Economic benefits of decarbonising the global electricity sector

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Conventional economic analyses of stringent climate change mitigation have generally concluded that economic austerity would result from carbon austerity. These analyses however rely critically on the assumption of an economic equilibrium, which dismisses established notions on behavioural heterogeneity, path dependence and technology transitions. Here we show that on the contrary, the decarbonisation of the electricity sector globally can lead to improvements in economic performance. By modelling the process of innovation-diffusion and non-equilibrium dynamics, we establish how climate policy instruments for emissions reductions alter economic activity through energy prices, government spending, enhanced investment and tax revenues. While higher electricity prices reduce income and output, this is over-compensated by enhanced employment generated by investments in new technology. We stress that the current dialogue on the impacts of climate policies must be revisited to reflect the real complex dynamics involved in the global economy, not captured by conventional models.

INTRODUCTION

The common perception of climate change mitigation in the economic perspective is one of necessary future austerity. The costs of mitigation action, involving higher levels of investment in technology in comparison to no-climate policy baseline scenarios, are generally interpreted to imply significant future reductions in economic activity. While Stern has shown that the macroeconomic costs of adaptation are likely much higher than those of mitigation, this analysis still presupposes, by construction, that emissions reductions necessitate significant but necessary sacrifices to the global economy now in order to avoid dangerous levels of climate change in the future. This view contributes in strengthening the contemporary impression that a world in recession cannot afford climate policy.

The context of this perception is in large parts one of equilibrium economics where the Business As Usual (BAU) use of economic resources (labour and capital) is assumed optimal, and therefore diverting resources for emissions reductions leads to lower economic performance, when measured using the Gross Domestic Product (GDP, see Methods). Macroeconomic impacts being assumed negative by construction, little is actually known on the economic impacts of mitigation if the equilibrium assumption is challenged. Meanwhile, bottom-up energy technology models generally use cost-optimisation algorithms (the ‘social planner’ assumption) featuring no representation of heterogeneous investor decision-making driven technology diffusion dynamics. Equilibrium economic models widely used in climate change research typically treat technology Research and Development (R&D) as an external parameter. However, it is well established that R&D led technological change accounts for the larger part of economic growth, the dominant driver involving the ‘creative destruction’ of old socio-technical regimes with the diffusion of new innovations. The lack of dynamic representation of technological change and its economic impact in climate change mitigation economic analyses is clearly misleading since important transitions of technologies in carbon intensive sectors are necessary to reduce emissions, bound to generate structural changes in the economy, aspects that have not been considered in previous studies.

Here we present simulations of the global economy in a scenario of global electricity sector decarbonisation that challenge the climate austerity view with a counter-example, using a non-equilibrium model of the global economy incorporating technology diffusion in the electricity sector. Two interacting methodologies are used: on the one hand investor level technology selection and diffusion is modelled which enables to simulate the evolution of the electricity sector without any cost-optimisation procedure, incorporating notions of transitions theory, embodied in the model FTT:Power. On the other hand, a highly disaggregated non-equilibrium macroeconomic model is used to simulate the evolution of the global economy and greenhouse gas emissions, E3MG. With a model that (1) does not assume BAU optimal use of economic resources, (2) conserves climate investment flows back in the economy and (3) recycles the income from policy instruments, we trace the propagation of economic costs and benefits of strong climate policy across the economy, and evaluate their climate impacts. With a detailed representation of climate policy instruments and technology uptake, we produce computational evidence that through enhanced investments and tax revenue recycling, 89% emissions reductions in the largest emitting sector, electricity (38% of global emissions), can lead to overall beneficial impacts to the economy while contributing to avoid climate change.
In order to frame the discussion on emissions and climate policy, the approach adopted by the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) is in terms of a product of population, GDP per capita and the carbon intensity of GDP (the Kaya identity). This description, while true by construction, suggests that (1) emissions and energy use scale proportionally with, and are single valued functions of economic activity, and that (2) the carbon intensity of GDP is an external decreasing function of time. Following these premises, one could conclude that emissions reductions must be accompanied by economic slowdown, the level of which, in equilibrium systems, is determined by the price of carbon, ideally set equal to a social cost of carbon difficult to determine.

