EEIST

NATIONAL DECARBONISATION PLAN CASE STUDIES

This document presents only the modelling case studies related to national decarbonisation plans 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 global energy transition, the power and industrial sectors, transport, agriculture, impacts of the transition and finance, go to https://eeist.co.uk/eeist-reports/new-economic-models-of-energy-innovation-and-transition/

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DECARBONISATION PLANS

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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CASE STUDY:

Economic Impacts of Net Zero in India by 2070

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Policy question: What are the macro-economic impacts of achieving net zero in India by 2070?

Region: India

Method: E3ME-FTT:Power

Key finding(s): (1) Solar energy becomes a dominant technology by 2070, covering a 57 per cent share of primary energy demand, which is enabled by the electrification of many end-use technologies, (2) a transition to a net-zero economy likely leads to net-positive macroeconomic impacts for India, where the GDP could grow by an additional US$ 840bn by 2070 compared to the baseline scenario, (3) the transition towards net zero will likely lead to a decimation of jobs in the fossil fuel-related sectors, with more than 2 million jobs at risk, and (4) will support job creation in other sectors such as the power generation, construction and services sectors.

Engagement: This case-study emerged and evolved from multiple engagement activities with Indian stakeholders organised by The Energy Research Institute (TERI) over the course of the EEIST timeline.

Summary: The authors use the E3ME-FTT:Power model to explore likely future power system configurations in India, with a special interest on the combination of policies in key energy intensive sectors to achieve net zero. The model uses self-reinforcing mechanisms of technology uptake and explores the combined impacts of a range of policies, including: (i) carbon price, (ii) energy efficiency investments, (iii) biofuel blending mandates, (iv) vehicles taxes and subsidies, (v) road tax, (vi) fuel tax, (vii) EV mandates, (viii) phase-out regulations on carbon-intensive processes, (ix) investment subsidies on low-carbon processes, (x) strategic power investments, and (xi) feed-in-tariffs.

Introduction

With a growing population,[209] economy and living standards,[210] and a high dependency both on coal and on energy imports,[211] India faces many challenges to achieve its pledge of achieving net-zero emissions by 2070. Substantial emissions could be released if future demand is met via today's supply chains using today's energy systems. Reducing these emissions would be necessary to limit global warming to well below 2°C. However, climate change mitigation does not have to be a net cost and can provide opportunities for some regions, and risks to others.[212] India is a net importer of fossil fuels and in a net-zero setting its energy trade balance is likely to improve. Furthermore, a transition to net zero invokes economic activity and leads to additional jobs, replacing jobs in the fossil fuel sectors (mainly coal supply). Models can provide insights on how India could potentially achieve net zero by 2070, either from a perspective of what a good combination of technologies might be or from a perspective of what the expected outcomes of policies are. A large-scale change such as this will prove a risk to some economic agents and an opportunity to others. Those employed in fossil fuel-related industries will likely lose their jobs (e.g. coal mining) or see the nature of their employment change (e.g. vehicle manufacturing).

In this case study, we investigate a decarbonisation scenario and compare the results to the baseline using E3ME-FTT. The baseline is aligned with a 'current policies scenario'. The net zero scenario that will be presented here is but one of virtually infinite pathways India's economy can potentially undergo to achieve net zero by 2070. A key feature of E3ME-FTT is that it is not an optimisation model that assumes that economies operate at (near) equilibrium with perfect allocation of resources. Often, spare capacity can be called upon to invoke change. This can come in the form of underutilised labour force, or additional investments being made available without crowding out investments elsewhere (e.g. through loans), among others. In addition, E3ME-FTT allows for a multitude of policies beyond carbon pricing. This makes it possible to test the effects of different combinations of policies, and see which approaches are most effective in reducing emissions and contributing to positive economic outcomes.

Table 11 shows an overview of the policies implemented to achieve net zero by 2070 in India, and similar policy packages are simulated for all other regions in the world. It is unlikely that any one country will commit to such a stringent policy package without other large economies also committing to similar targets. The policy package consists of carbon-penalising policies, such as carbon prices or phase-out regulations on energy-intensive technologies, and of low-carbon promotion policies, such as subsidies. This policy package has been developed on a trial-and-error basis, since E3ME-FTT is a simulation tool. Simulation does not guarantee the desired outcome; it only presents the likely outcome. An initial version of this policy package was developed to investigate stranded fossil fuel assets due to decarbonisation and extraction strategies.[213] While numerous variations of the presented policy package are possible, past endeavours have shown that essentially all policy levers need to be used to achieve a strict target such as net zero.

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[209] United Nations Department of Economic and Social Affairs, Population Division. (2022). World Population Prospects 2022: Summary of Results.

[210] OECD. (2023). Real GDP long-term forecast (indicator). doi: 10.1787/d927bc18-en (Accessed on 06 January 2023)

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[212] Mercure, J. F., et al. (2021). Reframing Incentives For Climate Policy Action. Nature Energy, 6(12): 1133-1143.

[213] Mercure, J. F., et al. (2021). Reframing Incentives for Climate Policy Action. Nature Energy, 6(12): 1133-1143.

Table 11: List of policies implemented to simulate net zero by 2070 in India.

Sector(s)	Policy	Policy details
Multiple	Carbon price	Starts at US$40/tCO2 in 2024 and increases to US$325 $/tCO2 in 2070 (2022 values).
	Energy efficiency investments	Sector-specific reduction in final energy demand.
	Biofuel blending mandate	Blending e.g. bioethanol with petrol. Affects all oil-based transport applications.
Road transport	Vehicle tax	Increased registration tax on ICE vehicles from 2024 onwards.
	Vehicle subsidy	Subsidies on the purchase price of EVs from 2024 onwards.
	Road tax	Increased road tax on ICE vehicles from 2024 onwards.
	Fuel tax	Increased fuel tax on oil products from 2024 onwards.
	Phase-out regulation	Ban of ICE vehicle sales. Inefficient (older) ICE models are banned in 2024. More efficient ICE models are banned in 2040.
	EV mandate	Force manufacturers to offer a certain minimum number of EVs in their portfolio.
Power generation	Investment subsidy	From 2024 onwards, a 20 per cent subsidy on nuclear power, a 50 per cent subsidy on CCS applications and a 60 per cent subsidy on BECCS is applied.
	Phase-out regulation	Coal power is gradually phased out by 2060. Other unabated fossil-fuelled power generation is not allowed to increase from 2028 onwards.
	Strategic public investment	Strategic investments in BECCS between 2024 and 2026 to seed the system.
	Feed-in tariff	Feed-in-tariffs on wind power from 2024 to 2036 with a full phase-out by 2046.
Residential heating	Phase-out regulation	Ban on sales of fossil-fuelled domestic heating systems from 2024 onwards.
	Fuel tax	A fuel tax in line with carbon taxes.
	Investment subsidies	Subsidies on heat pumps and solar thermal from 2024 onwards.
Steelmaking	Investment subsidies	From 2024 onwards, a 10 per cent subsidy on upfront investment of CCS applications and a 50 per cent subsidy on other primary low-carbon technologies is applied.
	Energy subsidies	Hydrogen (50 per cent) and electricity (25 per cent) use are subsidised from 2024 to 2046, followed by a gradual phase-out by 2057.
	Strategic public investment	Strategic investments in hydrogen-based steelmaking from 2024 to 2032, and in electrolysis methods from 2035 to 2039 to seed the system.
Land use	Mitigation of land-use emissions (assumption-based)	Mitigation of land-use emissions include reduced emissions from agriculture, reforestation, afforestation and other land-use based measures.

Description of E3ME-FTT

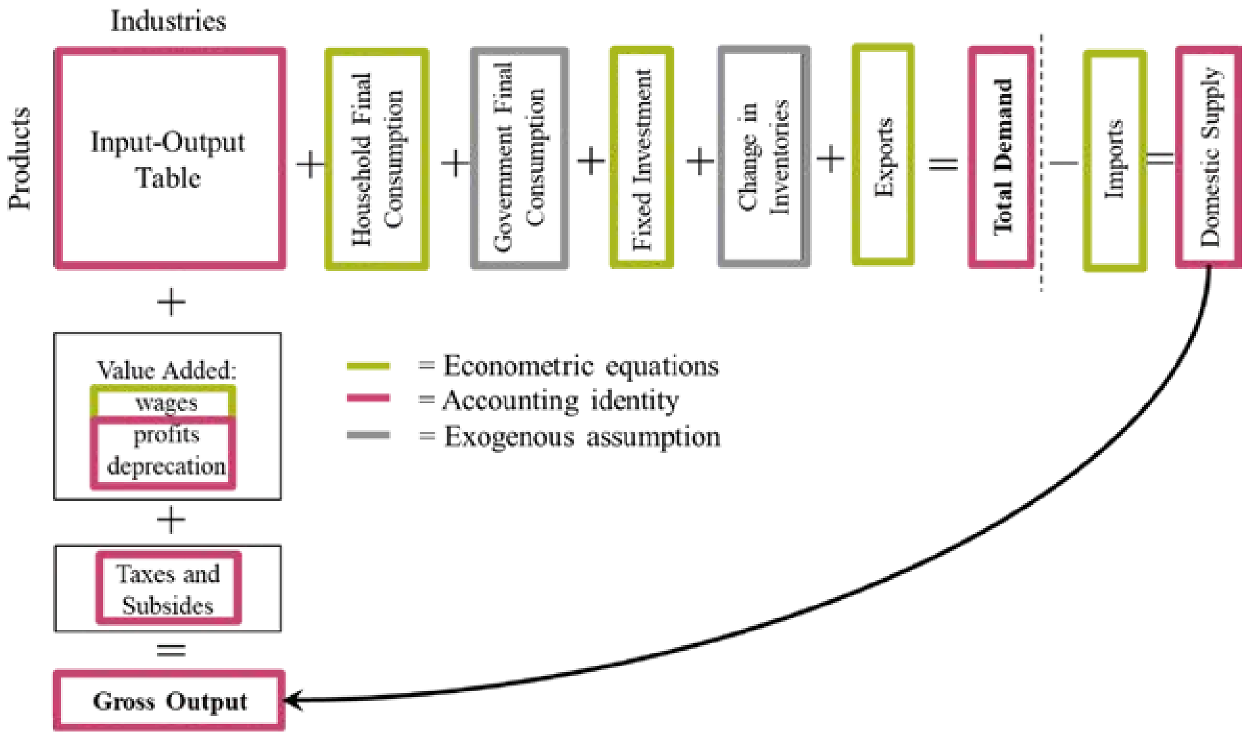
Description of E3ME
E3ME is a computer-based model of the world's economic and energy systems and the environment. Economic activity undertaken by persons, households, businesses and other groups in society has effects on other groups (possibly after a time lag) and these effects may persist into future generations. But there are many actors and the effects, both beneficial and damaging, accumulate in economic and physical stocks. A detailed description can be found on the Cambridge Econometrics website.[214]

The effects of economic transactions by economic agents are transmitted through the environment, the economy and the price and money system (via the markets for labour and commodities), as well as through global transport and information networks. The markets transmit effects in three main ways: 1) through the level of activity creating demand for inputs of materials, fuels and labour; 2) through wages and prices affecting incomes; and 3) through incomes, leading in turn to further demands for goods and services. These interdependencies suggest that an E3 model should be comprehensive and include many linkages between different parts of the economic and energy systems. Hence why E3ME was designed with a high geographical and sectoral resolution.

