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Capital investment requirements for greenhouse gas emissions mitigation in power generation on near term to century time scales and global to regional spatial scales

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ABSTRACT

Our paper explores the implication of climate mitigation policy and electricity generation technology performance for capital investment demands by the electric power sector on near term to century time scales. We find that stabilizing GHG emissions will require additional investment in the electricity generation sector over and above investments that would be needed in the absence of climate policy, in the range of 15 to 29 trillion US$ (48–94%) depending on the stringency of climate policy during the period 2015 to 2095 under default technology assumptions. This increase reflects the higher capital intensity of power systems that control emissions as well as increased electrification of the global economy. Limits on the penetration of nuclear and carbon capture and storage technology could increase costs substantially. Energy efficiency improvements can reduce the investment requirement by 18 to 24 trillion US$ (compared to default technology climate policy assumptions), depending on climate policy scenario. We also highlight the implications of different technology evolution scenarios for different regions. Under default technology set, the heaviest investments across scenarios in power generation were observed in China, India, SE Asia and Africa regions with the latter three regions dominating in the second half of the 21st century.

1. Introduction

Decarbonization of electricity production and electrification of end-use sectors have been identified as an important component of a cost-effective greenhouse gas (GHG) emission mitigation strategy on both global (Ang et al., 2011; Edmonds et al., 2007; IEA, 2012; IPCC, 2007) and regional scales (Carley, 2011; Chen et al., 2011; Lanz & Rausch, 2011; Odenberegr et al., 2009; Pappas et al.,2012; Shukla & Chaturvedi, 2012; William et al., 2012).

In the absence of climate policy, electricity production would be expected to remain dominated by fossil fuels in most of the regions of the world (Ang et al., 2011; Edmonds et al., 2007; IEA, 2012; IPCC, 2007). For example, the rapidly growing economies of China and India have energy systems that are dominated by abundant and inexpensive coal. A climate policy on the other hand could fundamentally change the electricity production system around the world.[1]

Deploying an energy system consistent with deep emission reductions raises several important implementation questions, not the least of which is: How much investment do we need in electricity production system? This question forms the central motivation for this paper.

Very few studies have analyzed capital investment requirements for electricity generation under alternative combinations of technology availability and climate mitigation policies (GEA, 2012; Doi et al., 2011; WB, 2010; WEO, 2009, 2010; UNESCAP, 2008; Frankfurt School-UNEP, 2012; UNFCCC, 2007; IEA, 2003; McCollum et al., 2013; Carraro et al., 2012). Most of these studies focus on the near term. Appendix 1 presents a summary of some recent studies, most of which have focused on a time horizon of 2030 or closer.

In general the studies in Appendix 1 report an increase in the investment requirement for electricity generation sector for meeting emission mitigation objectives. However, there are two important gaps in the existing literature. First, the suite of scenarios examined is very limited in its scope. Many studies report one reference and one mitigation scenario across studies. There can be numerous future scenario pathways depending on different combinations of technology and climate policy choices having varied implications for different regions and technologies. Second, the time horizon is generally limited to 2030–35 (the exceptions are (GEA, 2012; McCollum et al., 2013; Carraro et al., 2012)), so there is little information available about medium term (to 2050)

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[1] It is interesting to note that model intercomparison exercises examining the long-term behavior of energy systems in the context of policies to limit climate change have shown that some models converge towards a common energy system across regions while others retain strong differences across regions over time (Clarke et al., 2012), which will be reflected in electricity supply technology mix across regions.

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and no information about investment requirements in the second half of the 21st century.

A recent study by McCollum et al. (2013) analyzes the investment requirement up to 2050 for the whole energy system transformation required for meeting a 2 °C climate change target. This study reports investment results derived from model comparison exercise LIMITS for overall energy system, but also gives some information for electricity sector investments. In the overall, this study also reports an increase in required investment for total energy system as well as electricity sector for meeting emission mitigation objective. Renewable electricity sector would potentially require the largest increase in investments compared to reference scenario, 150 Bn US$/yr for industrialized countries and 400 Bn US$/yr for developing countries average during 2010–50. Investment in nuclear energy varies across models due to varying underlying assumptions about the penetration of this technology, reflecting the widely varying risk concerns across the world. The strength of this study lies in the comparison across models that have different analytical frameworks and hence arrive at different results and insights. Interestingly, one model—IMAGE, does not show any perceptible increase in supply side investment requirement under a stringent climate policy compared to the reference scenario. This study does not explore the implications of alternative technology evolution pathways on future investment requirement, which is an important contribution of our study.

