EEIST

GLOBAL ENERGY TRANSITION CASE STUDIES

LEAD AUTHORS: PETE BARBROOK-JOHNSON, SIMON SHARPE, ROBERTO PASQUALINO, FERNANDA SENRA DE MOURA, FEMKE NIJSEE, PIM VERCOULEN, ALEX CLARK, CRISTINA PEÑASCO, LAURA DIAZ ANADON, JEAN-FRANCOIS MERCURE, CAMERON HEPBURN, J. DOYNE FARMER AND TIMOTHY M. LENTON

This document presents only the modelling case studies related to the global energy transition in the 'New economic models of energy innovation and transition: Addressing new questions and providing better answers' report, produced by the EEIST project.

To view other parts of the full report, including case studies on the power and industrial sectors, transport, agriculture, impacts of the transition, national decarbonisation plans and finance, go to https://eeist.co.uk/eeist-reports/new-economic-models-of-energy-innovation-and-transition/

CONTRIBUTING AUTHORS: CASE STUDY AUTHORS LISTED UNDER EACH CASE STUDY

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About

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change.

By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

Led by the University of Exeter, EEIST brings together an international team of world-leading research institutions across Brazil, China, India, the UK and the EU.

The consortium of institutions are UK: University of Exeter, University of Oxford, University of Cambridge, University College London, Anglia Ruskin University, Cambridge Econometrics, Climate Strategies, India: The Energy and Resources Institute, World Resources Institute, China: Beijing Normal University, Tsinghua University, Energy Research Institute, Brazil: Federal University of Rio de Janeiro, University of Brasilia, Universidade Estadual de Campinas (UNICAMP) EU: Scuola Superiore di Studi Universitari e di Perfezionamento Sant'Anna.

Contributors

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Contributing authors are drawn from a wide range of institutions. For full institutional affiliations see **www.eeist.co.uk**

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CASE STUDY:

Empirically Grounded Energy Technology Cost Forecasts

RUPERT WAY (UNIVERSITY OF OXFORD), MATTHEW IVES (UNIVERSITY OF OXFORD), PENNY MEALY (WORLD BANK/UNIVERSITY OF OXFORD), J. DOYNE FARMER (UNIVERSITY OF OXFORD)

Policy question: How much will the energy transition cost?

Region: Global

Methods: Stochastic experience curves used to produce probabilistic energy technology cost forecasts and a simple energy system model.

Key findings: The energy transition is likely to save the global economy trillions of US dollars and the savings are greater if the transition happens quickly.

Engagement: Owing to its global scope, this work has been widely disseminated with a large number of policy and media partners. Highlights include: feeding in a net zero review by the UK government, being presented at the California Energy Commission, discussions with White House and US State department officials, and being featured in media outlets around the world (e.g. BBC, Asiana Times, Guardian, New Yorker, Bloomberg).

Summary: The authors combine a well-validated data analysis approach for forecasting energy technology costs with a simple energy system model to consider how much the energy transition might cost at a global scale. In contrast to many traditional models, they find that the energy transition, and especially a fast transition, is likely to save the global economy trillions of US dollars.

Introduction

Decisions about how and when to decarbonise the global energy system are highly influenced by estimates of the likely cost. Most energy-economy models have produced energy transition scenarios that overestimate costs due to underestimating renewable energy cost improvements and deployment rates.

This case study[39] presents probabilistic cost forecasts of energy technologies using a method that has been statistically validated on data for more than 50 technologies. Using this approach to estimate energy system costs, we find that a rapid green energy transition is likely to result in trillions of net savings. Even without accounting for climate damages or climate policy co-benefits, transitioning to a net-zero energy system by 2050 is likely to be economically beneficial. This method of forecasting costs can also be useful for informing policy choices about the technologies to use for decarbonisation of different sectors.

Approach

For technologies that are experiencing improvements in costs, improvement rates are remarkably consistent.[40] For these technologies there are two dominant methods for quantitatively forecasting costs based on historical data. The first is a generalised form of Moore's law, which says that costs drop exponentially as a function of time. The second is Wright's law, which predicts that costs drop as a power law of cumulative production. We focus on Wright's law because it satisfies the basic intuition that exerting greater effort induces greater effects. However, we do repeat all our modelling experiments using Moore's law and find that the qualitative conclusions are similar.

Wright's law has usually been used to generate point forecasts, meaning that the forecast is a deterministic function of experience, with no estimate of error. Early attempts at introducing error bars did not provide a priori functional forms, which made the data requirements for out-of-sample testing prohibitive.[41 42] More recently, a priori error estimates were derived that predict forecasting accuracy as a function of historical improvement rates and volatility, and the number of data points available for forecasting.[43] Based on comprehensive backtesting, this method was shown to generate reliable probabilistic estimates of future costs. This was done by selecting reference dates in the past and then, using only the data available at the time, making forecasts over all time horizons up to 20 years into the future with respect to each reference date. Using historical data for 50 different technologies, based on roughly 6,000 forecasts, the empirically observed forecast accuracy closely matched the a priori derived estimates on all time horizons up to 20 years ahead. 2,5 Our main contribution in this work is to systematically apply this method – which we call the stochastic experience curve or stochastic Wright's law – to the energy transition.

Testing our approach to forecasting costs

To test the accuracy of the stochastic experience curve method for forecasting costs of energy technologies, we applied it to historical data for solar, wind, batteries and polymer electrolyte membrane (PEM) electrolysers (see Figure 12). Data prior to each forecast year were used to estimate parameters, then observed deployment data in subsequent years were used to generate forecasts conditioned on experience. The forecasts for solar, wind and batteries are reasonable: most of the future values lie within the 95 per cent confidence interval (CI), consistent with the a priori error estimates. Due to the short dataset and high historical volatility, forecasts for electrolysers are not as accurate, but the confidence intervals capture this.

[40] Farmer, J.D and Lafond, F. (2016). How Predictable is Technological Progress? Res. Policy 45: 647-665.

[41] Nagy, B. et al. (2013). Statistical Basis for Predicting Technological Progress. PLoS One, 8 (2013): Article e52669.