E3ME-FTT is a global model of 71 regions, with major economies represented individually, and distinguishes 70 economic sectors in European countries and 44 in non-European countries. E3ME is a demand-led macro-econometric model. It determines the components of demand using time-series econometrics to solve components of final demand and various other indicators. See Figure 71. The econometric parameters represent past and current behaviour in response to shocks.

The energy domain is also determined by econometric relationships and builds on some of the accounting identities displayed above, but also includes responses to endogenous innovation and energy prices. The wholesale part of non-renewable energy prices is formed via a cost-supply curve approach, which integrates an uncertainty parameter. Tax brackets are then added on top.

Figure 71: National accounts structure of E3ME.



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[214] Cambridge Econometrics (2022). E3ME Model Manual. Available at: https://www.e3me.com/what/e3me/

The role of technology in the E3ME-FTT model
Understanding why and how economic agents pick technologies is important in questions surrounding decarbonisation of the economy. Time series econometric equations require a long track of history in order to simulate the future. For novel technologies, such history does not exist and therefore econometric equations are not entirely suitable to address technology-induced transitions. This is where Future Technology Transformations (FTT) comes into play. FTT is a suite of models integrated with E3ME that describes technology decision making in the most emission and energy-intensive industries, such as power generation,[215] iron and steel,[216] household heating[217] and passenger vehicles.[218] It is based on the understanding of evolutionary economics that socio-technical regimes (why something is done the way it is done) change due to internal (e.g. innovation) and external (e.g. shortages or policies) pressures, and such change is often irreversible and non-marginal. FTT incorporates uncertainty in its input parameters which represents the heterogeneous character of economic agents as well as fundamental uncertainty.

FTT determines the technology configuration to meet the demand, which is determined elsewhere in E3ME-FTT. The core builds on the Lotka-Volterra replicator function, which compares all technologies on a pair-wise basis and takes investor preferences (determined as a binary logit), technology substitution frequencies and market shares of the previous year as inputs to determine market shares of the current year.[219] It includes positive feedbacks such as learning-by-doing based on global cumulative technology capacity additions, and negative feedbacks due to sectoral constraints, such as VRE deployment in the power sector leading to supply-demand mismatches or scrap availability being limited for recycling in the iron and steel sector.

How does E3ME differ from other models?
E3ME is often compared to Computable General Equilibrium (CGE) or Discrete Stochastic General Equilibrium (DSGE) models.[220] [221] In many ways the modelling approaches are similar; they are used to answer similar questions and use similar inputs and outputs. However, underlying this are important theoretical differences between the modelling approaches. Models like E3ME build upon data and try to infer economic relationships from that. Most other macro-economic or integrated assessment models (IAMs) try to build upon micro foundations and theory.

In a typical CGE or DSGE framework, optimising behaviour is assumed, output is determined by supply-side constraints and prices adjust fully so that all the available capacity is used. In E3ME the determination of output comes from the demand side of the economy and it is possible to have spare economic capacity. It is not assumed that prices always adjust to market-clearing levels.

The differences have important practical implications because they mean that, in E3ME, regulation and other policies could potentially lead to increases in output, if they are able to draw upon the available spare economic capacity. The role of the financial sector is key.

The role of finance
E3ME is a Post-Keynesian model and within this school of thought money is endogenous – i.e. it can be created by banks through, for example, lending. This approach differs from that in many other models where the supply of money is fixed.[222] A fixed supply of money implies full crowding out, whereas an endogenous supply of money does not per se imply full crowding out. E3ME is agnostic on finance. The model tracks the investment needs of a given sector as a result of the econometric relationships or the FTT outcomes, but it does not provide information on whether the demanded finance is accessible.

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[215] Mercure, J. F. (2012). FTT:Power: A Global Model of the Power Sector with Induced Technological Change and Natural Resource Depletion. Energy Policy 48: 799-811.

[216] Vercoulen, P., et al. (2018). Decarbonizing the East Asian steel industry in 2050. Meijo University Discussion Paper #0008.

[217] Knobloch, F. et al. (2021). FTT: Heat – A Simulation Model for Technological Change in the European Residential Heating Sector. Energy Policy 153: 112249.

[218] Lam, A and Mercure, J-F. (2015). The Effectiveness of Policy on Consumer Choices for Private Road Passenger Transport Emissions Reductions in Six Major Economies. Environmental Research Letters, 10(6): 064008.

[219] Mercure, J. F. (2015). An Age Structured Demographic Theory of Technological Change. Journal of Evolutionary Economics, 25(4): 787-820.

[220] Mercure, J. F., et al. (2019). Modelling Innovation and The Macroeconomics of Low-Carbon Transitions: Theory, Perspectives and Practical Use. Climate Policy, 19(8): 1019-1037.

[221] Lefevre, J., et al. (2022). Global Socio-Economic and Climate Change Mitigation Scenarios Through the Lens of Structural Change. Global Environmental Change 74: 102510.

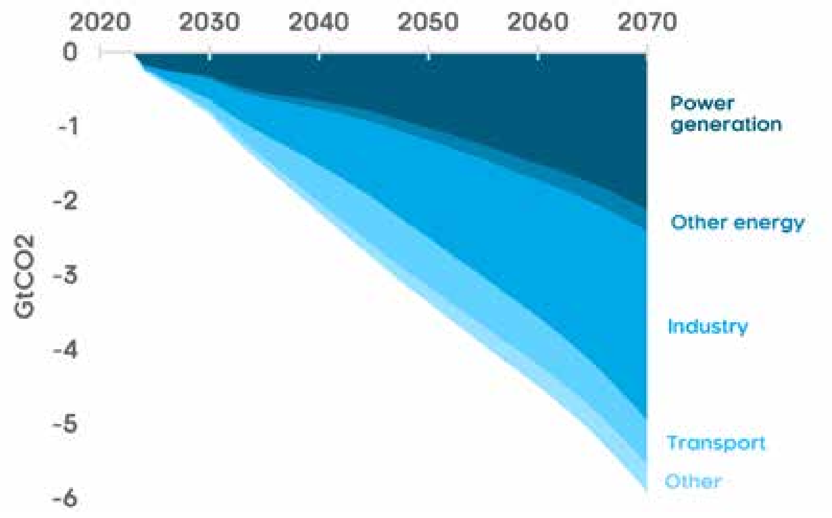
[222] Mercure, J-F and Pollitt, H. (2018). The Role of Money and the Financial Sector in Energy-Economy Models Used for Assessing Climate and Energy Policy. Climate Policy, 18(2): 184-197.

Results

CO2 emissions

Comparing the net zero scenario to the reference scenario (in line with current policies), a reduction of 5.9 Gt CO2 of energy and process-related emissions was found by 2070, amounting to a cumulative reduction in emissions of 141 Gt CO2 between 2020 and 2070. In percentage terms, this is a reduction of 91 per cent compared to the baseline, which leaves a residual of 0.5 Gt CO2 annual emissions by 2070, which is assumed to be offset via mitigation of land-use emissions (see Figure 72). Most of the reductions are achieved in power generation and industry, with smaller contributions from the transport and household sectors. The former two sectors rely on to a substantial degree on fossil fuels in the baseline scenario, which is removed due to technology switching as a result of the policy package. While the net zero scenario features an almost complete decarbonisation of the road transport sector by 2050, the baseline also features a more partial decarbonisation, particularly from 2045. The differences in CO2 outcomes between the net zero scenario and the base case are therefore somewhat limited in the transport sector. The household sector is almost completely decarbonised in the net zero scenario by 2070. But household emission levels are low in the baseline as well, as the majority of households switch from biofuel-based heating to low-carbon alternatives. In the net zero scenario, a portion of heating based on liquid petroleum gas (LPG) is replaced by clean technologies, contributing a small reduction in CO2 emissions.

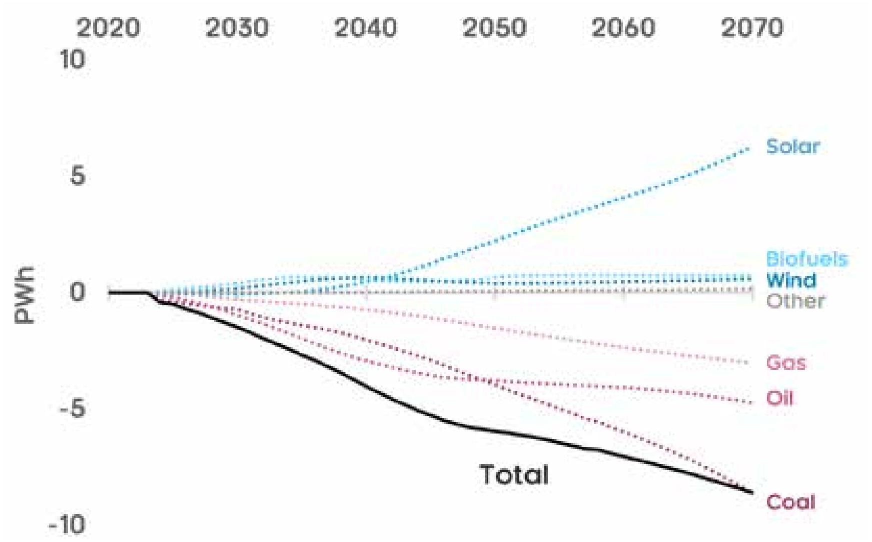
Figure 72: Energy and process-related CO$_2$ emissions, absolute differences from baseline, 2020-2070, GtCO$_2$.



Primary energy demand

The policy package removes most of the reliance on fossil fuels and this is illustrated by the changes in primary energy demand between the net zero scenario and the baseline (see Figure 73). Total primary energy demand falls by 8.6 PWh relative to the baseline by 2070 (a 24 per cent decrease), as businesses and consumers invest in energy efficiency measures, and switch to more energy-efficient technologies (such as electric vehicles). Coal- and oil-based primary energy production is replaced mostly by solar power, which is enabled by the electrification of many end-use technologies. This includes electrification of the road transport sector, with oil use from internal combustion engine vehicles mostly disappearing by 2050. Strong declines in oil use are also seen in the power generation and industrial sectors. Coal use sees strong declines across a range of heavy industries, including power generation, steelmaking and non-metallic minerals. Declines in gas demand are driven through reduced uptake of LPG as an energy source in households, as well as lower use of natural gas in industrial applications. Solar energy becomes a dominant technology by 2070, with a 57 per cent share of primary energy demand. Much remaining fossil fuel demand is for non-energy use, or for applications with carbon capture technology built in.

