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Improved representation of investment decisions in assessments of CO_2 mitigation

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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[1–5]. We investigate one such factor—how national institutions affect investment risks and thus the cost of financing[6–8]. We use an integrated assessment model (IAM; ref. 9) to represent 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[10]—and compute 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. Here, we introduce a new front in the research on how real-world factors influence climate mitigation. We also suggest that institutional reforms aimed at lowering investment risks could be an important element of cost-effective climate mitigation strategies.

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[6,11]. Such heterogeneity in investment risks can have important implications, as investors usually respond to risks by requiring higher returns for riskier projects; delaying or forgoing the investments; or preferring to invest in existing, familiar technologies[8]. In this paper, we use an IAM (refs 9,12) and incorporate decisions on investments based on risks along two dimensions (Table 1). Along the first dimension, we vary perceived risks associated with particular technologies. To do so, we assign a higher cost of capital for investment in low-carbon technologies as these involve intrinsically higher levels of regulatory and market risk (Supplementary Text, Section 1.1). The second dimension uses a proxy to vary investment risks across regions, based on an institutional quality metric published by the World Economic Forum (Fig. 1)[11]. In addition to these two dimensions of variation in investment risks, we 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 (Supplementary Fig. 1)[13]. We restrict the analysis to investments in the electricity generation sector, which are expected

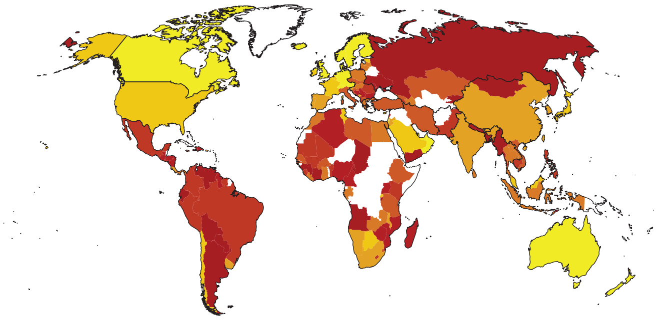

Figure 1 | Quality of national institutions based on the World Economic Forum's Global Competitiveness Index data set[11]. Assuming that non-uniformities in investment risks arise due to differences in institutional qualities, we use these data to represent costs of capital for investing in the electricity generation sector as a function of the quality of a country's institutions. This reflects behaviour of investors in the real world, where investors demand risk-adjusted rates of return that are higher in regions with inferior institutions.

to account for a significant share of future investments in the context of climate change mitigation[2,10].

This paper contributes to the growing literature on climate policy analysis under imperfect circumstances. Our central contribution is to demonstrate how disparities 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 in the electricity sector. We build on earlier studies such as those that have focused on imperfections in labour and technology markets as well as research that has explored the impact of delayed accessions in international climate policy regimes[14–18].

In the baseline (no climate policy) scenario with uniform investment risks, investments in the electricity sector occur in fossil fuel as well as low-carbon technologies (Fig. 2a). Note that sums of investments in low-carbon technologies are comparable to those in fossil-fuel technologies, although their share in total generation is much lower because the former are both intermittent and more capital intensive; consequently, more upfront capital