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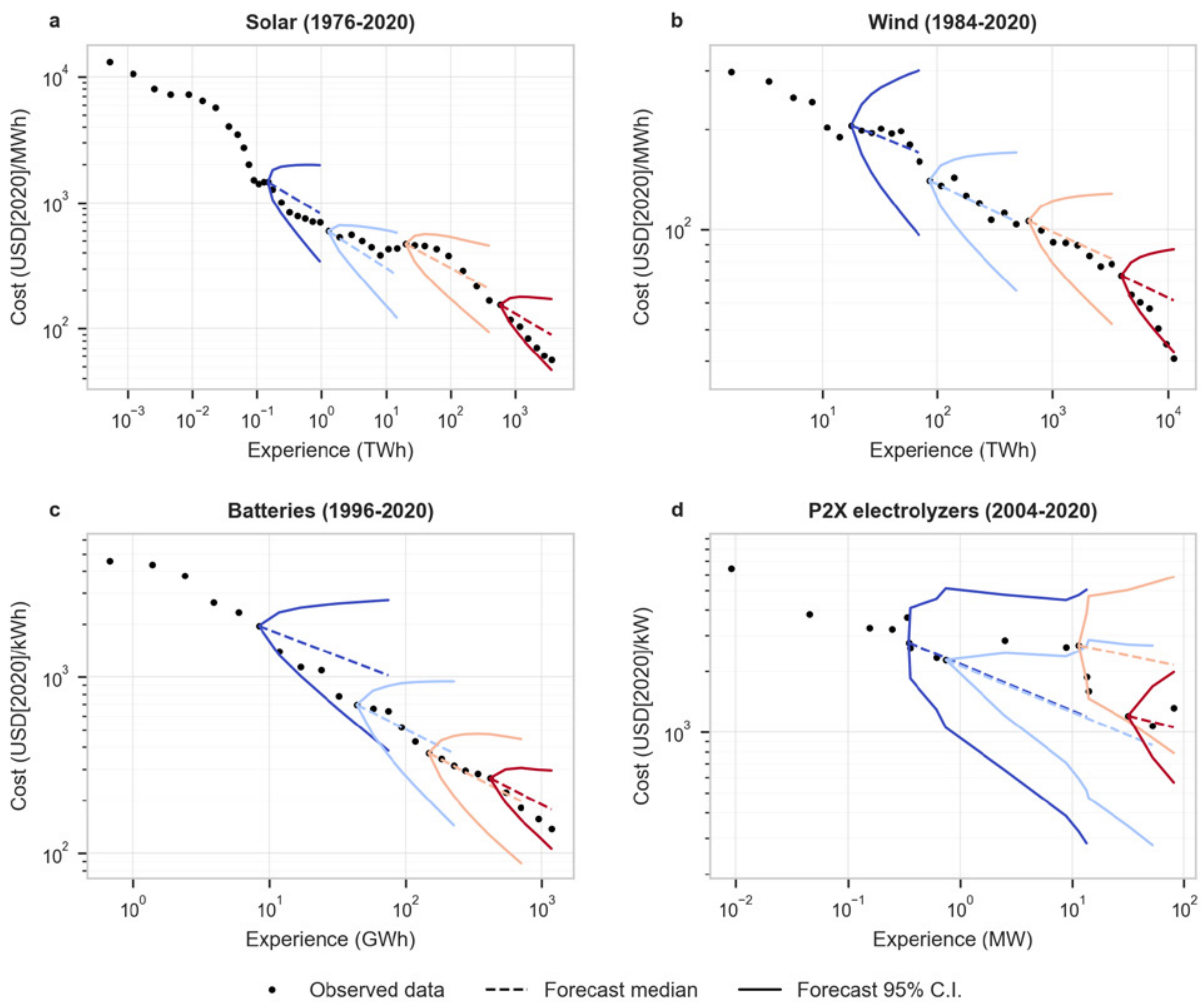
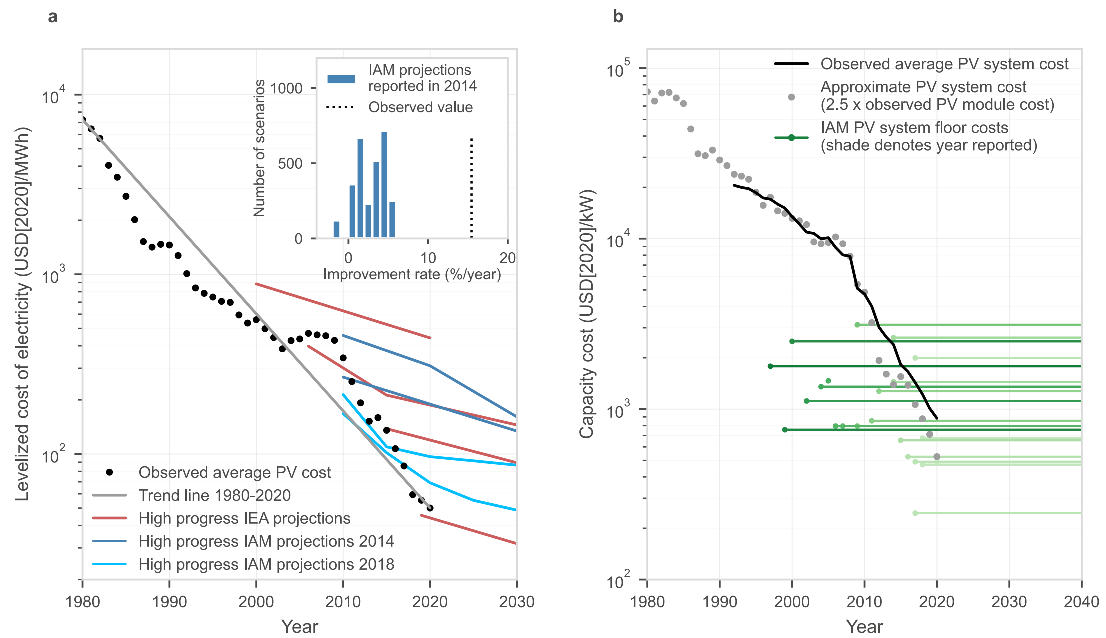
[43] Lafond, F. et al. (2018). How Well do Experience Curves Predict Technological Progress? A method for making distributional forecasts. Technol. Forecasting Soc. Change 128 (2018): pp. 104-117.

Figure 12: Historical performance of the stochastic experience curve forecasting method. Forecasts are made at regular intervals, using prior cost and deployment data to calibrate the model and 'future' deployment data to generate the forecasts. Forecast medians and 95 per cent confidence intervals (CIs) are shown, and colours denote forecast year, from earliest (dark blue) to most recent (red). Costs are LCOEs for solar and wind, and capacity costs for batteries and electrolysers. P2X electrolysers are assumed to be PEM electrolysers here. Source: Way et al. 2022. Empirically Grounded Technology Forecasts and the Energy Transition. Joule 6(9): 2057-2082.