While neoclassical optimal growth Cost-Benefit Analysis Integrated Assessment Models (CBA-IAMs) follow this proposition simply,\textsuperscript{3–5,17} Computable General Equilibrium (CGE) models\textsuperscript{18} improve this paradigm by including different sectors with varying energy and carbon intensities, and allowing factor substitution within each sector depending on prices. The cost of policy-induced substitutions are passed on through higher prices leading to losses of production. In equilibrium systems resources are fully employed, and mitigation thus diverts resources away from other productive sectors (crowding out), detrimental to the economy, and the best outcome for GDP is obtained in the absence of regulation. Emissions reductions are typically achieved through carbon pricing instruments alone, to which firms are able to adjust immediately, and thus the carbon price is considered a single valued function of emissions reductions. Furthermore, assuming constant returns to scale, the accumulation of knowledge does not influence productivity. More recently some equilibrium models were adapted to take account of 'endogenous' changes in technology,\textsuperscript{19} mitigating the calculated impacts of climate policy; however this improvement remains incomplete since their economic output does not fully benefit from this knowledge accumulation.

The most fundamental property established by technological change theory is that of \textit{path dependence},\textsuperscript{9–11,15,20,21} expressed primarily by the ability of the economic system to learn, adapt and diversify, which generates increasing returns through the accumulation of knowledge. This is conceptually at odds with equilibrium theory, where constant returns to scale and efficient markets operated by identical rational representative agents imply a timeless reversible system. Without such assumptions, as in thermodynamics, economics must be treated as a system out of equilibrium, in which the arrow of time takes meaning and the system becomes complex.\textsuperscript{21} A gap appears between the optimal output frontier and actual output, stemming from unused capital and labour resources.\textsuperscript{14} Complex economic dynamics feature even more richness: given that selection, mutation (innovation) and speciation (differentiation) take prominent roles in markets, the system is evolutionary.\textsuperscript{22} Crucially, it has been shown that \textit{technology variety} comes in tandem with \textit{economic development}.\textsuperscript{11,23,24} In particular, since the fitness of technologies to their markets irreversibly improves with innovation, influenced through market selection by a changing environment that includes policy, the dynamics of technological change, upon which climate change mitigation relies, are difficult to treat using equilibrium theory. Climate policy having no historical precedent, the world of technology is on the brink of major irreversible policy driven innovative transformative changes (waves of policy-driven \textit{creative destruction}). Technological change being at the heart of economic growth,\textsuperscript{7} as we show, it is actually possible to generate fast \textit{reductions} in emissions while \textit{increasing} economic output.

Meanwhile, in cost-optimisation models,\textsuperscript{25,26} technology networks operate near a cost-optimum with coordinated fully rational representative agents. As with CGE methodology, this approach encounters computational difficulties if learning curves or increasing returns are introduced since multiple equilibria emerge, hinting to the underlying richness and complexity being oversimplified.\textsuperscript{16,27} These widely used models of technology have recently been shown to feature either parametric or conceptual pessimism concerning rates of technology diffusion in comparison to observed historical trends,\textsuperscript{28} indicating an urgent need for improving current treatments of industrial dynamics. This is progressively overcome using simulation models of decision-making under bounded rationality (as done here), computationally lighter and conceptually richer,\textsuperscript{12,13,29–31} providing a closer relationship with transitions theory. As we show here, the use of combined diffusion dynamics and high sectoral resolution non-equilibrium economic dynamics with specific treatment of economies of specialisation generates economic impacts of climate change policy that contrast with those reviewed by the IPCC, suggesting that a revision of the economic models used could change significantly the current climate policy dialogue.

**AN INNOVATION-DIFFUSION PERSPECTIVE**

Figure 1 lays out the conceptual components of FTT:Power-E3MG translating climate policy into macroeconomic impacts in 21 regions of the world. Technology diffusion corresponds to investor choices filtering available options based on accessible and uncertain information, influenced by policy, generating a form of natural market selection (panel a). Resulting competitive industrial dynamics with technology producers constrained by technology lifetimes and industry growth rates produce technology population dynamics identical in form to those occurring with species in ecosystems
FIG. 1. Map of all economic feedbacks operating during the process of decarbonisation of the power sector in the combination of models FTT:Power (a.), GENIEem-PLASIM-ENTSem (b.) and E3MG (c.). See the Methods section for more details on the models. Red areas indicate processes contributing to economic slowdown, while blue areas indicate positive feedbacks. The green area indicates fuel import/export feedbacks beneficial to some regions while detrimental to others.

competing for resources, including logistic and Lotka-Volterra diffusion patterns and learning-by-doing, a proposition well substantiated by the empirical literature. In contrast to the cost-optimisation approach, this theoretical basis is appropriate to model path-dependent profiles of technological change, their timescales, and well known technology lock-ins at odds with minimisation of cost. In this perspective mitigation action corresponds to channelling investor choices and capital flows towards lower emission technology systems. Resulting emissions changes impact the level of future climate change, represented here using emulators of the carbon cycle, GENIEem, and of the climate system, PLASIM-ENTSem (panel b, for brief model descriptions see the Methods section).