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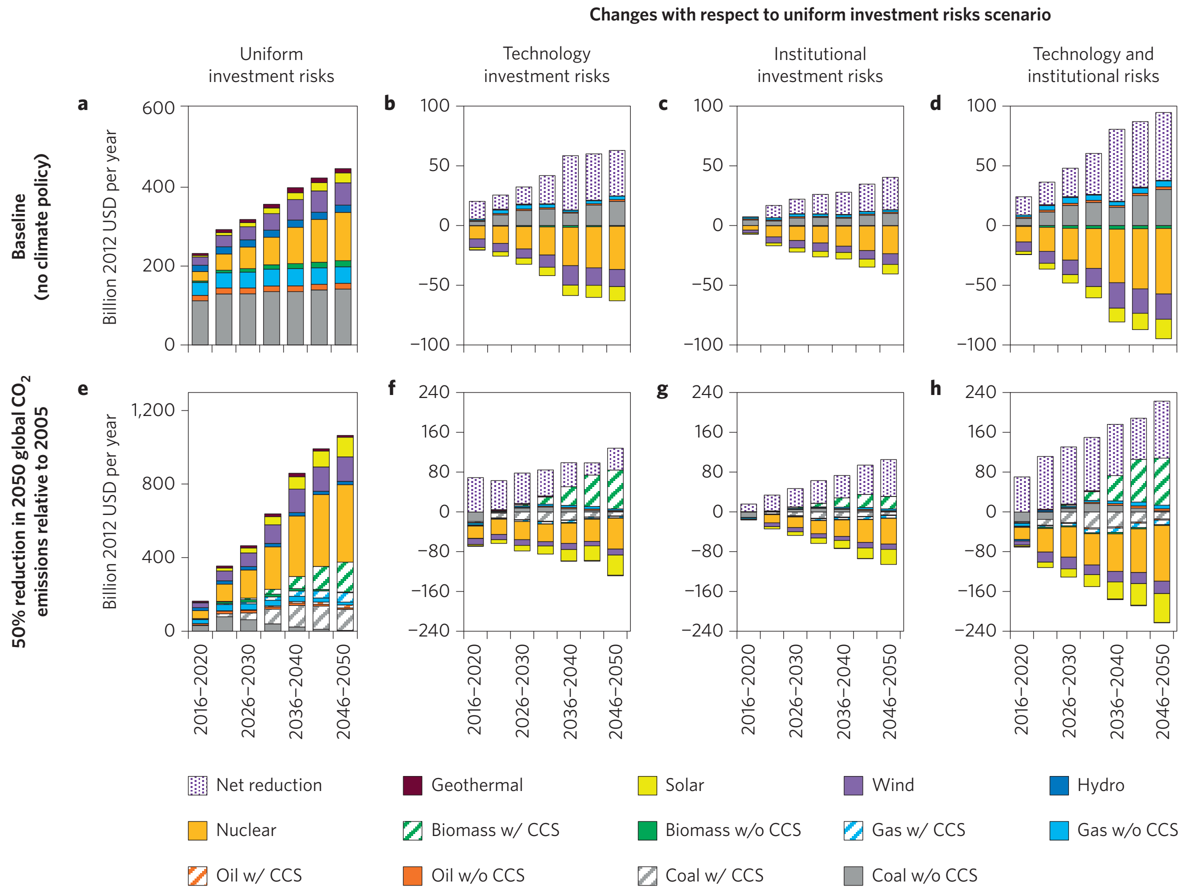

Figure 2 | Average annual investments in electricity generation in the baseline and the 50% global emissions target under the different investment risk scenarios (billion 2012 USD per year). **a**,**e**, Uniform investment risks. **b**–**d**, Changes with respect to uniform investment risks scenario assuming baseline (no climate policy). **f**–**h**, Changes with respect to uniform investment risks scenario assuming 50% reduction in 2050 global CO_2 emissions relative to 2005. **b**,**f**, Technology investment risks. **c**,**g**, Institutional investment risks. **d**,**h**, Technology and institutional risks. See Supplementary Table 3 for a comparison of above investment numbers with a previous study. Investment numbers presented here and in other figures 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 us analyse the effects of non-uniformities in investment risks keeping other variables fixed.

is required per joule of electricity generated from low-carbon technologies. When we introduce non-uniformities in investment risks across technologies, investments in low-carbon technologies decline (Fig. 2b). 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 Methods), raising electricity prices. This reduces demand for electricity, reducing total investment in the electricity sector.

When we introduce non-uniformities in institutional qualities, the result is a decline in investment in low-carbon technologies in regions with inferior institutions—places where investing is more risky. On the other hand, in regions with superior institutions (where investing is less risky), investments increase (Supplementary Fig. 2). 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, which are marked by relatively low institutional qualities (Fig. 2c). The combined effect of non-uniform investment risks across technologies and regions is a 36% reduction globally in investments in low-carbon technologies and a 11% increase in investments in fossil-fuel technologies, leading to a net reduction of 10% (Fig. 2d). The immediate consequence of such a shift in investment pattern is an increase in global baseline emissions (Supplementary Fig. 3).

Our modelling approach achieves the 50% global emissions target through a global price on carbon. In the presence of a high enough carbon price, the modelled energy system undergoes a marked transformation, resulting in a realignment of investment patterns in the electricity generation sector (Fig. 2e). Low-carbon

Table 1 | Investment risk scenarios explored in this study.

Technology investment risks: High risk technologies ↓	Institutional investment risks: No variation across regions	Institutional investment risks: 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

The investment risk scenarios explored in this paper vary along two dimensions. Along the first, investment risks vary across technologies and along the second, investment risks vary across regions. To vary investment risks across technologies, we classify technologies into low risk and high risk with fixed charge rates of 13% and 17% respectively. See Methods and Supplementary Tables 1 and 2 for details.

