and diffusion of low-carbon technologies in influencing the costs of achieving stringent climate change mitigation targets. What, then, should countries focus on in the near-term: promote the deployment and diffusion of low-carbon technologies in the near-term or improve domestic capabilities – such as the institutional environment in which such technologies are expected to diffuse? Do these issues have common areas of intersection? What kind of policies could address these issues? Future research analyzing the inter-linkages between these issues will be an important contribution to policy debates because such issues could potentially influence not only global costs of achieving long-term climate goals, but also the ability of countries to maximize national benefits associated with promoting low-carbon technologies.

Appendix A: Author contributions in the three essays of this dissertation

Chapters 2, and 4 of this dissertation led to publications as co-authored articles in peer-reviewed journals. Chapter 3 is submitted for publication.

For Chapter 2 (Iyer et al., 2015a), a round table comprising of Gokul Iyer, Nathan Hultman, Jiyong Eom, Leon Clarke and Haewon McJeon discussed the research question and designed the experiments. Gokul Iyer conducted all the experiments and wrote the first draft. The co-authors assisted in writing, further developing the argument, and refining the final version of the paper. Pralit Patel provided assistance in GCAM coding.

For Chapter 3 (submitted), a round table comprising of Gokul Iyer, Nathan Hultman, Leon Clarke and James Edmonds discussed the research question and designed the experiments. Gokul Iyer conducted all the experiments and wrote the first draft. The above co-authors assisted in writing, further developing the argument, and refining the final version of the paper.

For Chapter 4 (Iyer et al., 2015b), a round table comprising of Gokul Iyer, Nathan Hultman, Leon Clarke, James Edmonds, Brian Flannery, David Victor and Haewon McJeon discussed the research question and designed the experiments. Gokul Iyer conducted all the experiments and wrote the first draft. The above co-authors assisted in writing, further developing the argument, and refining the final version of the paper.

Appendix B: Derivation of growth rates in percentage per year from studies using S-curve

Studies looking at historical growth rates of technologies 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. Mathematically, if *f(t)* denotes the output of a technology at time *t*, and *g(t)*denotes the annual growth rate at time *t* in percentage, $g(t) = 100 \times \frac{f\prime(t)}{f(t)}$.

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. 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. The estimates of Grübler et al. (1999), Wilson and Grübler (2011) and Wilson et al. (2012) can be expressed in terms of annual percentage growth as follows.

Let us assume that the growth trajectory of a technology during the period when its market share is between 10% and 90% is linear and of the form $f(t) = mt + c$.[19] The annual growth rate *g*(*t*) at time *t* in percentage is then given as $g(t) = \frac{f\prime(t)}{f(t)} = 100 \times \frac{m}{mt+c}$. The average annual growth rate (y) in percentage in the time interval from t_0 to $t_0+\Delta t$, where t_0 is the time at which the market share is 10% and $t_0+\Delta t$ is the time at which the market share is 90% is then given by the integral $y = \frac{100}{\Delta t}\int_{t_0}^{t_o+\Delta t} \frac{m}{mt+c}\, dt$ which is

[19] The above studies do not specify the functional form of the S-curve trajectories. In the absence of that information, I make the approximation that the growth is linear during the time at which technologies grow from 10% to 90% of the market.

equal to $\frac{100}{\Delta t}\ln\frac{m(t_0+\Delta t)+c}{m(t_0)+c}$. Since $f((t_0 + \Delta t) = m(t_0 + \Delta t) + c = 90\%$ and $f((t_0) = m(t_0) + c = 10\%$, the above integral evaluates to 219.7/Δ*t*.

Appendix C: Representation of technology costs in Chapter 3

In this analysis, technology costs are represented as exponential functions of time. Costs of advanced technologies decrease at higher rates compared to reference technologies. In scenarios with delayed spillovers, the cost trajectory follows the reference cost trajectory for fifteen years and then diverges with an accelerated rate of improvement, asymptotically approaching advanced technology costs (Figure C-1). Following are the expressions for reference, advanced and delayed-advanced technology costs.

$$c_{ref}(t) = c(t_0)e^{-\beta_r t}$$

$$c_{adv}(t) = c(t_0)e^{-\beta_a t}$$

$$c_d(t) = c_{ref}(t) \quad \text{for } t < t_d$$

$$= c(t_0)e^{-\beta_r t_d} \; e^{-\beta_d(t-t_d)} \quad \text{for } t \geq t_d$$

where β_d is obtained as follows:

$$\beta_d = -\frac{1}{(T - t_d)} \ln \frac{c(t_0)/c_{adv}(t_f)}{e^{-\beta_r t_d}}$$