In the economic sphere, (panel c, showing with blue (red) positive (negative) impacts of climate policy onto economic growth), abatement costs can be decomposed into real economic components: changes in the price of electricity and fuels, enhanced investments in technology, additional climate policy-related government spending and income. Here, specific climate policy instruments are simulated: carbon pricing (CO$_2$P), technology subsidies (TSs), feed-in tariffs (FiTs) and direct technology regulations (REGs), influencing investor choices. Using multiple policy instruments in a path-dependent model with slow timescales of industrial adjustment means that the carbon price is not a single valued function of emissions reductions, and thus cannot be equated to the social cost of carbon as in CBA-IAMs.

Their impact goes much further: while CO$_2$P is generally passed on to consumers through a raise of the price of electricity, FiTs generate further price rises that ensure access to the grid for costly electricity generation methods. REGs over what can be built or not alter electricity production costs, also reflected in the price. While many economic sectors can avoid part of these price rises by reducing their consumption, they nevertheless all require electricity, thus these changes propagate throughout the economy, resulting in higher industrial and consumer price levels, and thus inflation. Household real income is reduced followed by consumption which, including a Keynesian multiplier effect, slows the economy and impacts employment, creating a vicious cycle. These effects are temporary, however, since
higher cumulative energy technology investments trigger enhanced energy efficiency (see Methods), and similar levels of industrial and household activity are achieved with lower electricity consumption.

Low-carbon technologies are more investment intensive than traditional (fossil) systems. Propagating throughout industry with a Keynesian multiplier effect, climate policy induced enhanced investment produces increased industrial activity, and in the short term this generates employment and real income that counteracts the impact of higher electricity prices. We show below that in our mitigation scenario, the two effects roughly cancel out. A similar compensating effect occurs in all scenarios where existing labour and capital resources are not exceeded. This also incentivises a virtuous cycle of industrial capacity expansions and R&D investment driven productivity improvements that contribute to economic growth in the long run, the source of endogenous growth in E3MG.

CO$_2$P and TSs are instruments that are used to bridge the difference in costs between inexpensive but polluting technology and new low carbon systems (bridging the technology ‘valley of death’). In scenarios where CO$_2$P and TSs are chosen in such a way, in combination with other policy instruments, that decarbonisation takes place, this can generate significant income (CO$_2$P) or costs (TSs) to governments. We show below that the income is much larger than the costs, and in a scenario where government finances are kept revenue neutral, this means a potentially substantial redistribution of funds to households. This generates additional household spending and thus an increase in GDP.
GLOBAL POWER SECTOR DECARBONISATION

The decarbonisation of the global electricity sector was simulated up to 2050 with FTT:Power-E3MG using various combinations and strengths of the four different types of energy policy instruments. The resulting emissions were fed to GENIEem in order to obtain concentrations and to PLASIM-ENTSem for climate impacts. 10 such scenarios were created, explored in detail elsewhere, with data available online at www.4cmr.group.cam.ac.uk/research/FTT/fttvviewer. We show there that the impacts of coordinated sets of policies do not correspond to the sum of the impacts of individual policies, and thus that strong synergies exist between instruments. A detailed policy scheme for all E3MG-FTT regions is built that decarbonises the global electricity sector by 89% below its 1990 emissions level before 2050, summarised in figure 2. The baseline scenario (panel a) is characterised by a strong fossil technology lock-in, which is difficult to break even with high CO₂P. While CO₂P is not sufficient, it is nevertheless necessary to break the lock-in. The combined use of CO₂P, TSs, FiTs and REGs (Extended data. fig. 1.) leads to the fast investor uptake of low carbon technologies and power sector decarbonisation, characterised by increasing technology diversity and fast phasing out of fossil fuel power technologies as they come to the end of their lifetimes (fig. 2, panel b). As shown in panels c and e, total emissions in the baseline reach 68 GtCO₂ and a concentration of 533 ppm in 2050, very likely to lead to 4°C of global warming or more in 2100 (panel f). Meanwhile, the decarbonisation scenario emissions reductions reach 31 GtCO₂ and a concentration of 485 ppm. We observe that even if the power sector decarbonises by 89%, it is likely not enough to maintain global average temperatures below a median average temperature rise value of 2°C or less if other sectors of anthropogenic emissions do not change significantly their technologies (panels d, e, f). Consistent cross-sectoral climate policies are required in order to curb total emissions below 20 Gt or less in order to maintain temperatures below 2°C beyond 2100. For example, further reductions of 12-15 Gt could be achieved in the transport, household and industrial sectors, likely to bring down concentrations below 450 ppm, generally considered a safe level.