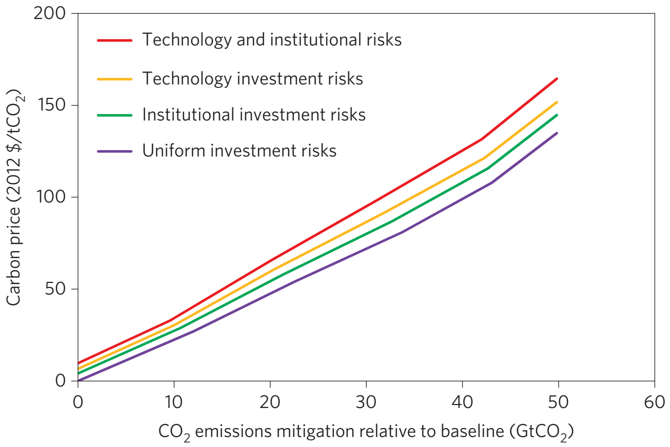

Figure 3 | Global marginal abatement cost curves. 2050 global marginal abatement cost (MAC) curves to achieve the 50% global emissions target under the different investment risk scenarios.

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[19].

When we introduce non-uniformities in investment risks across technologies, carbon prices required to meet the emissions target increase (Fig. 3 and Supplementary Fig. 4), significantly altering investment patterns (Fig. 2f). Compared with the case with uniform investment risks, investments in bio-CCS (biomass with CO_2 capture and storage) increase, even though such investments are more risky. 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, in spite of their higher generation costs, such technologies get deployed (again because of the technology choice specification discussed in the Methods), raising electricity prices and reducing demand for electricity by end-use sectors (Supplementary Fig. 7). 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 investments in the power sector globally.

The effect of non-uniformities across regions in the climate policy scenario 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 (Fig. 2g). 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 (Fig. 4a). For example, whereas investments in the US and Japan (higher institutional qualities) increase by 4% and 10% respectively, those in China and India (lower institutional qualities) decrease by 21% and 24% respectively. For regions such as Latin America and former Soviet Union (lower institutional qualities), investments decline by as much as 40% and 60% respectively (Supplementary Fig. 8). As emissions mitigation is proportional to investment (Supplementary Fig. 9), regions with superior institutions mitigate more and regions with inferior institutions mitigate less compared with the uniform investment risks scenario (Fig. 4b and Supplementary Fig. 10).

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; Supplementary Fig. 5). 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[16]) are higher for regions with superior institutions (Fig. 4c and Supplementary Fig. 11). 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 (Fig. 3), most of the increase is borne by regions with superior institutions (see Supplementary Text, Section 4 for a detailed sensitivity analysis on key assumptions in this analysis).

We assume higher investment risks in countries with inferior institutions; however, exceptions exist. A particularly important exception is China. Investment risks in the electricity sector in China are lower than in other emerging economies—such as India—owing to favourable policies and state-backed financial institutions (Supplementary Text, Section 1.2). Furthermore, China accounts for almost a third of global investments in the electricity sector (Supplementary Fig. 8). We therefore consider a sensitivity case in which investment risks in the power sector are low only in China. In this scenario, mitigation costs for China are higher in spite of investments being low risk (Supplementary Fig. 13). This is again because of the public goods effects of technologies explained earlier—marginal abatement costs in China decrease because of lower investment risks. 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 we 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 so long as 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[20].

The findings of our study suggest several new directions for policy and analytical research. Our results underscore the potentially large and negative implications of the practical difficulties in financing for alternative or new low-carbon technologies, and the concomitant importance of addressing those obstacles through a suite of policies and private sector initiatives. For policy makers, this suggests 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 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, absent such reforms, mitigation effort could be disproportionately focused on countries where investment risks are lower.