Where:

t	is the time from starting year
t_0	is the starting year of cost functions
$c(t_0)$	is the initial cost in the starting year t_0 same for all cases
β_r	is the percent rate of improvement in reference technology costs per year

T is the time interval between initial and final years

$c_{ref}(t)$ is the cost of reference technology at time *t*

$c_{adv}(t)$ is the cost of advanced technology at time *t*

β_a is the percent rate of improvement in advanced technology costs per year

$c_d(t)$ is the cost of delayed-advanced technology at time *t*

t_d is the time of delay for spillovers in the delayed-advanced case (assumed to be 15 years)

β_d is the percent rate of improvement in delayed-advanced technology costs per year

Reference assumptions about β_r and β_a are consistent with assumptions in Clarke et al. (2007) and McJeon et al. (2011). I consider five sensitivity cases based on β_r and β_a for wind and solar technologies (Table 3-3).

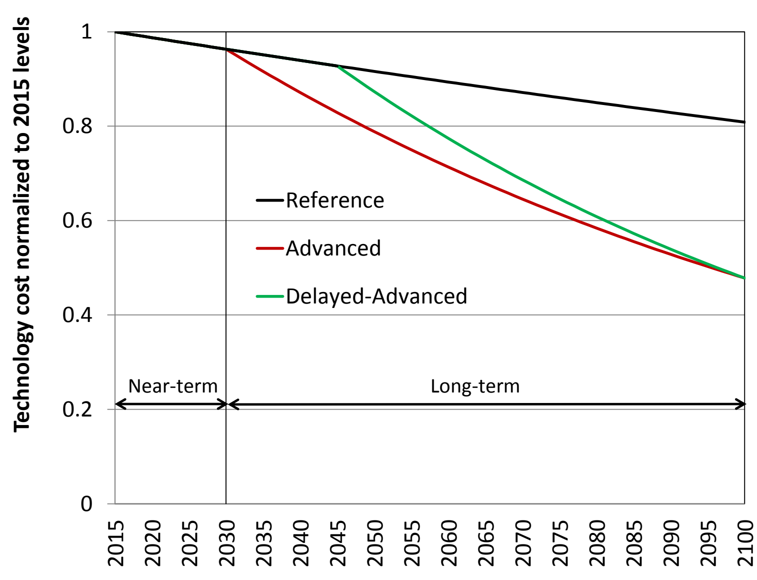

Figure C- 1 Representation of technology cost functions.

Appendix D: Sensitivity of domestic outcomes in Chapter 3 to assumptions about rates of technological change