It is instructive to compare the accuracy of these forecasts to the outputs of influential global energy-economy models. Integrated assessment models (IAMs) are used to evaluate policies and generate scenarios for deployment and cost that are consistent with given climate targets under the assumption of optimal decision-making by economic agents. Their outputs are typically called 'projections' to indicate that they are not intended to be used as forecasts. Figure 13 emphasises this point. Figure 13A shows past projections of solar PV energy costs by the International Energy Agency's (IEA) World Energy Model and several IAMs and compares them with the observed data.

Figure 13: Historical PV cost projections and floor costs. (A) The black dots show the observed global average LCOE. Red lines are LCOE projections reported by the IEA;[44] dark blue lines are integrated assessment model (IAM) LCOE projections reported in 2014;[45] and light blue lines are IAM projections reported in 2018.[46 47] IAM projections are rooted in 2010 despite being produced in later years. The projections shown are exclusively 'high technological progress' cost trajectories drawn from the most aggressive mitigation scenarios, corresponding to the largest projected cost reductions used in these models. The inset compares a histogram of projected compound annual reduction rates of PV system investment costs from 2010 to 2020 with what actually occurred (based on all 2,905 scenarios for which the data are available).[48] (B) PV system floor costs implemented in a wide range of IAMs. The colours denote the year the floor cost was reported, ranging from 1997 (dark green) to 2020 (light green). Observed PV system costs are also shown. The cost of PV modules scaled by a constant factor of 2.5 is provided as a reference. Source: Way et al. 2022. Empirically Grounded Technology Forecasts and the Energy Transition. Joule 6(9): 2057-2082.



The projections shown correspond to scenarios with the most aggressive climate policies and highest rates of technological innovation, i.e., those that produce the highest rates of key green technology deployment and the most optimistic cost declines. Nonetheless, their projected costs have been consistently much higher than historical trends.

This makes it clear that it would have been a bad idea to treat these projections as conditional forecasts. By contrast, the stochastic experience curve method produces reliable conditional forecasts of known accuracy (and a published forecast of 2020 solar costs, made in 2010 using the deterministic version of Wright's law, was indeed far more accurate than any of the IAM or IEA projections made at the time).[49] One of our goals in this work is to illustrate how such forecasts are useful for planning the energy transition.

Wright's law is widely used to generate technology cost projections in IAMs. However, it is typically used in conjunction with ad-hoc constraints such as deployment rate limits and floor costs, i.e. fixed levels that costs are assumed to never fall below. Because IAMs use costs to determine deployment (and vice versa), and many allow perfect foresight, constraints are necessary to prevent sharp cost declines due to Wright's law from leading to solutions in which key green technologies are deployed faster than is physically or socially plausible. It is difficult to know what constraints are realistic, which leads to ad-hoc choices that strongly influence the results. The imposition of excessively strong constraints is likely an important reason why the projections of these models have not corresponded to the historical record.

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[45] Riahi, K. et al. (2015). Locked into Copenhagen Pledges — Implications of Short-Term Emission Targets for the Cost and Feasibility of Long-Term Climate Goals. Technol. Forecasting Soc. Change 90 (2015): 8-23.

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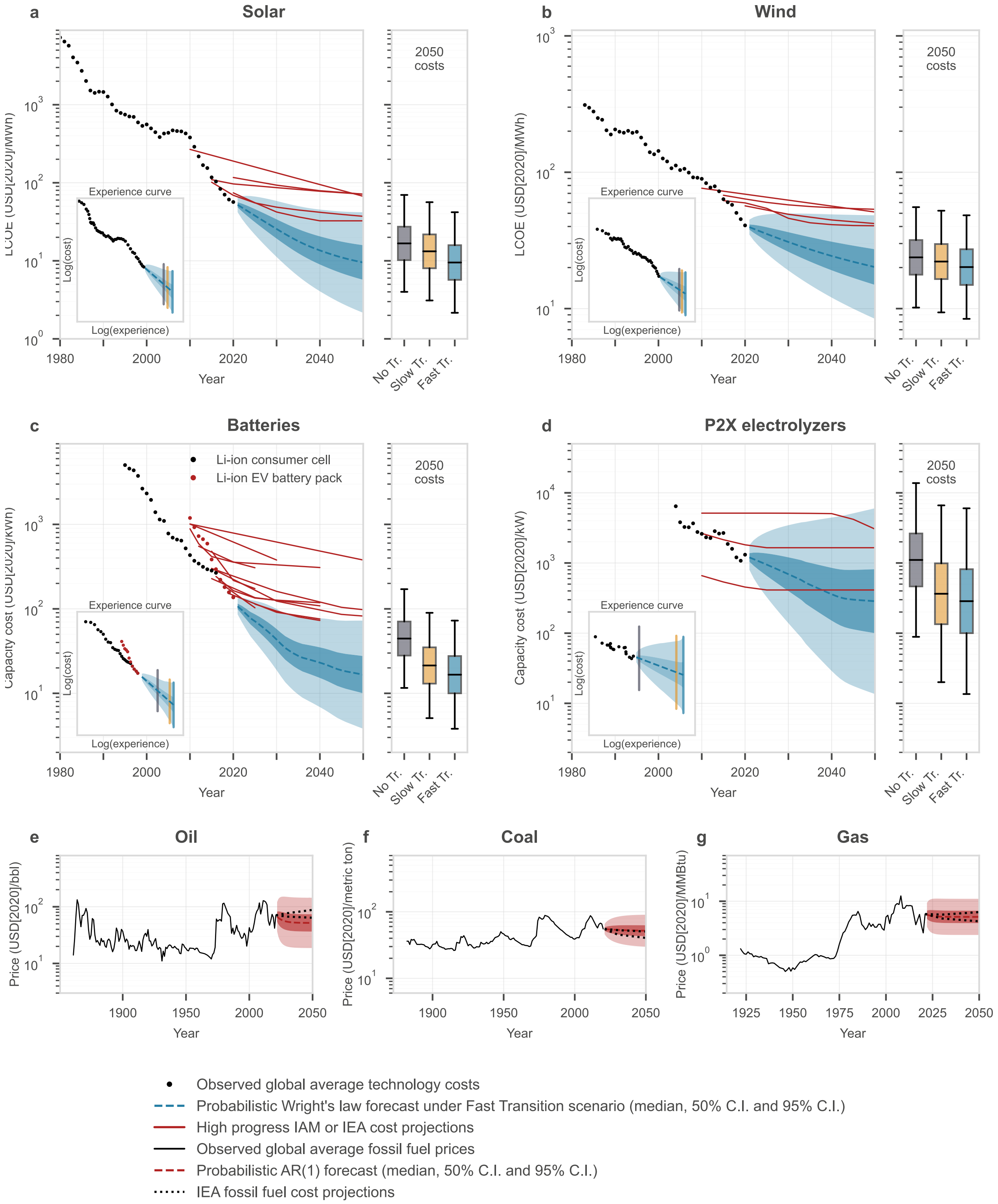
Figure 14: Technology cost forecasts. (A–D) The main panels show cost forecast distributions under the Fast Transition scenario for solar PV, wind, batteries, and PEM electrolysers; the 50 per cent confidence interval (CI) is dark blue, and the 95 per cent CI is light blue. Also shown are several representative recent and past projections corresponding to 'optimistic' mitigation scenarios made by IAMs and the IEA (red lines) (see Figure 13). For batteries, both lithium-ion (Li-ion) consumer cells and Li-ion electric vehicle (EV) battery packs are shown, although their costs have now converged; our forecasts are based on consumer cells, whereas the IEA projections shown are based on EV batteries. The boxplots in the right-hand panels compare cost forecasts in 2050 under the No Transition, Slow Transition and Fast Transition scenarios. The insets show historical experience curves and forecasts, with learning rates that are independent of the scenario, and vertical lines that indicate how far each technology moves down the probabilistic experience curve in each scenario. (E–G) These panels show probabilistic cost forecasts for oil, coal, and gas based on the AR(1) time-series model. Source: Way et al. 2022. Empirically Grounded Technology Forecasts and the Energy Transition. Joule 6(9): 2057-2082.