It is to be noted, following the dashed lines of panels b and d referring to the baseline, that a large contribution to emissions reductions stem from reductions of electricity consumption in a context of higher electricity prices. Depending on the nature of the redistribution of government income, this opens a discussion over potentially increasing energy poverty as a result of climate policy: climate change mitigation offers an opportunity and framework of analysis to address the planning of bringing energy access for all in under-developed countries.

ECONOMIC IMPACTS OF CLIMATE POLICY

Figure 3 presents a summary of the economic changes occurring in E3MG following climate policy and decarbonisation, as a result of the sum of the feedbacks of fig. 2. The sectoral transformation leads to enhanced investment in electricity technology (a), TSs to government spending (b) and CO₂P to government income (emissions × CO₂P, c), the latter larger than spending. CO₂P, FiTs and REGs lead to significant increases in electricity prices (d), responsible for the major decrease in electricity consumption of fig. 1. Enhanced investment and the redistribution of government income from CO₂P, after accounting for TSs, lead to additional employment (e) and increases in household real disposable income (f) and consumption (g) albeit higher price levels (h). GDP increases in all world regions as a result of electricity sector decarbonisation (i).

Further computations (Extended data fig. 2) show that a significant part of this positive push on GDP stems from the redistribution of CO₂P income back to households, which is spent again, a form of energy tax recycling. In a non-neutral revenue scenario without recycling, we find that global GDP remains mostly unchanged with mitigation, indicating that the price and investment feedbacks approximately cancel out. This also contrasts with standard equilibrium analyses, and we emphasise that this is due to processes of dynamic structural change arising when there are economies of specialisation: enhanced R&D driven productivity growth spilling across sectors. Thus the further decarbonisation of other sectors of emissions (transport, industry) also appears achievable without significant macroeconomic impacts, so long as labour and finance resources are available.

THE CLIMATE POLICY DIALOGUE

This work establishes clearly that the current perception that equates climate change mitigation with economic austerity requires revisiting. We presented a counterexample where global economic output increases while global emissions decrease. This could contribute the largest component of the effort required to meet a 2°C target. While the Kaya identity is not strictly wrong, it directs the policy dialogue in a misleading direction: emissions do not scale simply with GDP and the carbon intensity of GDP is not a particularly meaningful measure. That emissions can decrease while output increases suggests that the current "cost-benefit framing might actually be asking the
Meanwhile, economic equilibrium theory in its abstraction of detail equates abatement costs with macroeconomic costs by construction, not by conclusion, and thus does not bring any real insight on the economic impacts of climate policy. For this to be overcome, research in economics of climate change mitigation must move on beyond these theoretical paradigms and embrace non-orthodox fields such as behavioural, post-Keynesian, ecological, institutional and evolutionary economics, as well as transitions theory.

Large investment flows in new technology do not vanish from the economy, and thus cannot simply be subtracted from GDP in a macroeconomic framework but must instead be accounted for in the economy, as well as government revenue from climate policy. Costs of mitigation action become reflected in the price of electricity which, along with enhanced investments, disperse throughout the economy raising consumer prices in many sectors. Meanwhile, investments in new low carbon technology is redistributed to many sectors of the economy and generates higher levels of employment and income, in the short term, and enhanced long run economic growth providing a counteracting force. This indicates that high sectoral resolution and a treatment of the cumulative causation of knowledge accumulation in economic modelling is essential in order to address meaningfully the macroeconomic impacts of reducing emissions. With the addition of government revenue recycling, our research indicates that the balance of these forces tips in the direction of higher economic growth while contributing significantly to avoiding climate change, as opposed to a climate austerity view.

Underlying this, climate policy generates structural changes to both the economy and the energy system, of which
there are winners and losers, creating opportunities to address questions of economic development. As we show here, climate policy does not create an economic problem; it changes however who are the winners and losers of energy policy, a question of political economy. Therefore a strategy oriented towards supporting innovation, development and access to clean energy is feasible and more productive than one concerned with preserving the current economic structure. As opposed to the static neoclassical snapshot of the economic circular flow, such transformational change may send the World into a new economic paradigm where unused labour resources and abundant finance currently facing low returns are channeled in productive low carbon ventures.\textsuperscript{27} Investment in alternative technology generates learning cost reductions that permanently alter the energy sector with strong path dependence.\textsuperscript{6} Thus, many different futures of decarbonisation can be conceived using different combinations of strong climate policy. Fossil technologies are affordable primarily because they are dominating, and low carbon technologies are expensive because they have received less investment historically, but this situation can be reversed by appropriate use of energy policy tools designed to channel investment decisions and build capacity, which we have shown are affordable, given that finance can be attracted to low carbon innovations.\textsuperscript{27}

**METHODS SUMMARY**

Full Methods and associated references are available in the online version of the paper.