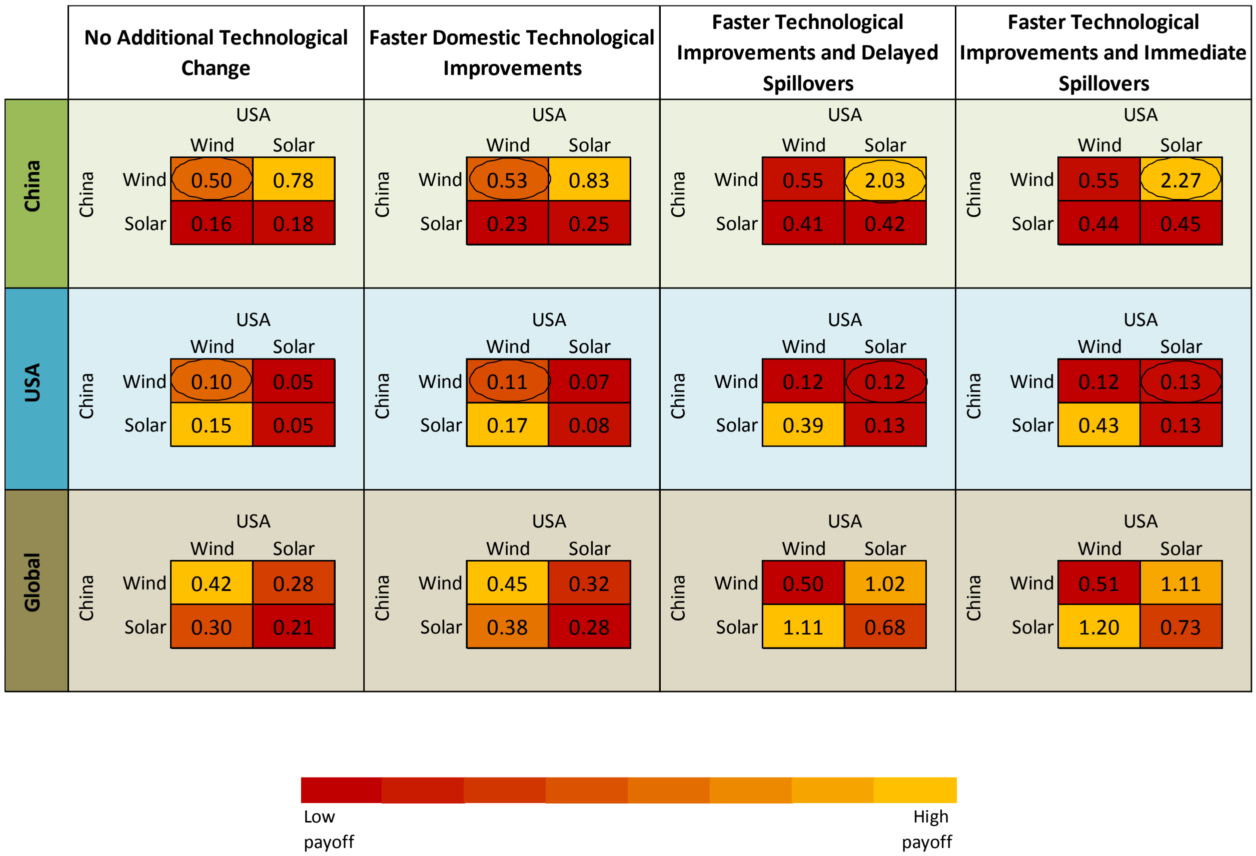

Figure D-1 Domestic and global payoffs from reduced long-term abatement costs (reductions in long-term abatement costs relative to the case without near-term deployment policies divided by near-term costs of deployment policies) assuming that reference solar technologies improve four times as fast as reference wind technologies and advanced wind and solar technologies improve twice as fast as reference wind and solar technologies respectively (see Table 3-3 for detailed assumptions). The circled payoffs show the Nash equilibrium under a technological change scenario.