Probabilistic cost forecasts for individual technologies
We applied the methods discussed so far to make forecasts of future energy costs and prices. To generate experience curve forecasts, parameters for each technology were estimated from historical data. We then specified scenarios for the future deployment of each technology as a function of time and predicted a distribution of future costs. We defined three representative deployment scenarios. The first scenario is consistent with the energy system transitioning away from fossil fuels by around 2050, and so we label this deployment scenario the 'Fast Transition'. The second scenario is consistent with eliminating fossil fuels by around 2070, so we label it the 'Slow Transition'. The final scenario is consistent with fossil fuels continuing to dominate the energy system, so we label it the 'No Transition'.

Figure 14 shows probabilistic forecasts for seven important energy technologies. The main panels of Figures 14A–D show forecasts for key green technologies in the Fast Transition scenario, which are made using the stochastic version of Wright's law. The insets show costs versus experience and emphasise that median costs develop identically as a function of experience in all scenarios. The side panels of Figures 14A–D illustrate that under Wright's law, forecast distributions depend on the scenario; as a result, in a faster transition, we are likely to reach lower costs sooner. Each Wright's law technology initially follows its current trend of exponentially decreasing costs, but then progress slows as its rate of deployment drops. To generate fossil fuel cost forecasts, an autoregressive model (AR(1)) was calibrated to observed data. For fossil fuels, model parameters depend on past data, but forecasts are independent of deployment, so each technology has a single forecast in all scenarios.

Figure 14 also shows a selection of future cost projections reported by IAM and IEA studies. As before, we show only their most optimistic projections. Consistent with the historical behaviour of these models illustrated in Figure 13, the cost projections are high relative to historical trends. They are also all substantially higher than our forecast medians.

The deployment corresponding to these cost projections is not the same as that used to make our forecasts, so they are not perfectly comparable. However, as the boxplot panels show, the disparities persist across all our scenarios, including No Transition. This makes it clear that our cost forecasts are, all things equal, significantly lower than those used in these influential energy-economy models.

From single technologies to full system costs
To forecast the likely costs of the green energy transition and explore how uncertainty in individual technology costs propagates through to uncertainty in system costs, we constructed a simple, transparent model of the global energy system based on well-defined technology deployment scenarios. We used the three transition scenarios introduced above. For more detail on these scenarios and the implementation of our simple energy system model, please see Way et al.1

To apply our probabilistic technology cost forecasting methods in a given scenario, we employed a Monte Carlo approach, simulating many different future cost trajectories, then exponentially discounting future costs to calculate the expected net present cost (NPC) of the scenario up to 2070. Figure 15A shows annual system costs through time for each scenario. The black boxplots represent the full cost forecast distributions, whereas the colored bars show median expenditures by technology group. This shows how, in the Fast Transition scenario, expenditures transfer rapidly from fossil fuels to key green technologies.

Figure 15: Scenario costs. (A) Coloured bars show median annual expenditures on fossil fuel and non-fossil fuel technologies in each scenario in trillions of dollars (tn USD). Boxplots show the median and interquartile range (IQR) of total annual expenditures, and whiskers extend from the box by 1.5 times the IQR. (B) Forecast distributions of the annual system cost in 2050 for each scenario. (C) Forecast distributions of the net present cost (NPC) of each scenario, for a fixed discount rate of 2 per cent. (D) Expected net present cost of each scenario relative to the No Transition scenario, as a function of the discount rate. The inset shows the probability that the NPCs of the Fast Transition and Slow Transition will be lower than that of the No Transition, as a function of the discount rate. Source: Way et al. 2022. Empirically Grounded Technology Forecasts and the Energy Transition. Joule 6(9): 2057-2082.