For analysts, our study introduces a methodology that illustrates how real-world investment risks can be incorporated in models of emissions mitigation. This research, along with other studies that seek to better represent real-world factors in mitigation strategies,

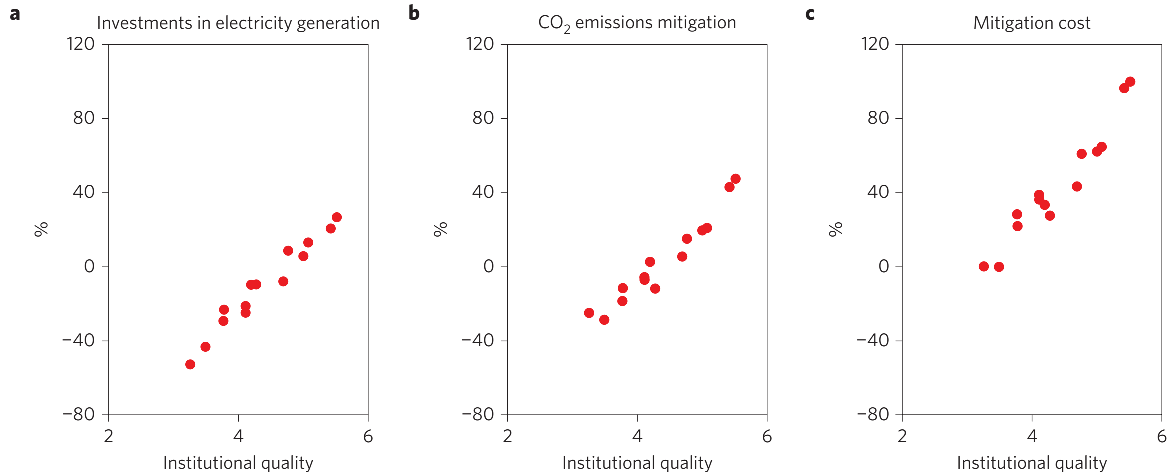

Figure 4 | Changes with respect to the uniform investment risks scenario. a, Change in investments in electricity generation. **b**, Change in CO_2 emissions mitigation. **c**, Change in mitigation costs when investment risks vary across technologies and regions. Investments are calculated as cumulative investments between 2020 and 2050. CO_2 emissions mitigation is calculated as cumulative mitigation in CO_2 emissions from fossil fuels and industry relative to the baseline between 2020 and 2050. Mitigation costs are calculated as cumulative net present values between 2020 and 2050. The cases presented here correspond to the 50% global emissions target.

suggests that such factors are important for assessing the costs and distribution of emissions mitigation patterns[15]. Although our particular example highlights the negative implications of differential financing costs, it is conceivable that other factors might have different or even counteracting effects that influence the rate and patterns of mitigation. The challenges of incorporating real-world factors in models are substantial—nevertheless, such improvements provide better understanding of the scope for mitigation and the comparability of effort in a world of technological, institutional and financial heterogeneity.

Methods

This analysis uses the Global Change Assessment Model (GCAM). Outcomes of GCAM are driven by assumptions about population growth, labour participation rates and labour productivity in fourteen geo-political regions, along with representations of resources and technologies[9,12]. Investment in GCAM depends on relative costs and the distribution among technologies determined 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[21–23] (Supplementary Text, Section 3).

Among different variables affected by differences in investment risks, we focus on the cost of capital for investment. Risk-averse investors expect risk-adjusted rates of return, raising the cost of capital for investing in projects involving greater risk. In theory, 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 (Supplementary Text, Section 1.1). In GCAM, the cost of capital is represented in the fixed charge rate (FCR), which is the amount of revenue per dollar of capital investment that must be collected annually by an investor against carrying charges on that investment[24]. In this analysis, we vary FCRs across technologies and regions. Whereas 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. As a point of departure, we also consider a counterfactual uniform investment risk scenario.

To represent variation of investment risks across technologies, we compile FCR values used for financial analyses of electricity generation technologies in the United States (Supplementary Table 1). We 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, we 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. We then look at spreads of macroeconomic costs of debt and equity risk premiums across countries (Supplementary Fig. 14). Next, we 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 Supplementary Fig. 14. Not only does this representation enable us to capture the macroeconomic effects explained earlier, but also reflects behaviour of investors in the real world, where investors demand risk-adjusted rates of return.

We restrict our 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[2]. In addition, biomass-based technologies in sectors other than electricity, for example biofuels and biogas, are included to avoid our 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 our analysis.

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, we consider the equal marginal abatement cost rule 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[25]. 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 programmes, and so on). Second, we 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 owing to economies of scale and network externalities[26]. Finally, we do not consider mitigation from land-use changes so as to retain focus on the effects of non-uniformities in investment risks in the electricity generation sector, keeping other variables fixed[2,19,27].

