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

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ABSTRACT

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

1. Introduction

Stabilizing the global climate will require substantial reductions in greenhouse gas (GHG) emissions, especially CO_2, in all sectors of the global economy [1]. This will in turn require fundamental changes in the way the world produces and uses energy. In particular this implies 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 [2,3]. Policy interventions are intended to affect not only the portfolio of new technologies that are deployed but also how rapidly and deeply they diffuse [4,5]. However, the deployment of low-carbon technologies is influenced, sometimes strongly, by other factors, including institutional, behavioral, and social factors, which can distort deployment trajectories, even in the presence of ostensibly favorable climate change policies [6]. In addition to such factors, the deployment of low-carbon technologies is also likely to be hampered by the uncertainty in international policy response to climate change which imposes new constraints on the diffusion of low-carbon technologies.

Previous studies employing integrated assessment models (IAMs) to explore the role of low-carbon technologies have made simple assumptions regarding the availability of specific technologies. For example, some studies have prohibited the construction of new capacity for some technologies, such as renewables and nuclear, while others have completely excluded technologies (e.g., CCS) or capped their maximum deployment (e.g., bioenergy) [7–10]. This paper contributes to the existing literature on limited technology availability by assessing the implications of expansion constraints that attempt to capture the drivers on the rate of technology upscaling that are not well represented in IAMs. We also add a temporal dimension to the study by investigating the implications of constrained

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expansion when there are major delays in globally coordinated mitigation efforts to address climate change. Specifically, we seek to answer the following questions: i.) How much do constraints on the diffusion of low-carbon technologies impact the cost and feasibility of achieving long-term climate targets? And ii.) How do these impacts change in the presence of major delays in global mitigation action? The remainder of the paper proceeds as follows. Section 2 provides a review of the factors that constrain the diffusion of low-carbon technologies. In Section 3, we review the historical diffusion rates of technologies in order to provide a background on the notion of "slow" and "fast" diffusion. In Section 4, we provide a description of the method and the scenario setting used in this study. Section 5 presents the results and findings of this study and Section 6 concludes with a summary of the findings and scope for future work.

2. Factors constraining the deployment of low-carbon technologies

Several studies in the past have used IAMs to analyze the importance of low-carbon technology options in achieving stringent climate stabilization goals [7–9,11,12]. An important common finding of these studies is that accelerated technology development offers the potential to reduce mitigation costs substantially. Although the modeling approaches and objective functions of the models used in these studies vary, they all assume that the final portfolio of technologies is dependent on relative prices. A direct inference of this assumption is therefore, that externality pricing and other pricing policies aimed at incentivizing the adoption of low-carbon technologies would induce profit-oriented firms to use low-carbon technologies and thus accelerate their diffusion. However, previous work has shown that while relative prices between energy technologies (and therefore, pricing policies) are influential in fostering a lower-carbon economy, they alone cannot fully account for the observed diffusion of technologies and that several other factors including institutional, behavioral, and social factors limit their actual adoption [5,6,13–16]. In the context of low-carbon technologies, the factors that tend to influence diffusion rates of new technologies can be grouped under two categories. In the first category are factors that influence the growth of low-carbon technologies even in the presence of favorable climate change policy environments (such as a price on carbon or a cap-and-trade mechanism). Examples include increasing returns for incumbent technologies, slow response of capital markets to the needs of new technologies, lack of adequate institutional and governance structures and public perceptions and oppositions. The second set of factors is associated with the uncertainty involved in climate change policy. An example is the rational behavior of investors under such uncertainty.

2.1. Factors in the presence of favorable climate change policies

Several characteristics of the industry including the market structure and flow of information within the industry may constrain the diffusion of new technologies even in the presence of favorable climate policies. The value of a new technology to one user may depend on how many other users have adopted the technology. In general, new adopters will be better off the more other people use the same technology. This benefit associated with the overall scale of technology adoption is referred to as dynamic increasing returns [5]. A new technology has to compete with existing substitutes that have already been able to undergo a process of increasing returns [17]. 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 [5]. An important contributing factor to dynamic increasing returns is the existence of what is called "network externalities" [5]. Network externalities exist when the utility derived from a technology depends on the number of other users of the same or a compatible technology [18]. 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 [13,19,20]. Firms may therefore decide to delay adoption of a new technology until they have information about the experiences of other firms [21]. Jacobsson and Johnson [20] 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 [22,23]. 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 [24]. 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 [17,23].

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 [20]. Therefore, financial support, even on the long term may be required to ensure deployment of such technologies [25,26]. 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 [24]. 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 [27]. In addition, the venture capital market, which sometimes serves as an important source of capital for

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