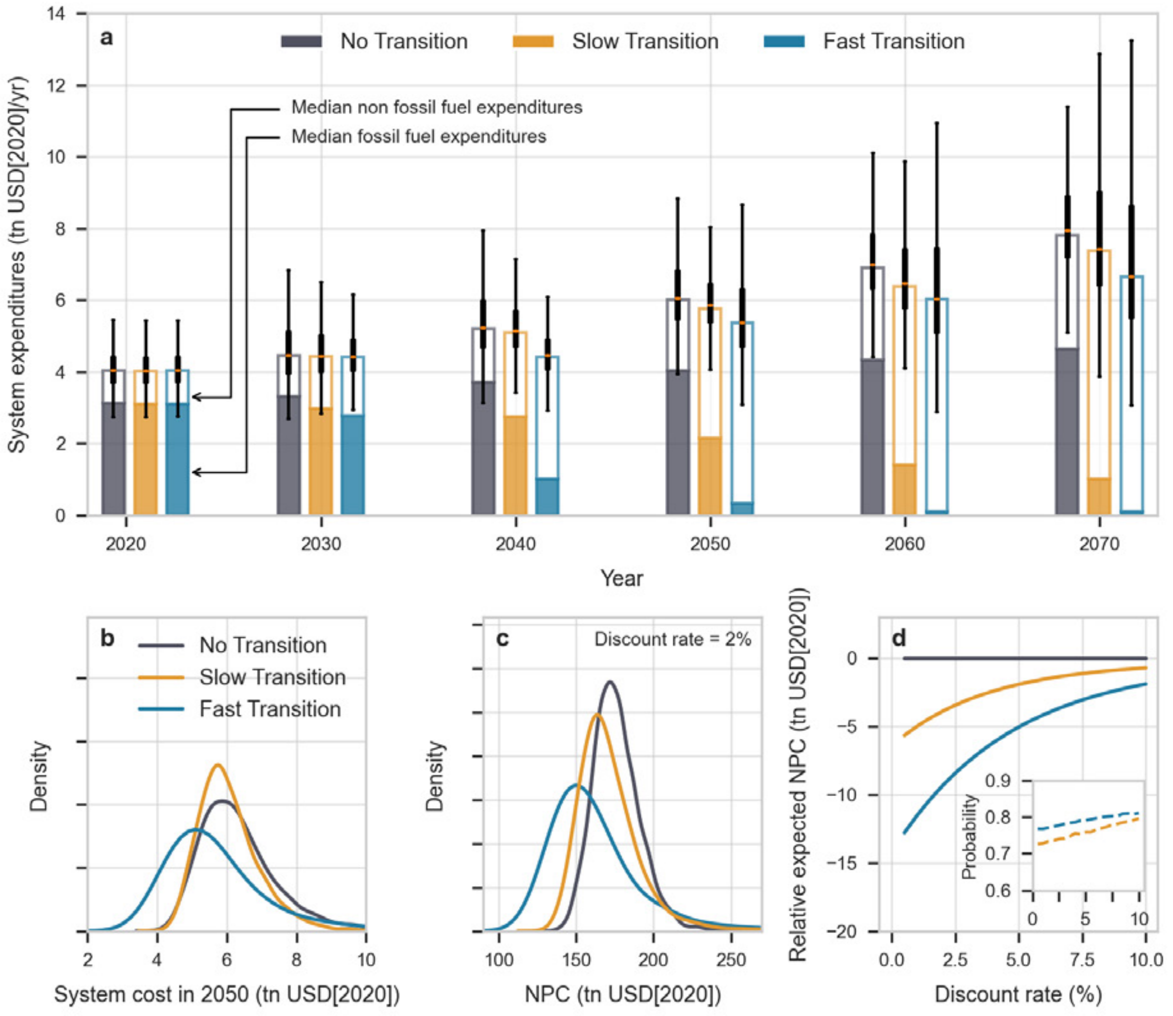


Figure 15B shows the annual system cost forecast distributions in 2050. Rapid replacement of fossil fuel technologies by low-cost key green technologies – in power and transport in particular – causes the expected annual energy system cost in 2050 for the Fast Transition scenario to be $514 billion cheaper than that for the No Transition scenario, although the distribution of possible costs for the Fast Transition is wider. After 2050, as shown in Figure 15A, while the median and interquartile range (IQR) remain relatively low, the uncertainty of the Fast Transition in relation to No Transition increases. If costs are in the upper end of the uncertainty range, cheaper alternatives would be used; we are not taking this into account, which is a drawback of our method.

Figure 15C shows the forecast distribution of the NPC of each scenario at a fixed discount rate of 2 per cent. Although there is considerable uncertainty, the NPC of the Fast Transition is likely to be quite a bit lower than that of the No Transition. By contrast, the Slow Transition is not as cheap as the Fast Transition. This is because the current high spending on fossil fuels continues for decades, and the savings from key green technologies are only realised much later. Nonetheless, it also generates savings relative to the No Transition scenario. Similarly to Figure 15B, the NPC distribution of the Fast Transition is wider than that of the No Transition. Although this is caused by higher technology uncertainty, it is important to note that this increased uncertainty is compensated for by the leftward shift in the distribution, due to expected cost declines associated with scaling up key green technologies.

Figure 15D shows how the expected NPC of each scenario varies with the discount rate relative to the No Transition scenario. The inset shows that there is roughly an 80 per cent chance that the NPC of the Fast Transition is lower than that of the No Transition, regardless of discount rate. Previous analyses have suggested that whether or not it makes good economic sense to quickly transition to clean energy technologies depends on the discount rate. But here we show a striking result: the Fast Transition is likely to be much cheaper at all reasonable discount rates. Using the 1.4 per cent social discount rate recommended in the Stern Review,[50] for example, the expected net present saving is roughly $12 trillion. At the higher discount rate of 5 per cent, the expected saving is around $5 trillion.

Conclusion

The belief that the green energy transition will be expensive has been a major driver of the ineffective response to climate change for the past 40 years. This pessimism is at odds with past technological cost improvement trends and risks locking humanity into an expensive and dangerous energy future. While arguments for a rapid green transition cite benefits such as the avoidance of climate damages, reduced air pollution and lower energy price volatility, these benefits are often contrasted against discussions about the associated costs of the transition. Our analysis suggests that such trade-offs are unlikely to exist: a greener, healthier and safer global energy system is also likely to be cheaper. Updating expectations to better align with historical evidence could fundamentally change the debate about climate policy and dramatically accelerate progress to decarbonise energy systems around the world.

While we are critical of some IAMs assumptions, we believe our approach is complementary to them, building upon historical trends directly and thus providing a counterweight to projections by IAMs. We have demonstrated that the constraints that are commonly used in IAMs are likely an important cause of the mismatch of their projections with historical data. Future work could explore how softening these constraints within IAMs changes their projections. We want to stress that, unlike IAMs, we are not attempting to find optimal solutions. There are likely other scenarios that are cheaper than the Fast Transition scenario, which was constructed to explore whether (with sufficiently rapid deployment) a rapid transition can achieve net cost savings, and if so, with what probability.

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CASE STUDY:

Policy Options for Rapid, Smooth Decarbonisation and Sustainable Growth

FRANCESCO LAMPERTI (SCUOLA SUPERIORE SANT'ANNA) AND ANDREA ROVENTINI (SCUOLA SUPERIORE SANT'ANNA)

Policy question: Which climate policy packages are better at fostering and sustaining the energy transition without destabilising the economic system and the public budget?