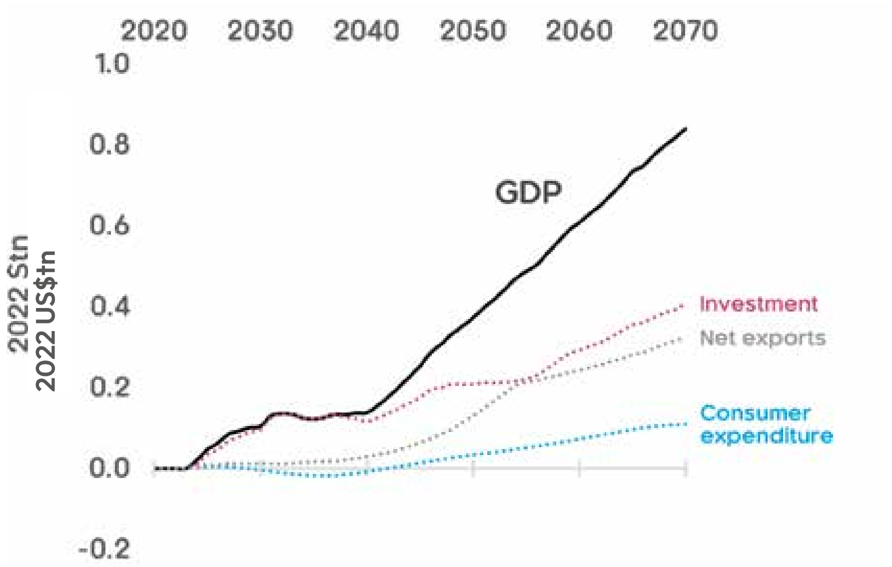
Figure 73: Primary energy demand by carrier, absolute differences from baseline, 2020-2070, PWh.



GDP and components

Our modelling suggests that a transition to a net-zero economy likely leads to net-positive macroeconomic impacts for India. GDP could grow by an additional US$840bn by 2070 compared to the baseline (see Figure 74). This represents a 2.5 per cent increase. Much of this additional demand is driven by investments in low-carbon technologies and energy-efficiency measures, which creates economic activity in construction and electrical engineering, and which dominates between 2024 and 2040. Afterwards, there is also a substantial gain from the reshoring of energy production. As various energy users switch to electrical technologies, output in the domestic power-generation sector increases substantially, leading to a lower reliance on imported fossil fuels, which improves the trade balance. A smaller impact can be seen from the effect of the transition on consumer expenditure. Employment gains from increased output in a number of sectors (see below) contribute to an increase in real incomes and consumption. Similarly, households apply more efficient technologies, which reduces energy bills and unlocks spending in other goods and services.

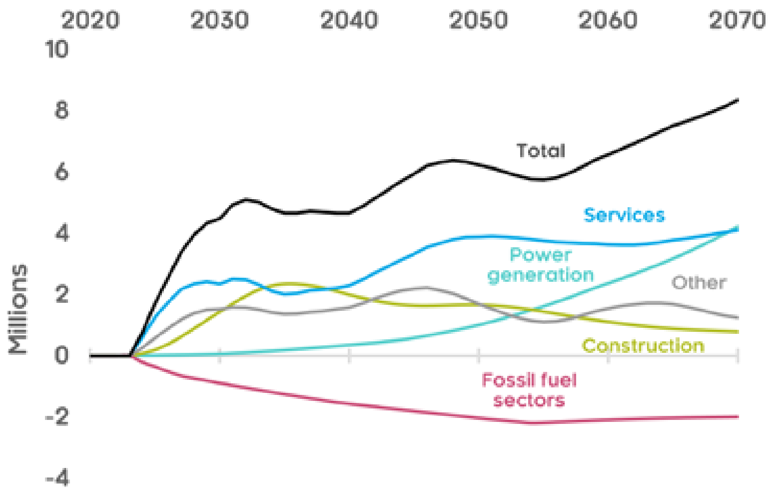
Figure 74: GDP and components, absolute differences from baseline, 2020-2070, 2022 US$tn.



Employment

While the GDP results indicate mostly positive impacts, the simulations do show that not everyone stands to gain. A transition away from fossil fuels – particularly coal – will likely lead to a decimation of jobs in the fossil fuel-related sectors, including extractive and refining sectors. More than 2 million jobs are at risk. These jobs could be at risk due to automation regardless of mitigation policies, as might be the case for China.[223] However, these job losses are compensated by job creation in other sectors. Much of this employment would be concentrated in the power-generation sector, as energy production is reshored into India's economy. There is also a strong boost to employment in construction, particularly in the early and middle part of the scenario period, as the building and renovation work required to deliver the transition gets underway. Increasing employment in these sectors boosts incomes of consumers, and their additional consumption is concentrated on services sectors, which then also see output and employment increase. Overall, our modelling results suggest that India's aggregate employment would see an 8.4m boost by 2070 as a result of the clean energy transition – a 1.6 per cent increase on baseline levels.

Figure 75: Job, absolute differences from baseline, 2022-2070, millions.



Discussion and conclusion

First and foremost, no single model tells a complete picture. A few important aspects are missing in these simulations. First, skills are not tracked and therefore it is implied that jobs are interchangeable. This will unlikely be the case, and reskilling of those that lose their job in fossil fuel-related jobs would be necessary. Second, the supply of money is endogenous in E3ME-FTT. However, it is agnostic on the source of investments (e.g. loans, foreign investment, accumulated savings or wealth, etc). Here, the investments to facilitate this transition are assumed to be available. Therefore, the additional investments shown in the net zero scenario should be interpreted as the investments needed to achieve the transition described above. Third, increased carbon sequestration or reduced emissions from land use is assumed. At the moment, the model does not include a representation of land use. Fourth, climate and pollution damages are not accounted for in any scenario. The likely reduction in climate and pollution damages provide another benefit to decarbonisation that is often overlooked, and – admittedly – difficult to estimate.

Despite these model limitations, we deem it to be likely that many opportunities lie ahead for India on the road to net zero by 2070. The transition provides opportunities of improving India's energy security position, a more efficient energy supply system overall, large-scale net job creation, and – most importantly – large-scale reduction in emissions. It is important to note that the rest of the world also enacts policies to decarbonise, which contributes to making low-carbon technologies more accessible due to a global push.

In this representation of net zero, we found that important technology transitions are found in the power sector towards solar PV, onshore wind power and some bio-based power generation. Road transportation transitions to electric power trains, and domestic heating switches away from biobased and LPG-consuming units to solar thermal and various electric forms of heating. In the iron and steel industry, we find a large-scale transition to steel recycling and hydrogen-based steelmaking. All these transitions lead to supply-side efficiency gains, leading to a reduction in primary energy demand.

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[223] Clark, A. and Zhang, W. (2022). Estimating the Employment and Fiscal Consequences of Thermal Coal Phase-Out in China. Energies 15(3): 800. https://doi.org/10.3390/en15030800 (Note, this work is presented in this report in the case study on the coal transition in China).

CASE STUDY:

Decarbonising the Indian Economy: Policies and impacts

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Policy question: What are the most impactful policy combinations to decarbonise the Indian economy over the next three decades? What are the likely implications of enacting these policies on economic growth and employment?

Region: India

Method: System dynamics model

Key finding(s): Decarbonisation of the Indian economy is possible by focusing a range of policies on decarbonising the power, transport and industrial sectors, while creating net savings in costs and achieving better economic growth and employment outcomes.

Engagement: The decarbonisation scenario underlying this case study has been developed and refined in consultation with sectoral experts from industry, think tanks, academia, funding partners and a few members of the policymaking community. Key findings and insights from the analysis have been presented and discussed at platforms including the research collaborative for a proposed Global Climate Alliance (GCA)[224] and working groups set up by the Indian Ministry of Road Transport and Highways and the National Insititute for Transforming India (NITI Aayog) under the India Climate and Energy Modelling Forum (ICEMF).[225]

Summary: The authors use a system dynamics model to consider what policy combinations might be needed to decarbonise the Indian economy, and what the impacts of these might be on growth and employment. The authors suggest the model allows a more realistic representation of the interaction between policies and the economy, and they find that decarbonisation of the Indian economy is possible while creating net savings in costs and achieving better economic growth and employment outcomes.

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[224] The Global Climate Alliance (GCA) Collaborative is an independent research effort to evaluate how Global South countries can best secure the support of Global North countries to address the economy-wide impacts of climate change, including both adaptation and mitigation measures. Over the past two years, several academic institutions and think tanks have been collaborating on these issues and pooling their individual research efforts.

[225] India Climate and Energy Modelling Forum (ICEMF) is a platform for leading energy experts, think tanks, researchers, modellers and policymakers to collaborate and examine important climate, energy and environment-related issues, including their economic linkages, through integrated modelling exercises.

Introduction

India announced its goal to reach net zero emissions by 2070 at the 26th Conference of Parties (COP-26) in November 2021.[226] Charting a low-carbon development pathway for the country that meets the aspirations of its people, such as reliable access to adequate energy, will require a deep structural transformation of the Indian economy, which relies on fossil fuels for around three-fourths of its total energy needs at present.[227]

To design effective policy packages that meet India's decarbonisation and development objectives, an evaluation of the different policy options in isolation is not sufficient; it also requires policymakers to understand the potential relationships between policy options across different sectors and the economy, and how such interactions affect the achievement of policy objectives.

Analytical framework

The India Energy Policy Simulator (EPS),[228] an open-source, systems dynamics (SD) model, can provide such insight to inform policymaking by enabling an integrated assessment of cross-sectoral climate policy packages for India through 2050, along with their macroeconomic implications.

The policy options in the EPS span the main sectors of the economy: transportation, buildings, electricity supply, industry (including agriculture, waste, and wastewater), land use and hydrogen. Policy options included cover both pricing policies (e.g. taxes and subsidies) as well as mandates (e.g. for technology adoption or retirement). The structure, modelling approach, underlying data sources and assumptions of the India EPS are explained in a technical note available online.[229]

The main strengths of the modelling approach of the EPS, compared to those that have been used for climate policy analysis in India so far, include the following:

- The SD approach of the EPS can offer a more realistic representation of the dynamic interaction between policies and the economy compared to existing modelling approaches (most use a computational general equilibrium or partial equilibrium approach), giving rise to overall effects that are different from the sum of the effects of enacting individual policies. For example, the EPS calculates technology costs based on a combination of projected global prices and endogenous learning to account for the effects of local technology diffusion. This means a mandate or a subsidy to promote the uptake of a technology can create a reinforcing loop, whereby increased uptake of a technology due to a policy further brings down technology prices, which in turn accelerates its uptake.
- The cross-sectoral policy analysis enabled by the economy-wide coverage of the EPS can enable users to discover synergies and trade-offs in policy implementation across different sectors. For example, policies to decarbonise electricity supply failing to keep pace with end-use electrification policies preclude the latter from achieving their mitigation potential, and in extreme cases can result in an emissions penalty.
- The EPS includes an integrated input-output model, which calculates the impact of climate policies enacted in a scenario on macroeconomic parameters, such as GDP, employment and government accounts, considering direct, indirect and induced economic effects of the enacted policies. These are not outputs typically available in models presently used for climate policy analysis in India, and literature on the potential macroeconomic implications of climate action in India is limited. However, this is a particularly relevant component of analysis for Indian policymakers, for whom economic development is a key policy objective.