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1 Fisher, B. S., Nakicenovic, N. & Co-authors. Chapter 3. In Climate Change 2007: Mitigation. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, UK, 2007).

2 Edenhofer, O. et al. The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs. *Energy Journal* **31**, 11–48 (2010).

3 Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M. & Koehler, J. Induced technological change: Exploring its implications for the economics of atmospheric stabilization: Synthesis report from the Innovation Modeling Comparison Project. *Energy Journal* 57–107 (2006).

4 Nordhaus, W. D. Economic aspects of global warming in a post-Copenhagen environment. *Proceedings of the National Academy of Sciences* (2010).

5 Stern, N. The Economics of Climate Change (Cambridge University Press, Cambridge, UK, 2006).

6 Mercure, J.-F., Salas, P., Foley, A., Chewpreecha, U. & Pollitt, H. The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector. *Preprint available on ArXiv* (2013). URL [http://arxiv.org/abs/1309.7626](http://arxiv.org/abs/1309.7626).

7 Solow, R. M. Technical change and the aggregate production function. *The Review of Economics and Statistics* **39**, pp. 312–320 (1957).

8 Schumpeter, J. A. The Theory of Economic Development - An inquiry into Profits, Capital, Credit, Interest and the Business Cycle (Harvard University Press, Cambridge, USA, 1934).

9 Schumpeter, J. A. Capitalism, Socialism and Democracy (Martino Publishing, Eastford, USA, 1942).

10 Geels, F. W. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy* **31**, 1257 – 1274 (2002).

11 Geels, F. W. The dynamics of transitions in socio-technical systems: A multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860 - 1930). *Technology Analysis & Strategic Management* **17**, 445–476 (2005).

12 Mercure, J.-F. FTT:Power: A global model of the power sector with induced technological change and natural resource depletion. *Energy Policy* **48**, 799 – 811 (2012). URL [http://dx.doi.org/10.1016/j.enpol.2012.06.025](http://dx.doi.org/10.1016/j.enpol.2012.06.025).

13 Mercure, J.-F. An age structured demographic theory of technological change. 4th International Conference on Sustainability Transitions, Zurich, 2013 (2013). URL [http://arxiv.org/abs/1304.3602](http://arxiv.org/abs/1304.3602).

14 Barker, T. & Scrieciu, S. S. Modeling Low Climate Stabilization with E3MG: Towards a ‘New Economics’ Approach to Simulating Energy-Environment-Economy System Dynamics. *Energy Journal* **31**, 137–164 (2010).

15 Barker, T., Pan, H., Koehler, J., Warren, R. & Winne, S. Decarbonizing the global economy with induced technological change: Scenarios to 2100 using E3MG. *Energy Journal* 241–258 (2006).

16 Koehler, J., Grubb, M., Popp, D. & Edenhofer, O. The transition to endogenous technical change in climate-economy models: A technical overview to the innovation modeling comparison project. *Energy Journal* 17–55 (2006).

17 Anthoff, D. & Tol, R. The uncertainty about the social cost of carbon: A decomposition analysis using FUND. *Climatic Change* **117**, 515–530 (2013).

18 Waisman, H., Guivarch, C., Grazi, F. & Hourcade, J. The Imaclim-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. *Climatic Change* **114**, 101–120 (2012).
Holden, P. B., Edwards, N. R., Gerten, D. & Schaphoff, S. A model-based constraint on CO$_4$.

Metcalfe, J. S. Edmansfield and the diffusion of innovation: An evolutionary connection.

Hofbauer, J. & Sigmund, K.

Grübler, A.

Grübler, A., Nakicenovic, N. & Victor, D. Dynamics of energy technologies and global change.

Sharif, M. N. & Kabir, C. Generalized model for forecasting technological substitution.

Meinshausen, M.

Weiss, M.

IEA.

Mercure, J.-F. & Salas, P.

Dosi, G. & Metcalfe, J. S. On some notions of irreversibility in economics. In Savio, A. & Metcalfe, J. S. (eds.) Evolutionary theories of economic and technological change, 133–159 (Harwood Academic Publishers, New York, USA, 1991).

Saviotti, P. P. Present developments and trends in evolutionary economics. In Savio, A. P. P. & Metcalfe, J. S. (eds.) Evolutionary theories of economic and technological change, 1–30 (Harwood Academic Publishers, New York, USA, 1991).

Hausmann, R. & Hidalgo, C. The network structure of economic output. Journal of Economic Growth 16, 309–342 (2011).