Region: Global

Methods: Agent-based model

Key findings: Carbon pricing policies alone are ineffective to stay below the 2°C target, but a mix of fossil fuel ban, public construction subsidies and electrification standards policies shows a strong potential for emission-growth reduction while increasing growth and maintaining macro-financial stability, although with a (low) fiscal impact. Nonetheless, a small carbon tax can be added to the policy mix to further speed up the transition and neutralise its impact on the public budget.

Engagement: This case study benefited from various and frequent feedback received from stakeholders, policymakers and researchers across multiple rounds of interactions, particularly in Brazil. As such, parts of the research questions, policy instruments tested and outcome variables were co-decided with policy stakeholders.

Summary: The authors use a dynamic simulation to examine how alternative climate policy combinations are able to foster and sustain the energy transition and cut emissions without destabilising the economic system and the public budget. They use a macro-financial agent-based integrated assessment model calibrated on the global economy to simulate policy packages within a complex evolving economy with heterogeneous and interacting firms, and in persistent disequilibrium.

Introduction

Climate impacts are rapidly mounting and will likely destabilise the socio-economic and natural systems under the current emission trajectory.[51 52] A mix of policies are needed to combat global warming and achieve sustainable growth; however, the currently agreed pledges are insufficient to deliver the objectives of the Paris agreement. To cut emissions, economies must reduce their carbon intensity, shift away from fossil-fuel energy and related physical capital and foster a climate-technology revolution in less than three decades. In an adverse scenario, the transition to a low- carbon economy occurs either late or abruptly, with the costs of such transformation being potentially high and systemic.[53 54 55 56] Indeed, policymakers increasingly emphasise the need of finding the right balance between a rapid transition and the macroeconomic frictions it entails,[57 58] as well as the long-run growth opportunities it can generate.[59] However, while there is widespread agreement about the urgency of climate action to mitigate risks from uncontrolled climate change, the evidence on the suitable policy package to induce an effective and orderly transition is scarce[60] and the excessive reliance on policy instruments characterised by low political acceptability, such as carbon pricing, brings about concerns for the transition outlook.[61 62 63]

Using a macro-financial agent-based integrated assessment model calibrated on the global economy as a simulation laboratory, Lamperti et al.[64] and Wieners et al.[65] compare alternative climate policy combinations within a complex evolving economy in persistent disequilibrium, examining the ability to foster and sustain the transition and exploit technological opportunities without destabilising the economic system and the public budget. Results show that carbon-pricing policies alone are ineffective to stay well below the 2°C target. Indeed, current levels of carbon taxation are inadequate to the scope, while if the only policy, carbon prices high enough to induce a rapid transition have potentially destabilising effects on the macroeconomy. Conversely, a mix of regulation and subsidies for investments and R&D in green energy technologies can put the economy on a win-win sustainable growth pathway. Our model genuinely captures endogenous technological change under deep uncertainty and path dependence, in contrast to more traditional approaches which miss these factors. Our results stem from a mix of policies that tackle a wider range of barriers to rapid system change more directly than a carbon price, which only focuses on the carbon externality and mainly acts through market signals. In this context, carbon taxation can be effectively used to finance green public spending while not hampering the growth outlook. Mission-oriented policies act as a synergic tool with climate policy and have the potential to ease the shift to a new, low-carbon growth path.[66 67] Investments to improve the government's long-term capacities and dynamic capabilities are also needed to promptly adapt the public response in face of climate change and other pressing societal challenges (Lamperti et al., 2019b). Appropriately designed credit and macroprudential policies foster macro-financial stability in the face of climate risks while mildly mitigating emission growth, though their scope is limited in absolute terms (Lamperti et al., 2021).[68] Overall, our results suggest that large packages of policies and investments grounded on credible policy targets, and mission-oriented and risk-taking attitudes of governments, have the potential to foster win-win pathways characterised by rapid decarbonisation, high employment rates and long-term sustainable growth.

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[65] Lamperti, F. et al. (2022). Macroeconomic Policies to stay below 2°c with Sustainable Growth. Technical report, LEM Working Papers. Forthcoming.

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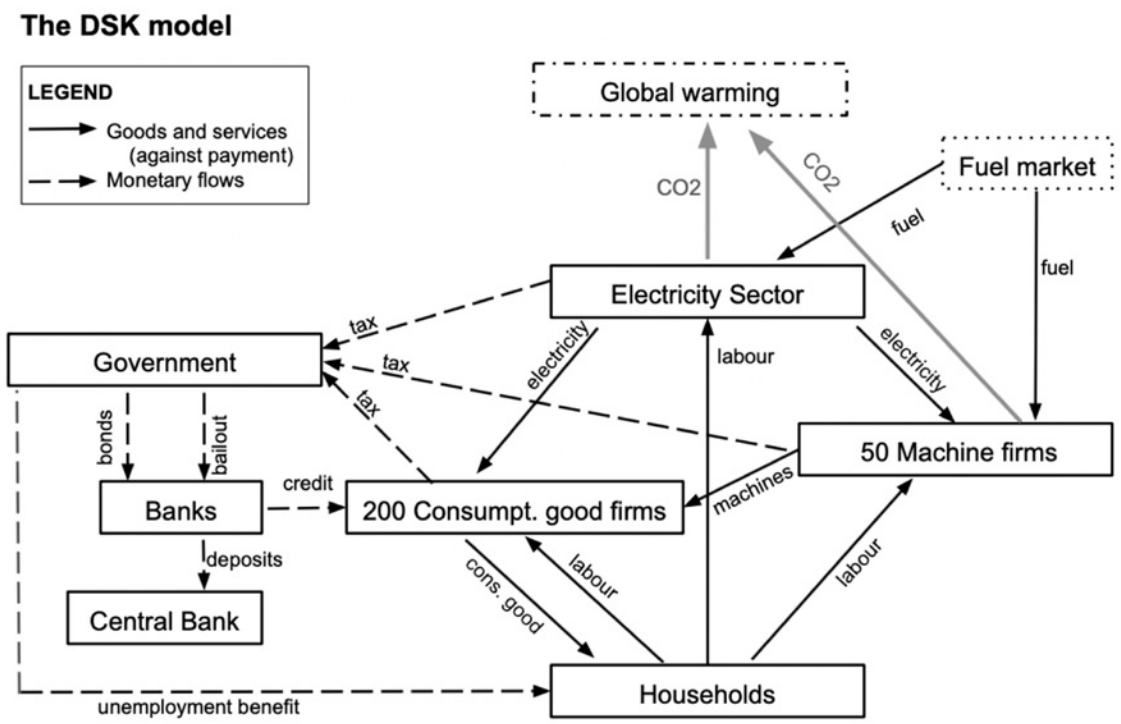
Methods