Some of the main limitations of the EPS are as follows:

- It simulates policies at an aggregate spatial (national) and temporal (annual) scale. Model outputs are available at an aggregate level and do not allow for the assessment of how effects of enacted policies – for example impacts on jobs and GDP – are distributed across regions or population groups, such as by income, gender or age.
- Indirect and induced economic impacts in the model are calculated based on transaction relationships between industries in the economy per India's input-output (I/O) tables as of 2015, which are assumed to hold over time.
- It is presently not possible to quantify the uncertainty in the model.

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[226] https://pib.gov.in/PressReleasePage.aspx?PRID=1768712

[227] https://www.iea.org/reports/india-energy-outlook-2021/energy-in-india-today

[228] https://india.energypolicy.solutions/scenarios/home

[229] https://www.wri.org/research/tool-designing-policy-packages-indias-climate-targets

Our analysis

We used the India EPS to analyse a policy package focusing on the power, industry and transport sectors, which would put India on course to reach net-zero CO2 emissions by 2070. Our policy package, henceforth referred to as the Long-term Decarbonisation (LTD) Scenario, builds upon existing policy targets for renewable energy, energy efficiency and electric mobility in the short term and considers the policy-supported phase-in of currently nascent technologies, such as hydrogen and battery storage, in the medium-term, to reach ambitious levels of implementation by 2050. The choice of the policies modelled in this scenario is guided by three main criteria: a) their alignment with current policies and targets in India and the emerging conversation around policies to support new green technologies like hydrogen, b) the relative effectiveness of a policy (when compared to other policy options available in the model) in contributing to greenhouse gas emissions abatement, and c) their impact on macroeconomic indicators – i.e., government accounts, GDP and jobs.

We present our results relative to a Reference Scenario, which incorporates the impact of existing policies, as of 2019.

The level of ambition for the policy settings and the rate of policy implementation in the LTD scenario is decided based on a combination of factors, including the existing level of achievement in the Reference Scenario, review of literature to identify the technical potential achievable for the technologies modelled within the policies, and preliminary consultations with sectoral experts on policy feasibility, given on-the-ground implementation challenges in India.

Our approach is to construct a forward-looking, or ‘what-if’, scenario aimed at evaluating the plausible outcomes of a given set of policy actions, rather than providing a set of ‘optimal’ policy actions. There are several alternative combinations of actions that may reach the same level of emissions in future, each with their own implications for other outputs such as costs, social benefits and economic impacts.

The specific questions of policy interest for our analysis were the following:

- What are the most impactful policies/policy combinations to decarbonise the Indian economy over the next three decades?
- What are the likely implications of enacting these policies for investment, economic growth and employment?

Results

The Reference Scenario sees India’s total emissions approximately double over the next three decades – emissions rise from just over 3 billion tonnes of carbon dioxide equivalent (BtCO2e) in 2022 to around 6 BtCO2e in 2050. Emissions rise despite a 61 per cent improvement in emissions per unit of GDP over this period, driven by economic growth and urbanisation.

The fastest growth in emissions is seen in the industrial and transport sectors – emissions approximately triple by 2050 compared to the present in both sectors. Power sector emissions, in contrast, do not increase significantly from present levels, owing to India’s renewable energy targets and falling technology costs, which are considered within the Reference Scenario. In 2050, the industrial sector comprises almost 50 per cent of the total emissions, followed by power (18 per cent) and transport (16 per cent).

Key policy levers for decarbonisation
Policies in the LTD scenario are primarily focused on decarbonising three sectors – namely, the industry and transport sectors, because of the rapid growth in emissions in the Reference Scenario, and the power sector, because green electricity is a prerequisite for the success of end-use electrification policies and green hydrogen production.

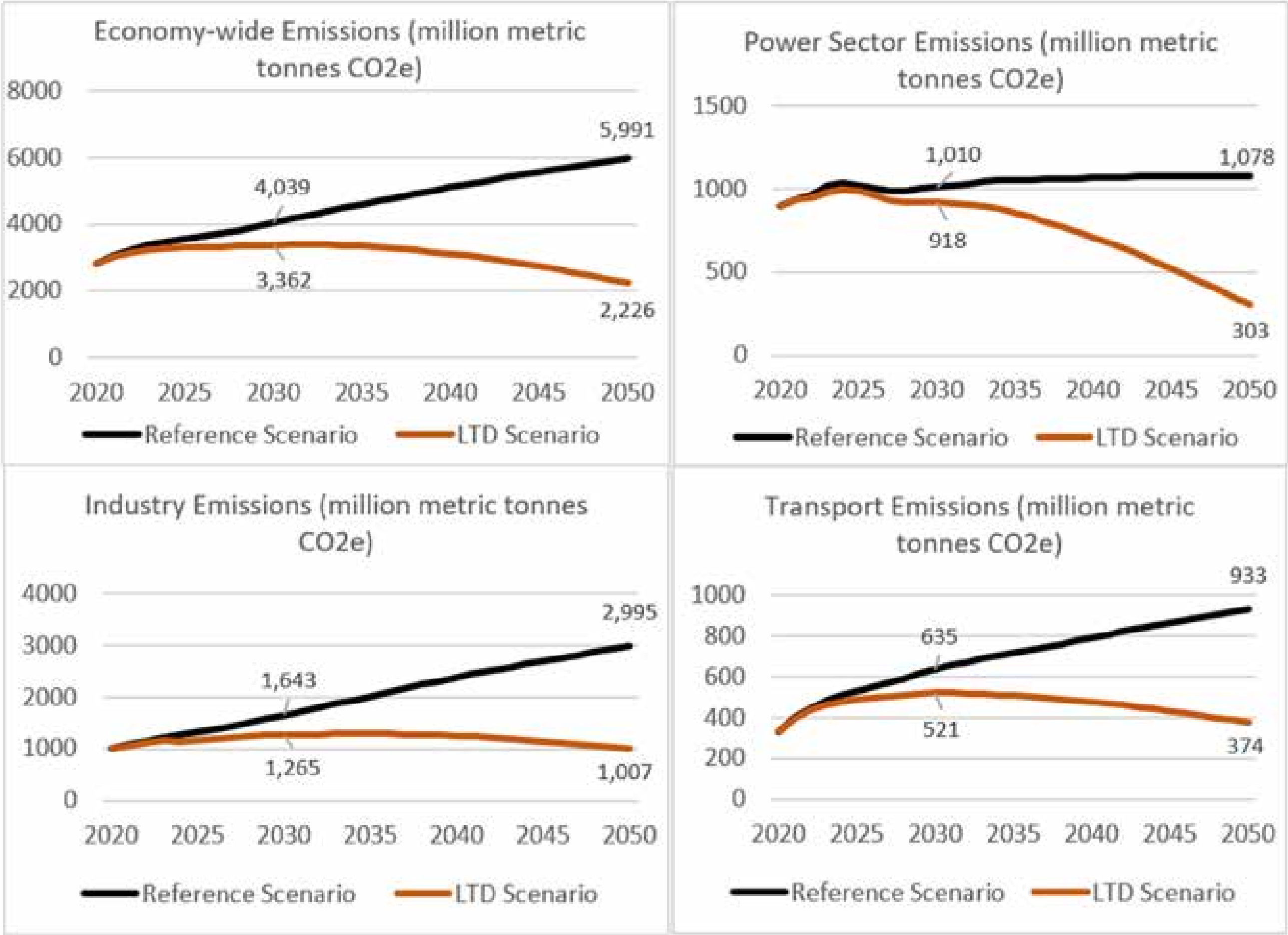
Policies (and their level of ambition) are chosen by applying the criteria mentioned in the previous section. For example, the mandates for clean electricity generation and electric vehicle adoption build on existing policy targets for renewable energy and electric mobility. Mandates for electrification and hydrogen adoption in the industry are chosen due to the high emissions abatement potential of underlying technologies, based on preliminary consultations with sectoral experts. A carbon tax is primarily chosen as a means to raise public revenue during the transition, although it also plays a complementary role in supporting decarbonisation mandates. The key policy assumptions of the LTD scenario are summarised in Table 12.

Table 12: Key policy levers in the LTD Scenario. *Unless otherwise noted, the policy is linearly implemented starting from 2020 to reach the full policy setting in 2050.

Policy	Reference Scenario (2050)	LTD Scenario (2050)*
Industrial electrification & hydrogen mandate (% Substitution of fossil fuels in industrial sector. Linearly increasing from 0 in 2030)	0	50%
Hydrogen production via electrolysis mandate (Linearly increasing from 0 in 2025)	0	100%
Carbon tax (per tonne of CO2e) (In the power and industry sectors)	0	INR 3500 (USD 50)
EV/hydrogen sales mandate (% of new vehicle sales) Passenger LDV, Passenger HDV Freight LDV, Freight HDV 2W, 3W (H2V sales mandate starting from 2030)	35%, 23% 14%, 4% 38%, 30%	80%, 50% (+25% H2V) 70%, 25% (+45% H2V) 100%, 100%
Material efficiency mandate (Demand reduction for emissions intensive goods w.r.t. Reference Scenario)	-	Cement: 15% Iron & steel: 20%
Carbon-free electricity generation mandate (mandated minimum %)	68%	93% (75%)
Early retirement mandate for coal power (linearly increasing from 300MW/year in 2027)	-	7 GW/year

The policies in the LTD scenario reduce Reference Scenario emissions by about a fifth in 2030 and two-thirds in 2050. In cumulative terms, the emissions reduced over the period 2020-2050 relative to the Reference Scenario amount to just over 46 BtCO2e. Figure 76 shows the economy-wide and sectoral emissions trajectories for the two scenarios over this period.

Figure 76: Comparison of greenhouse gas emissions in Reference and LTD scenarios.