Another study that needs to be mentioned is Carraro et al. (2012), which analyzes a reference and a suite of four climate policy scenarios. The policy scenarios aim at four GHG concentration stabilization levels at 680, 560, 500 and 460 ppmv CO_2-eq level in 2100. This research looks not only at power sector investment, but also total macroeconomic costs, investments in innovation, and revenues from carbon tax. This study shows that power sector investments under the 680 and 560 ppmv CO_2-eq scenarios decrease by approximately 5% between 2010 and 2050 relative to reference scenario. However, an increase of 3% and 10% respectively is observed under the 500 and 460 ppmv CO_2-eq scenarios respectively. Energy efficiency improvements in the power sector, particularly in non-OECD countries, play an important role in reducing investment requirement under the less stringent climate policy scenarios. Interestingly, even though power sector investment requirement decreases under the 680 and 560 ppmv CO_2-eq scenarios, the total macroeconomic costs are non-negative. This study is particularly valuable as it explores investment implications for a range of climate policy scenarios, something which the other literature largely lacks. As it is unclear as of now that which emission trajectory will the world move towards, the study gives a useful comparison of investments and costs across these different pathways. However, this study also does not explore implications of various technological pathways and scenarios in investment requirements, which is the research gap that we seek to contribute to.

The present study aims to fill these research gaps. Specifically we seek to examine the following questions:

1. Is additional capital investment required for electricity generation for meeting emission mitigation policy objectives?
2. What is the magnitude of additional investment requirement, if any, in the short, medium and long run under different technology and policy scenarios?
3. What are the reasons for increased or decreased capital investments?
4. What are the investment implications for different regions?, and
5. What are the investment implications of technology availability?

Our study highlights not just the total change in capital investments, but equally importantly, where those investments occur and which technologies receive them. The next section presents our method, scenario descriptions, and cost assumptions. Section 3 focuses on results and answers the five research questions outlined above. Finally, the conclusions of our research are presented in Section 4.

It should be noted that our results do not include investments in transmission and distribution, and focus only on investments in generation. The strength of our integrated assessment modeling framework is capturing the complex interactions between technology and climate policy scenarios for bringing out the investment implications. Our model includes a factor for T & D losses, but not these costs as these costs do not critically affect technology choice and competition. Capital cost, operation costs, and endogenously determined fuel costs are included in the cost of competing electricity generation technologies. We have hence kept T & D costs out of the scope of our analysis and focused on direct capital investments that are included in our analytical framework.

2. Approach

2.1. Modeling framework

We use Global Change Assessment Model (GCAM), a model of human and bio-geophysical Earth systems,[2] for understanding the evolution of electricity production system under various scenarios. GCAM is an integrated assessment model with closely coupled energy, economic and land-use component. GCAM tracks the production, transformation and consumption of fossil fuels, renewables, and nuclear energy to meet the energy-service demands for three final-demand sectors—buildings, industry and transport, and operates from 2005 to 2095 in five year time steps. In GCAM, the world is divided into 14 geopolitical regions. Energy consumption and emissions of 16 greenhouse gases including carbon dioxide are tracked for these 14 regions. GCAM has been extensively used for global and regional energy and climate policy scenario analysis (Calvin et al., 2009; Wise et al., 2009, 2010; Edmonds et al., 2012; Kyle & Kim, 2011; Eom et al., 2012; Chaturvedi et al., 2014; Calvin et al., 2014; Clarke et al., 2007; Thomson et al., 2011; Clarke et al., 2008; Chaturvedi et al., in press).

As our paper focuses on investment for electricity generation, it should be noted here that final energy demand for various sectors is sensitive to energy prices. Energy prices are endogenous to the model. Further details about end use energy demand for different sectors in GCAM can be found in (Kyle & Kim, 2011; Eom et al., 2012; Chaturvedi et al., 2014; Clarke et al., 2008).

2.2. Scenario description

We analyze and compare a total of 20 scenarios which are combinations of different technology availability and performance assumptions in conjunction with two alternative degrees of climate policy stringency (Table 1).[3] We explore the implications of technology variations across policy scenarios. The reference scenario is a No Policy scenario with default technology assumptions. As the future world can evolve in different ways which will have different investment implications, our technology variation scenarios explore this inherent uncertainty in future investment requirements. The same is true for the climate policy scenarios. The 20 scenarios test the sensitivity of our reference, no explicit greenhouse gas emission mitigation policy scenario. That reference scenario is described in Calvin et al. (2014), which in turn is similar in nature to the reference scenario for Representative Concentration Pathway 4.5 (Thomson et al., 2011).

We present results for 8 technology scenarios under No Climate Policy, 7 under a radiative forcing limit of 3.7 W/m^2 without overshoot, and 5 under a radiative forcing limit of 2.6 W/m^2 in the year 2095 with overshoot[4] allowed (radiative forcing of 3.7 W/m^2 corresponds to a 550 ppm CO_2-equivalent concentration and 2.6 W/m^2 corresponds to a 450 ppm CO_2-equivalent concentration).

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[2] Refer to http://wiki.umd.edu/gcam/index.php?title=Main_Page for detailed GCAM documentation.

[3] The scenario architecture is based on the Energy Modeling Forum 27 (EMF27) study protocol (refer to Kriegler et al. (2014)).

[4] An overshoot scenario is one in which the eventual limit is exceeded for some period prior to the evaluation period. For example, in an overshoot scenario a target of 2.6 W/m^{-2} in the year 2095 might be exceeded in periods prior to 2100 as long as the radiative forcing was returned to 2.6 W/m^{-2} in the target year, 2095.