Saviotti, P. P. The role of variety in economic and technological development. In Savio, A. P. P. & Metcalfe, J. S. (eds.) Evolutionary theories of economic and technological change, 133–159 (Harwood Academic Publishers, New York, USA, 1991).

Rogelj, J., McCollum, D. L., O’Neill, B. C. & Riahi, K. 2020 emissions levels required to limit warming to below 2°C. Nature Climate Change 3, 405–412 (2013).

Akashi, O., Hijoka, Y., Masui, T., Hanaoka, T. & Kaimuma, M. GHG emission scenarios in Asia and the world: The key technologies for significant reduction. Energy Economics 34, Supplement 3, S346 – S358 (2012).

Grubb, M. Chapter 11: The dark matter of economic growth. In Planetary economics (Taylor Francis / Routledge, London, UK, 2013). Book in press.

Wilson, C., Grubler, A., Bauer, N., Krey, V. & Riahi, K. Future capacity growth of energy technologies: are scenarios consistent with historical evidence? Climatic Change 118, 381–395 (2013).

Holtz, G. Modelling transitions: An appraisal of experiences and suggestions for research. Environmental Innovation and Societal Transitions 1, 167 – 186 (2011).

Safarzynska, K. & van den Bergh, J. C. J. M. An evolutionary model of energy transitions with interactive innovation-selection dynamics. Journal of Evolutionary Economics 1–23 (2012).

Kohler, J. et al. A transitions model for sustainable mobility. Ecological Economics 68, 2985–2995 (2009).

Saviotti, P. & Mani, G. Competition, variety and technological evolution: A replicator dynamics model. Journal of Evolutionary Economics 5, 369–392 (1995).

Metcalfe, J. S. Ed mansfield and the diffusion of innovation: An evolutionary connection. The Journal of Technology Transfer 30, 171–181 (2004).

Hofbauer, J. & Sigmund, K. Evolutionary Games and Population Dynamics (Cambridge University Press, Cambridge, UK, 1998).

Grübler, A. Technology and Global Change (Cambridge University Press, Cambridge, UK, 1998).

Grübler, A., Nakicenovic, N. & Victor, D. Dynamics of energy technologies and global change. Energy Policy 27, 247–280 (1999).

Wilson, C. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. Energy Policy 50, 81–94 (2012).

Wilson, C. Meta-analysis of unit and industry level scaling dynamics in energy technologies and climate change mitigation scenarios. Tech. Rep. IR-09-029, IIASA (2009). URL http://webarchive.iiasa.ac.at/Admin/PUB/Documents/IR-09-029.pdf.

Mansfield, E. Technical change and the rate of imitation. Econometrica 29, pp. 741–766 (1961).

Fishier, J. C. & Pry, R. H. A simple substitution model of technological change. Technological Forecasting and Social Change 3, 75–88 (1971).

Sharif, M. N. & Kabir, C. Generalized model for forecasting technological substitution. Technological Forecasting and Social Change 8, 353–364 (1976).

Weiss, M. et al. On the electrification of road transport - learning rates and price forecasts for hybrid-electric and battery-electric vehicles. Energy Policy 48, 374 – 393 (2012).

Holden, P. B., Edwards, N. R., Gerten, D. & Schaphoff, S. A model-based constraint on CO$_2$ fertilisation. Biogeosciences 10, 339–355 (2013).

Holden, P. B. et al. PLASIM-ENTSim: a spatio-temporal emulator of future climate change for impacts assessment. Geoscientific Model Development Discussions 6, 33493380 (2013). URL http://www.geosci-model-dev-discuss.net/6/3349/2013/.

IEA. Projected Costs of Generating Electricity 2010 (IEA/OECD, 2010).

Murphy, L. M. & Edwards, P. L. Bridging the valley of death: Transitioning from public to private sector financing. Tech. Rep., NREL (2003). URL http://www.nrel.gov/docs/gen/fy03/34036.pdf.

Foley, A. M., Mercure, J.-F., Salas, P., Holden, P. & Edwards, N. R. Modelling the climate impacts of mitigation policies in the energy sector. under preparation (2013).

Meinshausen, M. et al. Greenhouse-gas emission targets for limiting global warming to 2°C. Nature 458, 1158–1162 (2009).

Riahi, K. et al. Chapter 17 - Energy Pathways for Sustainable Development. In Global Energy Assessment - Toward a Sustainable Future, 1213–1214 (Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012).