In the power sector, the proportion of carbon-free electricity generation reaches close to 50 per cent by 2030 and over 90 per cent by 2050 (compared to slightly less than 25 per cent at present) because of mandates for carbon-free electricity generation and early retirement of coal power. The reduction in the cost of renewable energy (RE) due to technology diffusion, initially a result of these mandates, in turn drives further RE capacity addition, which further reduces costs. Thus, a positive reinforcing effect is created for RE technology uptake, and the carbon-free electricity generation exceeds the policy mandated requirement over time. This is complemented by a carbon tax, which makes fossil-fuel based electricity more expensive at the same time. Coupled with the increasing cost-competitiveness of RE relative to fossil fuels, power sector policies together result in no new coal capacity additions after 2024.

The rapid decarbonisation of the power sector supports mandates for fossil fuel substitution with electricity and/or green hydrogen in the industry and transport sectors in achieving their emissions mitigation potential. These fuel-switching mandates, phased in from 2025 or 2030, serve as the main policy levers for decarbonising the industry and transport sectors in the long term, while energy-efficiency policies play a role in the short term. These mandates are complemented by the carbon tax, like in the power sector. However, unlike in the power sector, this policy combination does not achieve a cost tipping point in the industry and transport sectors due to a more gradual implementation of the mandates and a greater difference in brown and green technology costs in these sectors. Nevertheless, significantly higher shares of electricity and hydrogen are achieved in the overall industrial and transport energy mix as a result of these policies, compared to the Reference Scenario (see Table 13).

Table 13: Share of electricity and hydrogen in industrial and transport energy mix over time.

	Industrial Energy Mix				**Transport Energy Mix**			
	Share of Electricity		**Share of Hydrogen**		**Share of Electricity**		**Share of Hydrogen**	
Year	Reference Scenario	LTD Scenario	Reference Scenario	LTD Scenario	Reference Scenario	LTD Scenario	Reference Scenario	LTD Scenario
Present	13%		0%		1.5%		0%	
2030	16%	20%	0%	2%	3%	6%	0%	0%
2050	16%	40%	0%	18%	9%	29%	0%	7%

Economic outcomes

We find that long-term decarbonisation of the Indian economy is possible while creating net cost savings across the economy over time, and achieving better economic growth and employment outcomes, relative to the Reference Scenario.

The transition to green technologies requires additional capital expenditure over the Reference Scenario. The additional annual capital expenditure amounts to around US$28bn (2018) (~0.5 per cent of GDP) in 2030, and rises constantly thereafter as RE infrastructure, EVs, battery storage and green hydrogen production is ramped up, to reach US$247bn (~1.5 per cent of GDP) in 2050. While the scale of upfront capital investments can present challenges in terms of financing, we see that the reduction in fuel and operations and maintenance costs across the economy from the uptake of green technologies outweighs the upfront capital costs over time, creating net savings in the long run starting in the decade of the 2040s.

The transition away from fossil fuels results in a contraction of brown sectors such as coal mining, petroleum refining and manufacturing for internal combustion engine vehicles. Moreover, a reduction in the use of petroleum products, which contribute over 25 per cent of the central government's total tax revenue at present, can significantly dent overall tax collection and aggravate the economic contraction by constraining government spending. Government spending on basic services such as education and healthcare has a multiplier effect on economic growth by improving productivity. However, we find a carbon tax (increased in a phased manner over time) has the potential to offset the loss in petroleum taxes during the transition by widening the tax base to all emissions-causing uses of fossil fuels, including industrial process emissions.

Productive public expenditure sustained by carbon tax revenues, together with growth in industries like clean electricity generation and hydrogen production, more than compensates for the contraction in brown sectors in the LTD scenario. Overall, the policy package in the LTD scenario delivers a GDP that is 2.3 per cent higher and generates 3.4 million more jobs by 2050, relative to the Reference Scenario.[230] The drivers for economic growth and employment are supply-side effects – while the overall demand for energy and materials reduces as a result of efficiency improvements, investments to decarbonise supply (along with associated indirect and induced effects) drive growth.[231] Figure 2 shows the macroeconomic outcomes of the LTD scenario relative to the Reference Scenario.

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[230] These include direct jobs (created due to enacted climate policies) and indirect jobs (created within industries that supply to directly affected industries). The agriculture sector is excluded from the jobs estimates presented here.

[231] Indirect effects refer to changes in output or employment of sectors that supply the sector directly affected by a policy. Induced effects are created by changes in re-spending of money by workers or government in the economy as a result of direct and indirect effects.

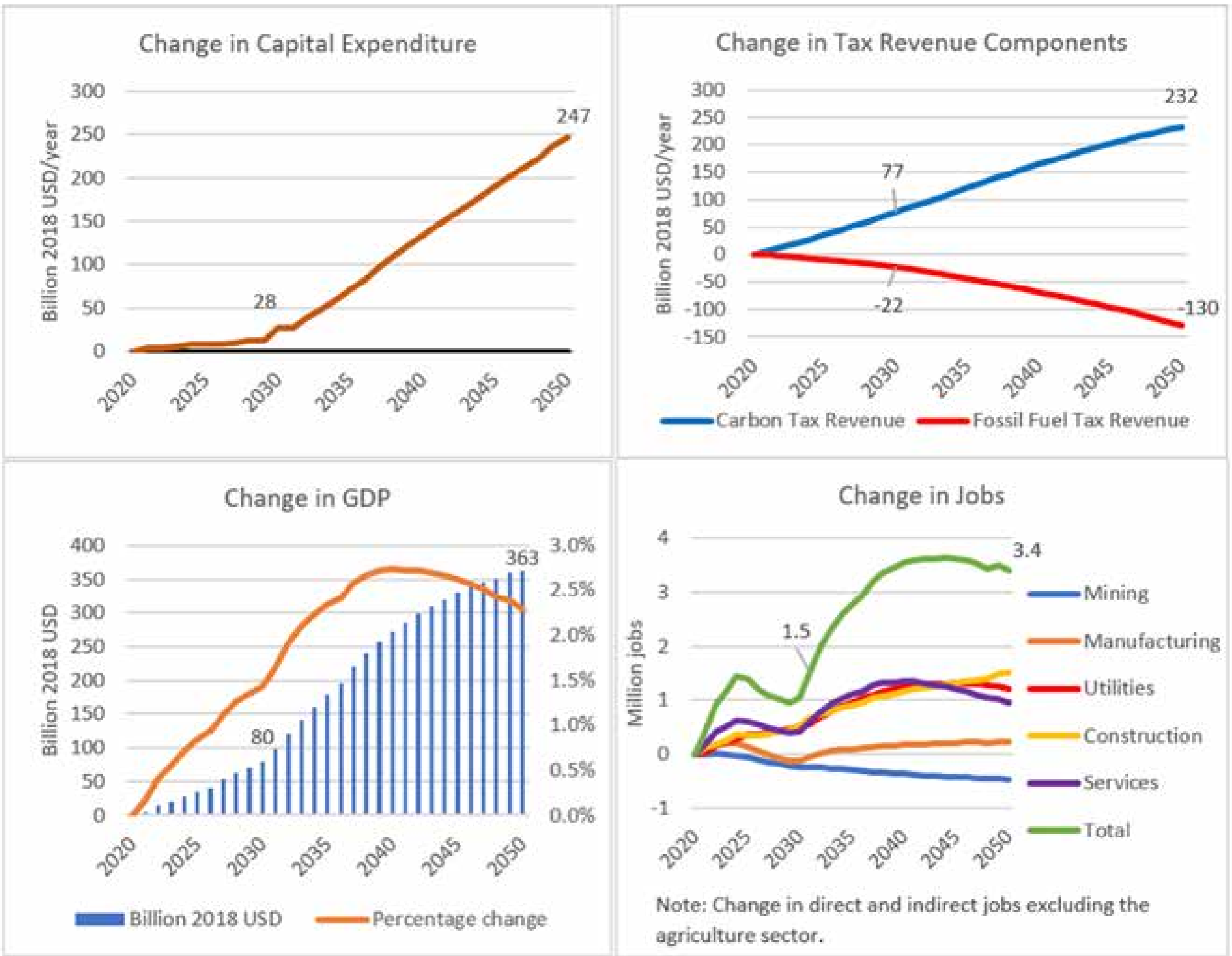

Figure 77: Macroeconomic outcomes in the LTD Scenario, relative to the Reference Scenario.

Note: Change in direct and indirect jobs excluding the agriculture sector.

Conclusion

Our policy package in the LTD Scenario primarily relies on early policy signals (e.g. mandates for renewable energy, electric mobility, and industrial fuels) to spur private investment in green technologies and, in turn, the reinforcing effect of falling technology costs from their uptake to accelerate further green technology adoption. A carbon tax serves as a complementary policy in this context by further reducing the cost of using green technologies relative to brown ones. In our policy package, the carbon tax also serves to offset the loss in public revenue from declining petroleum tax collections, thereby mitigating the negative impact on economic activity due to a cut in productive government spending. However, a carbon pricing policy can have a significant effect on essential commodity prices in the short run and be ineffective as a tool to raise public revenue in the long run, as fossil fuel use is eliminated from the economy. This underscores the need for careful design, including an evaluation of alternative sources of public revenue.

There are several policy types which we have not explored or have not been able to explore in our policy package, which can be critical for policymakers to evaluate and consider as India moves towards a low-carbon future. While we do not rely on subsidies in our policy package due to their implication for government accounts, technology-specific subsidies can serve as an important complementary policy in accelerating the adoption of nascent green technologies, such as offshore wind, hydrogen and battery storage, by creating cost tipping points for these technologies, in combination with other policies. A similar complementary policy, which is outside the purview of our policy package, is the creation of public infrastructure, such as EV charging stations and hydrogen distribution networks, to encourage the adoption of green technologies by consumers and industry.

Finally, to ensure that the low-carbon transition is also one that is sustainable and just, redistributive policies are a must to evaluate and include in any policy package to ensure that the costs and benefits of the transition are equitably distributed across all sections of society.

CASE STUDY:

Data-Driven Systems Mapping of SDGs and Energy Transition Interactions

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Policy question: What risks and opportunities for sustainable development goals (SDGs) will the energy transition create, and how might we manage these?

Region: Brazil

Method: A data-driven approach to systems mapping.

Key finding: Wind energy is relatively well-connected with Brazil's SDG and economic indicators, interacting with outcomes in the health, water and sanitation sectors, as well as having more intuitive connections to emissions and access to electricity. There is also some evidence of an underexplored connection between wind energy and biofuels. Conversely, solar energy production has a more distant connection with SDG and economic indicators, suggesting there is less evidence of strong synergies or trade-offs between solar and other objectives. Future work will look more closely at these relationships.

Engagement: This work has been presented to the EEIST Brazilian community of practice, but full engagement has not begun yet. The modelling work is ongoing and the core engagement work is planned for the next stage of development. This will involve presenting the full maps and analysis, focused on trade-offs and synergies between the transition and SDGs, to policy stakeholders as a basis for discussion of how more tailored analysis could be developed and used.