To test the risks and opportunities of alternative climate policies for the macroeconomy in the short and medium/long run, we rely on the Dystopian Schumpeter meeting Keynes (DSK) model.[69] The DSK model is an agent-based simulation laboratory representing a global economy co-evolving with dynamic interactions with the environment and the climate (see Figure 16). In particular, the model comprises heterogeneous and interacting consumption- and capital-good whose production requires energy and labor inputs, and it may need credit provided by a banking sector. Capital-good firms also carry out R&D activities aimed at improving the efficiency of production processes. In the power sector, energy plants rely either on low-carbon or fossil-fuel sources to supply electricity to the economy. Firms decide how much to produce, how many workers to hire, what investments to take, how much external financing to ask and how to search for new technologies; banks decide how much credit to offer, at which conditions and to which customers and, in addition, they demand government bonds; differently, consumers earn wages and dividends and demand final goods.

The government implements fiscal, innovation, and energy policy, and a central bank runs monetary and macroprudential policy. Anthropogenic emissions arise from the production of goods and energy. Cumulated emissions are linked to temperature increases through a single climate model. The model has been equipped to provide a stochastic micro-foundation of climate damages, which are modeled as a series of heterogenous shocks affecting several features of firms, consumers, and energy plants (Lamperti et al., 2018, 2019).[70] The distinctive feature of the model is that it couples a Schumpeterian growth engine featuring endogenous technical change affected by Knightian uncertainty and path-dependence with a Keynesian demand management approach and a financial sector composed of heterogenous commercial banks. All these features are framed in terms of behavioral routines and decentralised interactions – which have undergone a process of empirical validation, see Fagiolo et al. (2019)[71] – among an ecology of boundedly rational agents facing an evolving environment. In this model, effective decarbonisation depends on how policies affect the pace and direction of innovation as well as how they cope with the asymmetric information affecting each market.

Figure 16: Stylised representation of the DSK model from Wieners et al. (2022).



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Results and policy insights

In Wieners et al. (2022) we analyse a number of carbon tax schedules implemented within the DSK model (see Table 7 and Figure 17). In particular, we consider carbon taxes increasing the fossil fuel price either gradually – mimicking the policies suggested by the cost-benefit integrated assessment literature – or by a constant wedge.[72] The results are crystal clear and suggest that carbon pricing – when implemented alone – can be effective and risky at the same time (see Figure 17). On the one hand, excessively low carbon taxation is largely ineffective at triggering the green transition both in the power and industry sectors. We find that the relative likelihood of meeting the 2°C target approaches zero when the policymaker relies on carbon taxes that are below 100 per cent of the fossil fuel price. In other words, a policy doubling the fossil fuel price gives an approximate minimum threshold to produce some visible effect in escaping path dependence on emission-intensive technologies. Our results point to the difficulty to overcome inertia in the process of technology search and adoption by simply raising the carbon price. Indeed, the deep uncertainty surrounding innovation and the process of search for novel technologies makes prices a poor signal to rapidly direct technological change. This is true both for energy intense sectors and, even more markedly, for those where energy costs are relatively low. On the other hand, high carbon prices are found to foster economic instability, inducing a sharp increase in unemployment rates and a surge in firms' bankruptcies translating into a transitory yet long recession. Indeed, putting a price on carbon both raises variable costs of production and makes technological adoption more difficult; these effects increase financial fragility and reduce aggregate demand. When carbon prices are sufficiently high to increase the fossil fuel price by about 2.8 times (a value which would be required to obtain a fast enough transition to comply with the 2 degrees target), a crisis becomes substantially more likely.

While revenue recycling schemes directed towards either firms (to cover costs) or households (to sustain consumption) soften such adverse effects, they do not provide full insurance to the economy. Coupling these two results, Wieners et al. find that exponentially increasing carbon pricing schedules – often advocated in DICE and other mainstream integrated assessment models (see e.g. Nordhaus, 2019, 2014)[73] – risk pairing ineffectiveness in the short term with increased economic instability in the long run, making the transition even more difficult. These findings hint at moderate and careful use of carbon pricing, and call for an ampler policy mix where carbon taxes can be coupled with other policies.

An ample set of policy instruments focusing on quantities, regulation, innovation, nudging, social influence, information disclosure and mixed approaches,[74][75] is usually left out of the macroeconomic assessment of climate policy. To fill this gap, we tested a large ensemble of combinations, including subsidies to green power plant construction, R&D subsidies to low-carbon technologies, regulations banning fossil fuel power plants and standards imposing electrification. All the instruments were further coupled with carbon taxation to single out policy synergies (see Table 7 for the main results). Our study complements the ecological macroeconomic analysis of policies for the transition,[76][77][78][79] offering a bottom-up perspective wherein the process of technical change under deep uncertainty and path dependence is the key driver of system change. Further, we offer a comparison of alternative policy schemes across multiple dimensions, which encompass the speed of the decarbonisation process and several indicators of macro-financial performance. First of all, our results reveal a positive effect of command-and-control policies forbidding fossil-fuel plant construction as well as the use of fossil fuel. Both policies (labelled as B and E in Table 7) are implemented as regulations establishing a ban to be enforced after a grace period, with non-compliant firms being fined and

[72] Specifically, we test policies that raise the fossil fuel price by a factor ranging from 1 to 15, which allows studying carbon prices coherent with IPCC scenarios limiting temperature anomaly to 2 degrees as well as more aggressive policies. When modelling increasing rates, we consider exponential tax schedules following the same fossil fuel price trajectories of Nordhaus (2017)'s DICE model. Details in Wieners et al. (2022).