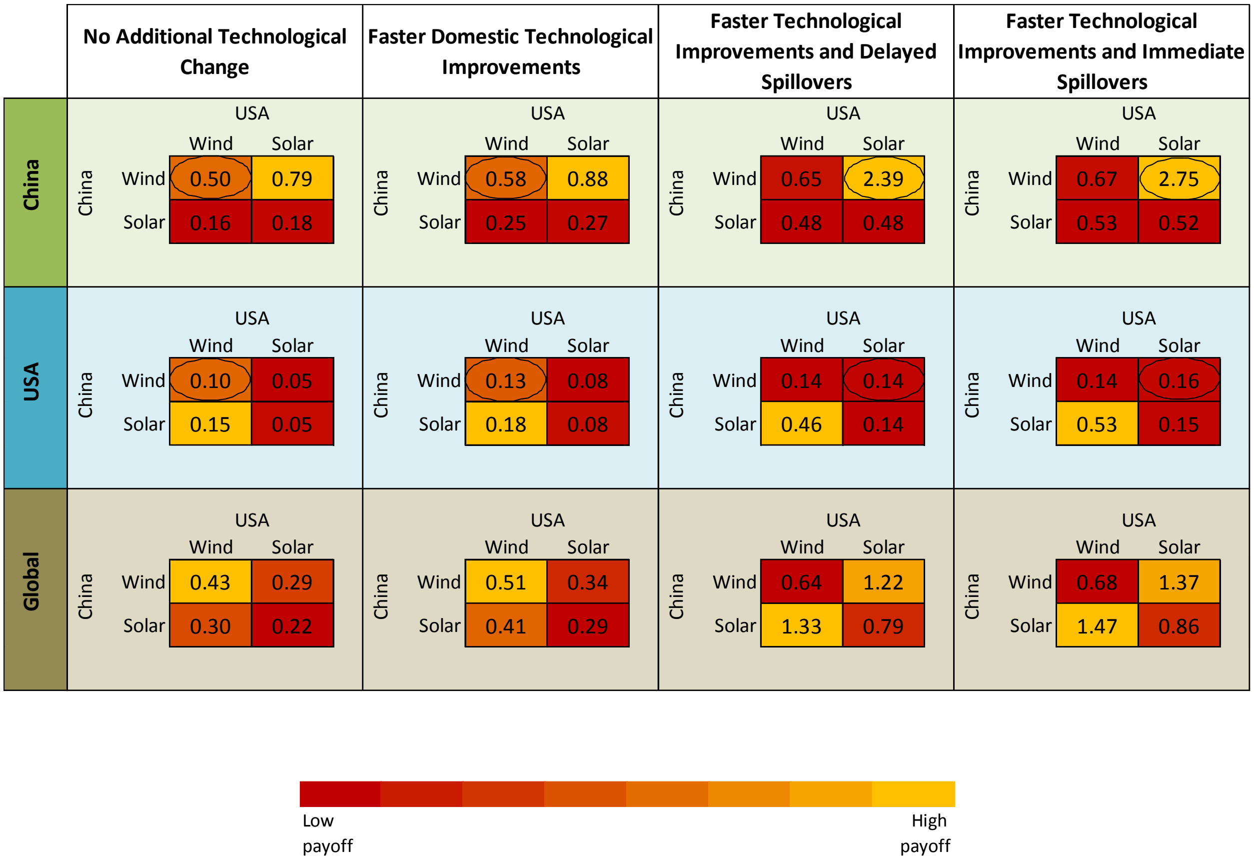

Figure D-2 Domestic and global payoffs from reduced long-term abatement costs (reductions in long-term abatement costs relative to the case without near-term deployment policies divided by near-term costs of deployment policies) assuming that reference solar technologies improve twice as fast as reference wind technologies and advanced wind and solar technologies improve four times as fast as reference wind and solar technologies respectively (see Table 3-3 for detailed assumptions). The circled payoffs show the Nash equilibrium under a technological change scenario.

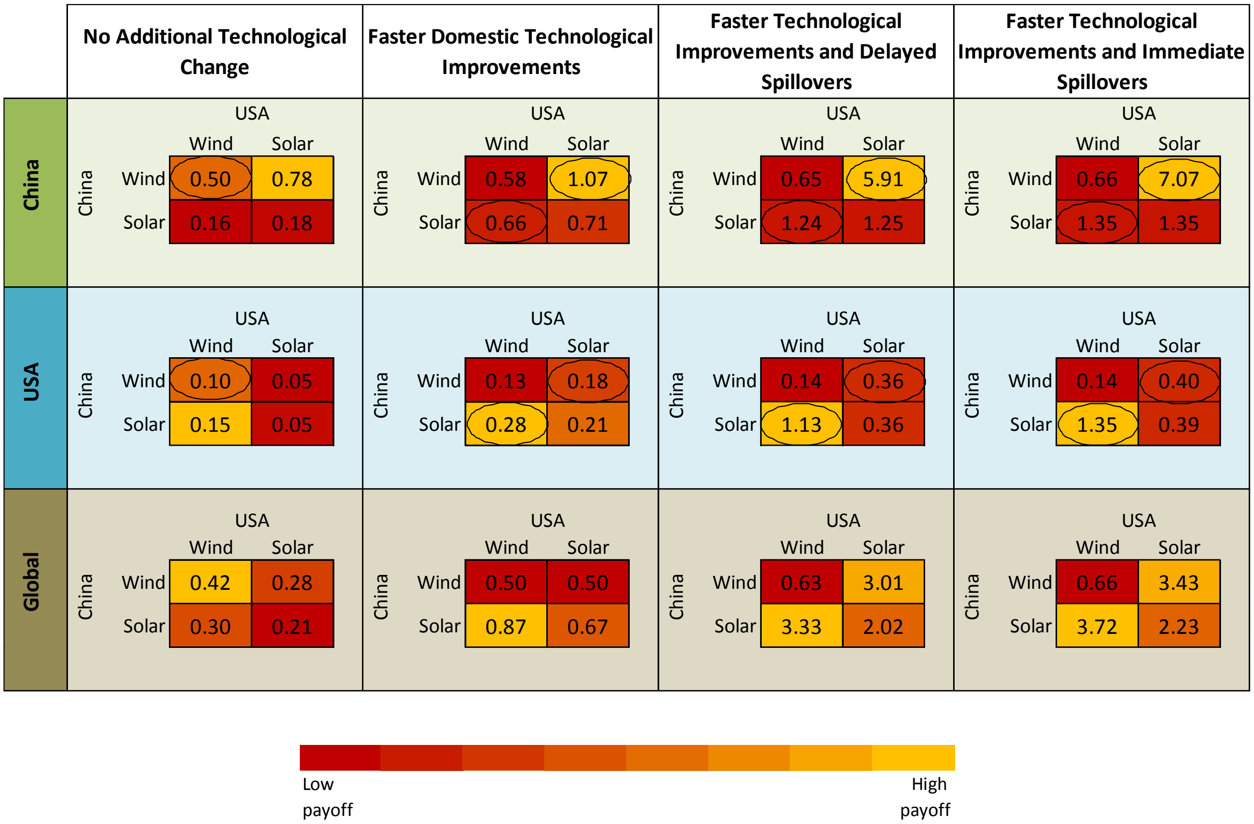

Figure D-3 Domestic and global payoffs from reduced long-term abatement costs (reductions in long-term abatement costs relative to the case without near-term deployment policies divided by near-term costs of deployment policies) assuming that reference solar technologies improve four times as fast as reference wind technologies and advanced wind and solar technologies improve four times as fast as reference wind and solar technologies respectively (see Table 3-3 for detailed assumptions). The circled payoffs show the Nash equilibrium under a technological change scenario.

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