Summary: The authors use a data model to consider more general development implications of increasing the role of renewables in Brazil's energy sector. The main objective of the study is to explore synergies and trade-offs between diversifying renewable energy and other dimensions of sustainable development so that policymakers can consider how to leverage synergies and tackle bottlenecks to achieve the country's SDGs. The study uses a data-driven systems mapping approach that combines data-based network estimation methods, standard network analysis and subjective map analysis, allowing for quantitative and qualitative representations of the broader systems in which renewable energy policies are embedded, which in turn can inform high-level decision making and cross-sectoral policy coordination.

Introduction

What risks and opportunities for the SDGs will the energy transition create, and how might we manage these? In this case study, we take a step back from narrowly focused simulation models and consider how the energy transition might be interacting with a broader set of objectives, represented by the SDGs. We use a data-driven systems mapping approach to explore the interactions between SDG, economic and energy transition indicators in Brazil. Specifically, we use country-level, time-series data to estimate networks of SDG, economic and energy transition indicators (our maps) and then analyse the resulting maps using subjective map and sub-map analysis to complement standard network metrics.

We focus on the interactions between the SDGs and the expansion of wind energy; and motivated by an initial set of results that suggests a link between wind energy and biofuels, we iterate to study further biofuels, with a focus on sugarcane. Nonetheless, the analysis using these types of maps is flexible, so more focused policy analysis, or contextualisation of other modelling results or advice, is also possible, as demonstrated in the ongoing EEIST sub-project on which this case study is based.[232]

The Sustainable Development Goals: a systems approach to policy

The 2030 Agenda for Sustainable Development, with 17 SDGs, was adopted by the United Nations General Assembly in 2015. For each goal, there are between five and 19 targets, and between six and 28 indicators. The 2030 Agenda envisioned the integration of economic, social and environmental development goals as components of an interlinked system, rather than individual targets. Applied academic work has reflected this systems approach to policy, and there is a fast-emerging literature on SDG interactions,[233] with many approaches conceptualising the interactions as networks of SDG indicators, as we do here. Moreover, with the 2030 deadline approaching and many countries falling behind on several goals, better understanding SDG interactions has become a key policy issue as synergies need to be leveraged and trade-offs tackled.

Interactions between the energy transition and SDGs have been considered. Nerini et al (2017)[234] summarise synergies and trade-offs between SDG7 (Energy) and non-energy SDGs based on expert elicitation. Similarly, McCollum et al. (2018)[235] map synergies and trade-offs between energy and other SDGs, but based on a large-scale, systematic review of the energy literature. The most recent IPCC Working Group III report summarises an assessment of the literature on the interaction between the SDGs and climate change mitigation options, including the energy transition.[236]

Energy transition and the SDGs in Brazil

In Brazil, the share of renewables in the energy supply matrix has been historically high (between 39 per cent and 58 per cent since 1970) and significantly higher than the world average (46 per cent versus 14 per cent in 2019).[237] However, given the environmental costs and climate exposure associated with further expanding hydropower from its current levels, wind and solar energy have gained relevance in the last 10 years as a means to diversify the production of renewable energy.

Within this context, currently, affordable and clean energy (SDG 7) is the only SDG achieved and maintained in Brazil. Others on track for achievement, but with challenges remaining, are Climate Action, Clean Water and Sanitation, and Quality Education.[238] In all other dimensions, the performance is less promising, so better understanding how Brazil's advantage in clean energy and the recent diversification of renewables in the energy matrix interact with other dimensions of sustainable development could inform key policies aiming at SDG achievement.

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The data-driven systems mapping approach

Bringing data into systems mapping

We use a novel data-driven systems mapping approach designed to allow us to explore broad interactions across different domains in a system, and to contextualise, communicate and embed the insights of new economic thinking in real-world policy questions. In a typical systems mapping exercise the main goal is to determine, often in a participatory fashion, the system's key factors and the links between them.[239] The core outputs are a mapping process and a corresponding map representing a comprehensive and shared vision of the forces at work, which in turn can be used as a framing and discussion tool in policy design, appraisal and evaluation.

Our key methodological contribution is to provide an approach for bringing data into the mapping process, and for building system maps directly from data. This approach allows us to build networks representing empirical regularities between a broad range of factors and analyse these networks in policy-relevant ways.

Network estimation: methods

We demonstrate the use of two data-driven network estimation techniques – correlation networks and the PC algorithm. These are just two of a longer list of methods we hope to combine in ongoing work.

Correlation thresholding is one of the most common network estimation techniques, largely because it is easy to implement and interpret, and does not impose restrictive assumptions on the relationships between the variables. The method consists of two main steps: first, given a set of nodes (i.e. the variables we bring into the analysis), we estimate a full correlation matrix. Then, starting with an empty network, for each pair of nodes we populate our network with an edge (i.e. a connection between them) if the estimated correlation between them is higher than the chosen threshold and/or if the probability of the observed test statistics, in case there was no real link between the variables (p-value), is lower than the chosen threshold.

Correlation thresholding is a good baseline, but as it focuses on pairwise relationships only, it cannot address issues caused by confounders or, more generally, map relationships between nodes of the system while accounting for the other nodes of the system (conditional dependence). One alternative is to think of the system as a network of conditional dependencies that can be modelled as a graph and use conditional independence tests to learn the structure of the graph. In other words, when assessing whether there is an edge between two nodes, all variables in the system are taken into account.

To implement such an approach, here we use the PC algorithm,[240] one of the main algorithms for causal structure learning. This works in three steps: 1) it determines the 'skeleton' of the network – that is, it estimates all network edges, without considering the direction of relationships; 2) it determines the edge orientation for v-structures x → z ← y, that is, a structure where two variables x and y have a common effect z; and 3) based on the results from steps 1 and 2, determines further edge orientations.[241]

Network estimation: data

We use country-level, time-series of SDGs, macroeconomic and energy sector indicators. Data on the SDG indicators were obtained from the United Nations SDGs database, which we complemented with data from the World Bank, Climate Watch Data, the Economic Commission for Latin America and the Caribbean, the World Inequality Database and the Brazilian Integrated System of Disaster Information (S2ID). Data on the energy sector, including energy transition indicators, and on macroeconomic factors are from the Brazilian Ministry of Mines and Energy, the Brazilian Institute for Applied Economic Research, the World Bank, the Brazilian Institute of Geography and Statistics, and the Brazilian Sugarcane Observatory.

Using and analysing system maps

Once a network has been estimated, different approaches can be used to analyse the system and interpret the results. We recommend following Barbrook-Johnson and Penn (2021, 2022)[242] and considering three broad types of use and analysis: (i) observing the structure of the full maps, i.e. using different layouts and visualisations to explore the overall map structure, looking for clusters, bottlenecks and disconnected factors, for example (ii) network analysis, i.e. using formal network measures to look for well-connected and influential factors, and (iii) submap analysis, i.e. looking at bespoke sub-sections of the map to consider specific questions – for example, what is influencing key outcomes, or what paths are between sets of activities or inputs, and outcomes.

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[239] Barbrook-Johnson, P. and Penn, A. (2022). Systems Mapping: how to build and use causal models of systems. Palgrave.

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[241] Heinze-Deml, C. et al. (2018). Causal Structure Learning. Annual Review of Statistics and Its Application 5: 371-391.

[242] Barbrook-Johnson, P. and Penn, A. (2021). Participatory Systems Mapping for Complex Energy Policy Evaluation. Evaluation 27(1): 57-79. Barbrook-Johnson, P. and Penn, A. (2022), Participatory Systems Mapping, Systems Mapping, Palgrave Macmillan.

Limitations

This case study is based on work in progress and here we only implement two network estimation methods, using a dataset that is still under construction. More generally, the key limitations of any data-driven systems mapping exercise will likely revolve around difficulties in merging it into participatory processes, communicating the richness of the maps and findings to others in an accessible way, and in obtaining usable and comprehensive data on all factors of interest.

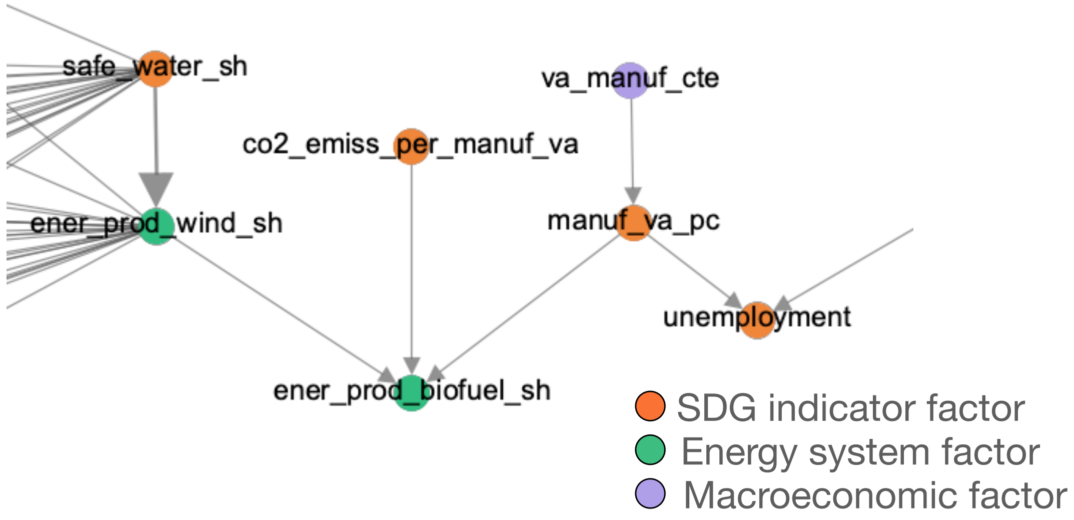
Example findings: Wind energy and biofuels

To illustrate our approach, in this section we present our preliminary findings on how wind energy interacts with other dimensions of sustainable development in Brazil and demonstrate how we iterate on a first set of results to further investigate the role of biofuels in the Brazilian SDG-energy system.

Our full map (not shown here) suggests wind energy is connected to several nodes in the correlation network and, as a result, wind energy is the most well-connected among the energy transition-related factors and one of the top five nodes in three standard network measures: betweenness (which captures if the node is a 'bridge' or 'bottleneck'), closeness (which captures if a node is 'in the thick of it') and degree (number of connections). Specifically, our preliminary findings suggest that wind energy is associated to total greenhouse gas emissions (SDG 13) and access to electricity (SDG 7), but they also indicate other somewhat less intuitive interactions with outcomes in the health sector[243] (SDG 3), with access to water (SDG 6) and to sanitation (SDG 6), with protected areas (SDGs 14 and 15) and with material consumption (SDG 12).