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References

1. Clarke, L. *et al.* International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Econ.* **31,** S64–S81 (2009).
2. McCollum, D. *et al.* Energy investments under climate policy: A comparison of global models. *Clim. Change Econ.* **4,** 1340010 (2013).
3. Kriegler, E. *et al.* The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change* **123,** 353–367 (2014).
4. Riahi, K. *et al.* Locked into Copenhagen pledges—Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol. Forecast. Soc. Change* **90,** 8–23 (2015).

5. Calvin, K. *et al.* The role of Asia in mitigating climate change: Results from the Asia modeling exercise. *Energy Econ.* **34,** S251–S260 (2012).
6. North, D. C. *Institutions, Institutional Change and Economic Performance* (Cambridge Univ. Press, 1990).
7. Faria, A. & Mauro, P. Institutions and the external capital structure of countries. *J. Int. Money Finance* **28,** 367–391 (2009).
8. Acemoglu, D. & Zilibotti, F. Was Prometheus unbound by chance? Risk, diversification, and growth. *J. Polit. Econ.* **105,** 709–751 (1997).
9. Kim, S., Edmonds, J., Lurz, J., Smith, S. & Wise, M. The ObjECTS framework for integrated assessment: Hybrid modeling of transporation. *Energy J.* **27,** 63–91 (2006).
10. Clarke, L. *et al.* in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) Ch. 6 (IPCC, Cambridge Univ. Press, 2014).
11. Schwab, K. *Global Competitiveness Report* (World Economic Forum, 2013).
12. GCAM-wiki; http://wiki.umd.edu/gcam/index.php?title=Main_Page
13. IPCC *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) (2014).
14. Tavoni, M., De Cian, E., Luderer, G., Steckel, J. C. & Waisman, H. The value of technology and of its evolution towards a low carbon economy. *Climatic Change* **114,** 39–57 (2012).
15. Iyer, G. *et al.* Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technol. Forecast. Soc. Change* **90,** 103–118 (2015).
16. Calvin, K. *et al.* The distribution and magnitude of emissions mitigation costs in climate stabilization under less than perfect international cooperation: SGM results. *Energy Econ.* **31,** S187–S197 (2009).
17. Guivarch, C., Crassous, R., Sassi, O. & Hallegatte, S. The costs of climate policies in a second-best world with labour market imperfections. *Clim. Policy* **11,** 768–788 (2011).
18. Jakob, M., Luderer, G., Steckel, J., Tavoni, M. & Monjon, S. Time to act now? Assessing the costs of delaying climate measures and benefits of early action. *Climatic Change* **114,** 79–99 (2012).
19. Chaturvedi, V., Clarke, L., Edmonds, J., Calvin, K. & Kyle, P. Capital investment requirements for greenhouse gas emissions mitigation in power generation on near term to century time scales and global to regional spatial scales. *Energy Econ.* **46,** 267–278 (2014).
20. Clarke, L., Calvin, K., Edmonds, J., Kyle, P. & Wise, M. in *Post-Kyoto International Climate Policy: Implementing Architectures for Agreement* (eds Aldy, J. E. & Stavins, R. N.) Ch. 25 (IPCC, Cambridge Univ. Press, 2010).
21. Clarke, J. F. & Edmonds, J. Modelling energy technologies in a competitive market. **15,** 123–129 (1993).
22. McFadden, D. Econometric models for probabilistic choice among products. *J. Bus.* **53,** S13–S29 (1980).
23. Train, K. *Qualitative Choice Analysis: Theory, Econometrics, and an Application to Automobile Demand* (MIT Press, 1993).
24. Short, W., Packey, D. J. & Holt, T. *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies* (National Renewable Energy Laboratory, 1995).
25. Den Elzen, M. G. J., Höhne, N., Hagemann, M. M., van Vliet, J. & van Vuuren, D. P. Sharing developed countries' post-2012 greenhouse gas emission reductions based on comparable efforts. *Mitig. Adapt. Strateg. Glob. Change* **15,** 433–465 (2010).
26. North, D. C. in *Handbook of New Institutional Economics* (eds Ménard, C. & Shirley, M. M.) 21–30 (Springer, 2008).
27. Carraro, C., Favero, A. & Massetti, E. Investments and public finance in a green, low carbon, economy. *Energy Econ.* **34,** S15–S28 (2012).

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Author contributions

All authors jointly designed the experiments and analysed the results. G.C.I. conducted the experiments and wrote the first draft of the paper. All authors contributed to writing the paper.

Additional information

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Competing financial interests

The authors declare no competing financial interests.