Mercure, J.-F. & Salas, P. On the global economic potentials and marginal costs of non-renewable resources and the price of energy commodities. Energy Policy – (2013). URL http://dx.doi.org/10.1016/j.enpol.2013.08.040.
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AUTHOR CONTRIBUTIONS

J.-F. M. designed the research project, designed and built FTT:Power and its underlying theory, integrated it to E3MG and performed the simulations. P. S. assisted FTT:Power work. A. M. F. ran the climate simulations. N. E. and P. H. created the climate/carbon cycle emulators and facilitated their use. H. P. and U. C. contributed in creating the scenarios, modifying and maintaining E3MG as well as in the integration of FTT:Power, and helped to critically analyse E3MG outputs. All authors contributed to the conceptual content of the work. J.-F. M. wrote the manuscript.

METHODS

Missing investment flows in conventional models. In the construction of neoclassical optimal growth cost benefit analysis models of Nordhaus (RICE 2010),

Hope (PAGE 2009, used in the Stern Review)

and Tol (FUN3.7),

mitigation costs are treated in the same manner as climate impact costs: they are money flows that vanish (in Nordhaus they are subtracted from output in the model equations; optimal growth is found in a mitigation scenario only due to the benefits of avoided climate impacts in the non-mitigation scenario.). This violates the accounting principle that spending by one agent must be matched by revenues for another. Mitigation costs correspond to new investments in the economy, which reappear in specific industrial sectors (construction, engineering, materials) and employment, additional household income that is spent again later in the economy. These investment flows must be taken into consideration in the investment equations. Meanwhile, in Computable General Equilibrium (CGE) models,

while investments are accounted for, investing in emissions reductions diverts capital from other sectors (crowding out), leading to reductions in production in those sectors, which are equivalent to the losses of the neoclassical case. This can only be the case if capital resources are already fully employed, but this assumption is not strictly justified or demonstrated to take place.\textsuperscript{11}

Innovation/Diffusion in FTT:Power. The diffusion theory underlying technology substitutions in FTT:Power is described by J.-F Mercure,\textsuperscript{12,13} in which the Lotka-Volterra equation of competing population dynamics is derived from demographic principles applied to technology, describing the associated industrial dynamics. It tracks the birth, ageing and scrapping of technology units in time, enabling a realistic representation of non-linear rates of substitution respecting technology lifetimes and competition. This is quite important for the power sector, in which technologies have very long and varied lifetimes. The non-linear difference equation calculating these changes independently in each of the 21 world regions is

\[ \Delta S_i = \sum_j S_i S_j (A_{ij} F_{ij} G_{ij} - A_{ji} F_{ji} G_{ji}) \frac{1}{\tau} \Delta t, \]

where the \( S_i \) represent the capacity shares of technologies \( i \) in a particular world region. This equation effectively represents \textit{flows of market shares} between technology options. The matrix \( F_{ij} \) represents probabilistic investor choices, while the matrix \( A_{ij} \) provides the frequencies of substitutions between all possible pairs of technologies, and the matrix \( G_{ij} \) maintains the system within technical constraints of operation. \( \tau \) is an overall time scaling constant. Technology choices \( F_{ij} \) are influenced by technology costs, which follow learning curves:

\[ C_i = C_{i,0} \left( \frac{W_i}{W_{i,0}} \right)^{-b}, \]

where \( C_i \) is the investment cost, \( W_i \) is the cumulative capacity of a technology (including previous decommissions), \( C_{i,0} \) and \( W_{i,0} \) are values at the start of the simulation and \( b \) is the learning exponent, related to the learning rate.\textsuperscript{12}
Macroeconometrics in E3MG. E3MG is formed of 33 econometric relationships (energy demand, industrial investment, prices, hours worked and employment, imports, exports, etc). The magnitudes of these relationships are evaluated using multi-variate regressions onto historical data since 1970, currently using 43 industrial and investment sectors, 28 consumption categories, 21 World regions, 22 types of fuel users and 12 types of fuels. These relationships are used to project into the future the complete set of variables of the model (in each sector, region, category etc, generating thousands of equations), which includes economic output, investment, prices, consumption, employment, disposable income, imports, exports and CO₂ emissions that stem from fuel combustion. Meanwhile, sectors are connected to one another using input-output tables expressing intra-industry flows of goods and investments, resulting in typical Keynesian multiplier effects. The model does not assume optimal growth, economic equilibrium, full employment or use production functions. It is demand led and supply constrained.

Energy demand is modelled using an econometric equation that incorporates induced technological change by incorporating accumulated investment and R&D expenditures, for fuel i and region j, of the form

$$X_{ij} = \beta_0^{ij} + \beta_1^{ij}Y_{ij} + \beta_2^{ij}P_{ij} + \beta_3^{ij} TP{I}_{ij} + \epsilon_{ij},$$

where $X_{ij}$ is the fuel demand, $Y_{ij}$ represents output, $P_{ij}$ relative prices and $TP{I}_{ij}$ is the technological progress indicator. The introduction of endogenous accumulated investment and R&D makes this equation non-linear, path-dependent and hysteretic. For example increases in prices lead to enhanced energy-saving R&D that permanently reduces energy demand per unit of output, which would not have occurred without price changes.