Besides being connected to several nodes in the correlation network, in the PC algorithm network the wind energy share is associated with the share of biofuels, a major source of energy in Brazil. Motivated by this connection, we further investigate the influence of biofuels in the SDG-energy system. Looking upstream from biofuels (Figure 78), we can see that manufacturing value added and CO2 emissions per unit of value added in manufacturing (both SDG 9 indicators) have a relationship with it. Since biofuels include sugarcane products, firewood, vegetable oils and waste energy sources, which in turn can be transformed into thermal, mechanical and light energy, the plausibility of these associations and any mechanisms behind them would be interesting topics for further research, as would discussions with stakeholders in the energy and manufacturing sectors, especially considering that industrialisation is an important dimension of the SDGs.

Figure 78: Ego network[244] of biofuels. This shows the two-step ego network (i.e. all nodes connected directly or via one step) of biofuel production, but cuts out many of the nodes connected via wind energy production.



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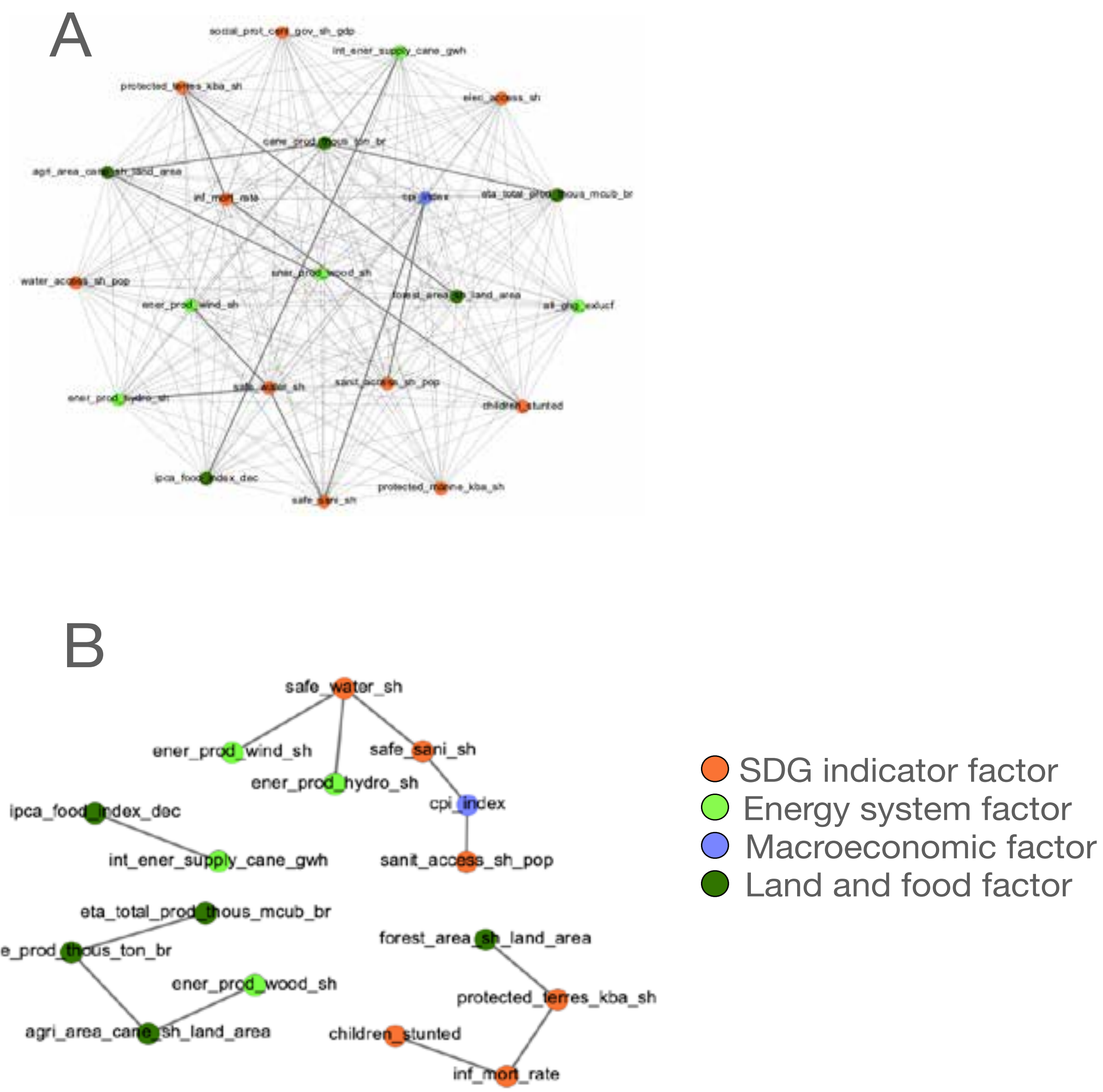
[243] Share of women with anaemia, infant and neonatal mortality, children stunted.

[244] An ego network is a subset of a network focused on one particular node and its neighbours.

To demonstrate how submaps exploration can inspire further literature reviews, data collection and mapping, we iterated again, this time with an extra focus on the role of biofuels and land use as the starting point. The idea is to explore the interdependencies between biofuels, land use and food prices in Brazil, in light of a strand of literature that considers co-movements in oil and agricultural output prices, as the latter is increasingly used as input for energy production.[245]

We collected additional data to disaggregate biofuels, with a focus on sugarcane. Specifically, we included sugarcane and ethanol production, as well as data on the supply of electricity from sugarcane. Other sources of renewable energy included are woodfire, solar, wind and hydro. We also include data on the sugarcane and forest shares of Brazil's land area, and a food price index. The resulting submaps are shown in Figure 79. This iteration shows the biofuel factors much more tightly connected into the map, with all of them holding a central position.

Figure 79: Ego networks of biofuels 2. A) The two-step ego network of the biofuel-related factors. B) The same network, but with only the edges appearing in both correlation and PC algorithm networks shown.



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When we thin the map by only including connections which appear in both PC algorithm and correlation networks, we see a different picture. Firstly, we see an intuitive chain from land area producing sugarcane, to sugarcane production, to ethanol production. While the PC algorithm was not able to direct these edges, for policy purposes, expert knowledge and/or further data collection could be used to complete this section of the map. We also see a relationship between electricity supply from sugarcane and food prices, but electricity supply from sugarcane is not linked to the rest of the chain – an issue that could be discussed with sector specialists.

Similarly, the link between land area producing sugarcane and the share of energy production from wood could be further investigated, as well as the lack of a link between forest area (SDG 15) and sugarcane production, especially considering that the extent to which sugarcane production may influence deforestation is an important issue to be considered in both energy (SDG 7) and forest conservation policies (SDG 15).

In sum, our data-driven maps show wind energy well-connected to other nodes in the SDG-energy system, potentially interacting with outcomes in the health, water and sanitation sectors (SDGs 3 and 6) besides being linked to emissions (SDGs 9 and 13) and access to electricity (SDG 7). Wind energy may also be connected to biofuels, which, when further disaggregated with a focus on sugarcane energy and land use, are also well-connected in the correlation network. Finally, the PC algorithm network of biofuels offers interesting suggestions for further investigations on interactions among sugarcane production, forest area and emissions.

Conclusion

This preliminary data-driven systems mapping exercise has shown how wind and biofuels appear to be more connected into the SDG and economic indicators in Brazil than solar. This suggest efforts to seek out synergies and opportunities, or address trade-offs and risks between the transition and SDGs, may be best focused on wind and biofuels. In future work, we will explore these relationships in greater detail and present them to policy stakeholders tasked with supporting Brazilian progress on SDGs, to inspire further rounds of analysis driven by stakeholder questions.

We believe this approach to data-driven systems mapping is a useful tool to complement more narrowly focused models and to combine with qualitative systems mapping approaches (as seen in the case study What is the most cost-effective form of carbon pricing?). Systems mapping has proved useful and popular among analysts working in policymaking, from policy design through appraisal to evaluation,7 and we believe we should make more use of the different types of systems mapping, including more data-driven approaches. Specifically, within a new economic thinking and modelling framework, systems mapping is a key early step in Risk-Opportunity Analysis[246] and is a useful method for opening up economics, making its insights more accessible and encouraging pluralism.

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CASE STUDY:

The Green Complexity and Competitiveness of China's Exports

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Policy question: How is the comparative advantage of nations likely to be affected by the energy transition? What policies are best deployed to help countries navigate changing comparative advantage and position themselves for future prosperity?

Region: China

Method: Green complexity index based on economic complexity literature.

Key findings: (i) Understanding a country's existing green complexity index, and its green complexity potential, provides an indication of directions of likely future comparative advantage; (ii) Strategic long-term policies can drive a nation towards areas of potential comparative advantage; (iii) China has succeeded in doing this over the last two decades, with its rise as a green product exporter proving even more powerful than its position as the leading global manufacturer.

Engagement: The methods in this case study have been developed in an academic context as a general framework on capabilities. Much of the data and results for most countries globally has been made publicly available on the Green Transition Navigator (https://green-transition-navigator.org/). This resource has been used for multiple reports on green export capabilities of various countries. This particular case study on China emerged as part of a collaboration between the Oxford team and Lombard Odier, a Swiss private bank, and a version of it was presented at a side-event of COP26 in Glasgow, among other places.

Summary: The authors use a data analysis approach to explore global trade data and the comparative advantage different countries have in green products. The study presents the Green Complexity Index approach, which builds on the economic complexity literature. This literature has had a huge influence on how we think about countries' development; here it is applied to China's green competitiveness and shows China's rise as a green product exporter is even stronger than its rise as the leading global manufacturer.

Introduction

This case study presents the application of economic complexity-based measures to understand green competitiveness in China. The transition to a low-carbon economy will require switching to greener technologies in many sectors, implying that countries with high production of green technologies stand to be likely beneficiaries of the green transition. Acquiring the capabilities to export sophisticated green products can be part of a green growth strategy, but may not be easy everywhere. Here, we assess 25 years of global trade in green products to understand recent trends in China's green competitiveness and product complexity, and consider what might lie ahead. This type of analysis can give insight into the industrial dynamics and impacts we might expect in different countries as the green transition unfolds. This case study is a summary of the application of the approach by Mealy and Teytelboym (2020)[247] to China and other countries by Andres et al. (2021).[248]

Measuring green competitiveness

The 'green' products we track are a list of 295 products as defined by Mealy and Teytelboym, who amalgamate environmental goods lists compiled by the WTO, the OECD and APEC. The sub-categories within this include renewable energy products, efficient consumption of energy technologies, carbon capture and storage products, and wastewater management and potable water treatment. The countries potentially well-placed to gain from the low-carbon transition are those who manufacture and export sophisticated equipment to make the transition happen, such as solar panels, wind turbines, electrolysers, and batteries and their components.