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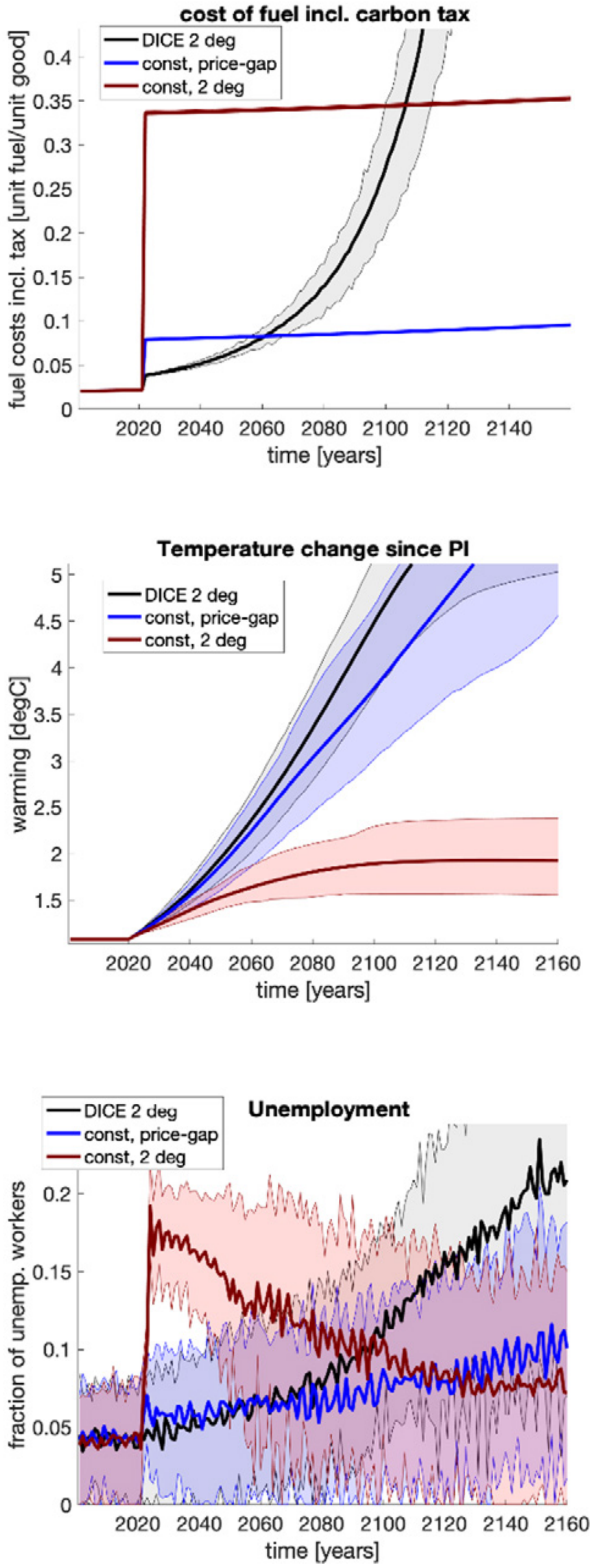
forced to leave their respective markets. Instruments of this kind are now increasingly entering the policy arena (e.g. the UK ban on gas boilers from 2025) and the macro effect they could produce at large scale needs to be uncovered. The grace period allows firms to adjust to the new regulation, which is assumed to be credible and immediately internalised by economic agents. These policies foster a higher pace of investment in low-carbon technologies, both in the energy and manufacturing sectors, and encourage a faster abandonment of emission-intensive production techniques than other policies (e.g. carbon taxation).

Public subsidies for green plant construction and green R&D are another key instrument for climate policy. They (i) accelerate the transition in the power sector, which is crucial to sustaining the adoption of electrification-based solutions, and (ii) sustain the creation of jobs. Indeed, experiment B+C+E (see Table 7) – which combines a fossil fuel ban, public green construction subsidies and electrification standards – shows a strong potential for emission-growth reduction while increasing employment and maintaining macro-financial stability, though adversely affecting public deficit. In particular, the fossil-fuel ban and electrification standards effectively re-direct the process of technological change towards low-carbon technologies, while subsidies speed up the search and uptake of innovations. The overall cost induced by non-tax-based policies on the public budget is modest (estimated at around 1.5 per cent [0.5 per cent-3 per cent] of GDP per year in a prototypical developed country). To absorb such costs, different carbon taxes were tested: in general, we report evidence of a synergic effect of mild carbon taxation. Indeed, a relatively small carbon tax can be added to the policy mix to further speed up the transition, generate revenues from high-emitting firms and neutralise the impact on the public budget that a policy mix composed of regulation and green public spending would have (experiment B+C+E+T). Numerical simulations suggest that a constant carbon tax increasing the 2020 fossil fuel price by a factor of 2.5 until 2100 can provide revenues to finance the innovation, command-and-control and green plant construction policies that are crucial in the early phase of the transition; at the same time such carbon pricing is small enough to prevent the emergence of significant transition costs at the macroeconomic level. These results suggest that a fast, smooth and employment-enhancing transition is possible, and a simple policy mix coupling price-based instruments with active industrial policy can achieve it.

Table 7: Macroeconomic consequences of different climate policies with respect to a business-as-usual (no policy) scenario. Authors' analysis based on data collected in Wieners et al. (2022). Red stands for reduced; inc. for increased; const. for constant and sub. for subsidy. Source: adapted from Lamperti and Roventini (2022).

	Emissions growth		Output growth		Financial Stability	Public deficit
Policy	**Energy**	**Industry**	**Short-run**	**Long-run**		
Const. low carbon tax (T)	mildly red.	unaffected	mildly red.	mildly red.	mildly inc.	mildly red.
Const. high carbon tax	strongly red.	red.	strongly red.	strongly red.	strongly red.	red.
DICE-like carbon tax	mildly red.	unaffected	strongly red.	strongly red.	strongly red.	red.
Sub. to green plants (C)	red.	unaffected	inc.	unaffected	mildly inc.	mildly inc.
Sub. to green R&D	mildly red.	unaffected	inc.	mildly inc.	unaffected	mildly inc.
Ban on fossil fuel use (B)	strongly red.	red.	mildly red.	unaffected	mildly red.	inc.
Electrification standard (E)	unaffected	strongly red.	strongly red.	red.	mildly red.	mildly inc.
B+E+C	strongly red.	strongly red.	mildly red.	unaffected	unaffected	inc.
B+E+C+T	strongly red.	strongly red.	mildly red.	unaffected	unaffected	unaffected

Figure 17: The effect of carbon taxes on climate stabilisation and the macroeconomy. 'DICE 2 deg' mimics a tax schedule having the same dynamics as in the DICE 2017 model; 'const, price-gap' is a constant tax (in real terms) that is sufficiently high to induce a transition by the end of century; 'const, 2 deg' is a constant tax (in real terms) that is sufficiently high to mitigate emissions and stabilise the climate in accordance with the Paris Agreement.



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