Economic growth occurs endogenously in E3MG, where investments in industrial sectors generates capacity expansions and adds to the pool of knowledge (cumulative R&D expenditure, i.e. technological progress), which enables production at lower costs in the long run. This lowers prices, which increases industrial activity, which itself generates more industrial investment. Sectors being connected by input-output coefficients, these investments propagate through the economy.

Emulating the climate system. (GENIEem) The carbon cycle is represented in this work by an emulator of the Grid Enabled Integrated Earth systems model (GENIE-1) Earth System Model, a simulation of the climate, ocean circulation and sea-ice, together with the terrestrial, oceanic, weathering and sedimentary components of the carbon cycle. GENIEem is designed to be a more sophisticated and computationally faster alternative to simplified climate-carbon cycle models. GENIEem transforms E3MG-FTT emissions into atmospheric concentrations with an analysis of uncertainty performed using the ensembles method representing large numbers of runs of the original model.

(PLASIM-ENTSsem) The climate system is represented by an emulator of the Planet Simulator (PLASIM) climate, coupled to the Efficient Numerical Terrestrial Scheme (ENTS). PLASIM-ENTSsem also uses the ensembles method for evaluating uncertainty, and is driven here by atmospheric concentrations calculated by GENIEem. Therefore a second layer of uncertainty emerges in addition to that of the carbon cycle. The combination of both emulators in the context of this work, with combined uncertainty analysis, is described in detail by Foley et al. Warming is in practice affected by the concentration of other ‘non-CO₂’ GHGs such as CH₄ and N₂O. However, we use the same values for non-CO₂ forcing, taken from the RCP8.5, in both scenarios, owing to a lack of capacity for modelling emissions unrelated to fuel consumption (e.g. agriculture and forestry). E3MG-FTT projects reductions in fuel use-related CH₄ and N₂O emissions of around 10-15% in 2050 in the mitigation scenario (levelling out later unless other sectors reduce emissions, notably transport), producing a small reduction in forcing of roughly 0.1 W/m² in comparison to the total forcing of between 7.3 and 8.3 W/m² (median of 7.9 W/m²) in the baseline and between 5.3 and 6.2 W/m² (median of 5.8 W/m²) in the mitigation scenario. We neglected this change of order 1-2%.

Policy assumptions The baseline (BAU) scenario assumes that current policies are maintained up to 2050, and this includes carbon pricing in the EU only through the Emissions Trading Scheme. For this, we used the projection given in 2008 dollars by the dashed line in extended data fig. 1. In addition, feed-in tariffs exist in Japan, Germany, the UK and France for solar and wind technologies. These reduce the levelised cost of producing electricity, using these technologies to 5-15% below the share weighted average cost of producing electricity in the grid, making these technologies competitive. No technology subsidies are present anywhere, however regulations to shut down existing nuclear power stations are in place in Germany and Japan. These are assumed to close down at the end of their lifetime and decrease exponentially from 2010 onwards.

The 89% decarbonisation scenario introduces carbon pricing in all regions of the World, with a summary for six regions given in extended data fig. 1 (averages across nations weighted by national emissions). Feed-in tariffs are offered for solar and wind technologies in all regions, adjusted specifically to each regional situation. Technology subsidies are introduced for all low carbon technologies in all regions excluding those benefiting from feed-in tariffs.
(the list of technologies used can be found in our previous work\textsuperscript{12,45}). These range between 20 and 50\% of technology capital costs, adjusted to each specific regional situation. A global average is given in figure 1. Complete information can be obtained online on the 4CMR website at \url{http://www.4cmr.group.cam.ac.uk/research/FTT/fttviewer}. 
Extended Data Figure 1. (left) Carbon price assumptions. Solid lines refer to the decarbonisation scenario while the dashed line refers to the baseline. (right) Average technology subsidies for the decarbonisation scenario (defined as negative fractions of technology capital costs). The legend shows all FTT:Power technologies, however those not visible in the graph do not benefit from subsidies.
Extended Data Figure 2. Summary of economic changes due to climate policy resulting in the decarbonisation of the electricity sector in a scenario without revenue recycling. Values are expressed as changes from the baseline scenario in six aggregate regions, in billions of constant 2000 US dollars (a), in billions of nominal US dollars (b,c) or percent (d to h). No losses of economic output are observed, and this is due to both a short run Keynesian effect and a long run productivity growth impact of investments in technology.