Our methodology also identifies countries that have the export capabilities that may allow them to move into exporting green products in the future. This is based on the idea that industrial development is often path-dependent.[249] Empirical evidence has shown that countries and regions are significantly more likely to develop competitiveness in products and services which require similar capabilities to those they already possess.[250] There is further evidence to suggest that countries which specialise in more technologically sophisticated products tend to enjoy greater income and GDP growth.[251]

To capture these phenomena, we employ an approach first introduced by Hidalgo et al[252] and extended by Mealy and Teytelboym to measure competitiveness in exporting green products. The proximity of a product to a country's current capabilities is strongly associated with the probability that this country will develop relative competitiveness in this product in the future (if it does not already export it competitively).[253]

We use the algorithm developed by Hidalgo and Hausmann to calculate the Product Complexity Index (PCI), which is a proxy for technological sophistication. We will occasionally refer to the Economic Complexity Index (ECI), which measures the overall complexity of a country's export basket. A country's ECI has been shown to be a significant predictor of that country's future GDP growth.[254]

We apply the approach of Mealy and Teytelboym here and combine these measures of complexity with the combined WTO, OECD and APEC list of traded green products to develop indices of green complexity or green competitiveness. We use two key metrics to assess countries' progress in capitalising on the growing green product market.

1. **The Green Complexity Index (GCI)** measures the number and complexity of green products that a country has exported competitively. It constitutes a composite measure of green competitiveness and allows us to compare countries directly on their current green export strengths.

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[247] Mealy, P and Teytelboym, A. (2020). Economic Complexity and the Green Economy. Research Policy: 103948.

[248] https://www.inet.ox.ac.uk/publications/predictors-of-success-in-a-greening-world/

[249] Grubb, M. et al. (2014). Planetary Economics: Energy, Climate Change and the Three Domains of Sustainable Development. Planetary Economics.

[250] Hidalgo, C. et al. (2007). The Product Space Conditions the Development of Nations. Science, 317: 5837; Neffke, F. et al. (2011). How Do Regions Diversify over Time? Industry Relatedness and the Development of New Growth Paths in Regions. Economic Geography, 87.3.

[251] Hidalgo, C. et al. (2007). The Product Space Conditions the Development of Nations. Science 317: 5837; Hausmann, R. et al. (2007). What You Export Matters. Journal of Economic Growth, 12.1.

[252] Hausmann, R. and Hidalgo, C. A. (2009). The Building Blocks of Economic Complexity. Proceedings of the National Academy of Sciences, 106(26): 10570-10575.

[253] Hidalgo, C. et al. (2007). The Product Space Conditions the Development of Nations. Science, 317: 5837; Neffke, F. et al. (2011). How Do Regions Diversify over Time? Industry Relatedness and the Development of New Growth Paths in Regions. Economic Geography, 87.3.

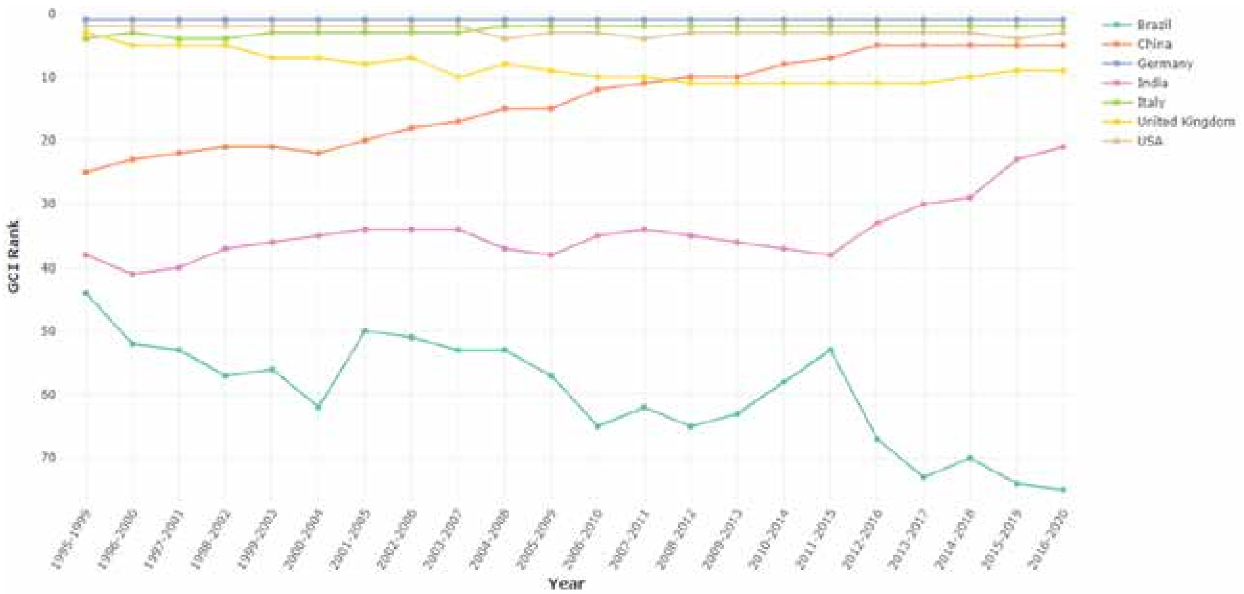
[254] Hidalgo, C. et al. (2007). The Product Space Conditions the Development of Nations. Science 317: 5837; Hausmann, R. et al. (2007). What You Export Matters. Journal of Economic Growth, 12.1.

2. **The Green Complexity Potential (GCP)** measures each country's proximity to complex green products that it does not yet export competitively. We use a measure of proximity between products that is based on how often two products are co-exported. Proximity between a product and a country indicates how similar a product is to a country's current export capabilities. Identifying products that are closely related to a country's capabilities allows us a glimpse of what those future paths might look like, due to the path dependency often observed in industrial development. GCP has been shown to be a significant predictor of a country's future GCI.[255]

To prevent our analysis from being skewed by short-term fluctuations in trade, we use annual average values over rolling five-year periods (1995-1999, 1996-2000, etc). For more details on the methodology, please refer to the report [256] this case study is based on and Mealy and Teytelboym (2020).[257]

Germany and Italy have consistently scored high on GCI between 1995 and 2020 (see Figure 80), and Germany currently holds top rank. The UK has stayed consistently in the top 10. India has risen close to the top 20, whereas Brazil has dropped into the 70s. However, arguably the most striking positive trend is the rise of China.

Figure 80: GCI through time for selected countries.



China's green complexity trends and opportunities

Over the past decade, China has become the world's largest manufacturing economy. It is also the world's largest emitter of greenhouse gases. However, its global dominance in manufacturing is mirrored by its clean technology production capabilities. China currently ranks 42nd in economic complexity overall (ECI), but fifth in green complexity (GCI).

China's national industrial strategy is aimed at progressing the technological frontier. 'Made in China 2025'[258] announced in 2015 as a major piece of industrial policy, identified 10 industries in which China aims to become the world leader by 2025. These included both green vehicles and rail transport technology. Its focus on high-tech industries may raise both its economic and green complexity ranking. China's 14th five-year plan (for 2021-2025) emphasises a similar set of industries. It also outlines plans for more scientific and technological self-reliance and stronger collaboration between industry and research institutions.[259] More recently, the 2022 government Central Economic Work Conference again outlined technological priorities considered key in forging China's outward industrial competitiveness, with energy technologies central; however, there was more emphasis on self-reliance than previously.

Next, we will discuss past trends in China's green product categories, then highlight detailed products that form strengths and potential diversification options, and finish with an analysis of China's EV industry.

Trends in China's green competitiveness

China's share in global green exports increased from 3 per cent in 1995-1999 to 19 per cent in 2015-2019. Its share of green imports increased as well, but to a lesser extent: from 2.87 per cent at the start of the period to 8 per cent during the most recent period. China is a net exporter of green goods (reflecting its dominance in global manufacturing exports more broadly).

China's GCI rank increased from 25th in the 1995-1999 period to fifth in the latest 2015-2019 period, while its GCP rank increased from seventh to first. This indicates that China not only increased its green export share, but also moved into relatively complex green technologies. Its high GCP in particular indicates that China is well-positioned to further increase its global green competitiveness in the future. Renewable energy products are China's most important green export, as well as import.

Export values increased in many categories over the course of the study period, but especially in more complex ones (Figure 81). The top three categories are renewable energy products, followed by products in efficient consumption of energy technologies and carbon capture and storage, then wastewater management and potable water treatment. As Figure 82 shows, China's average proximity to green products has increased for all environmental categories. This indicates that China's productive capabilities are increasingly aligning to those required to competitively produce green technologies. This is also captured by its high rank in GCP.

Figure 81: Export value through time by environmental product category.

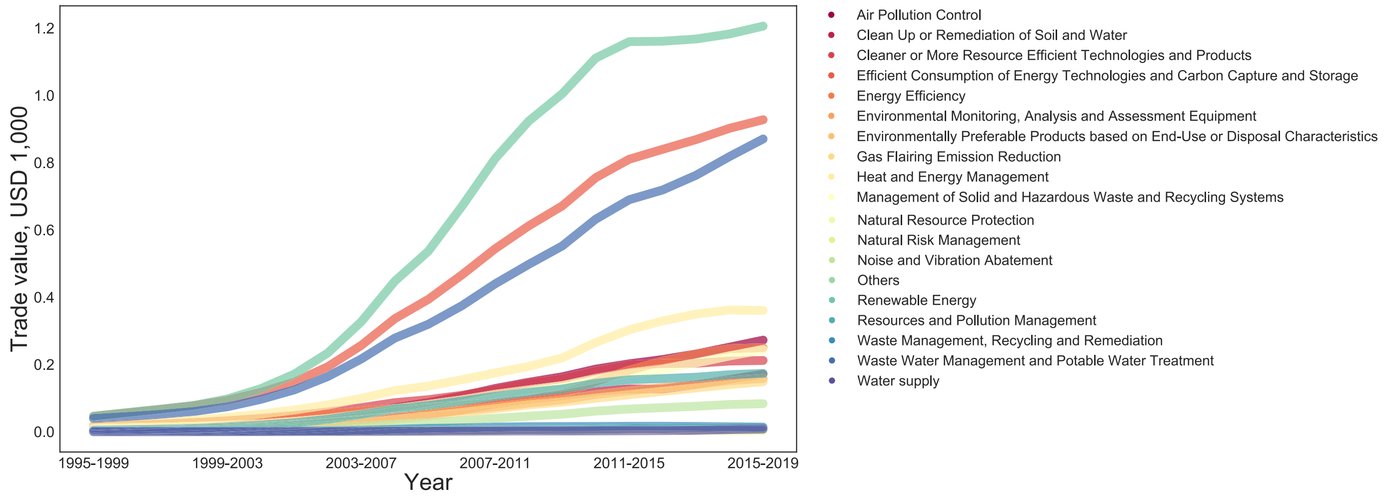
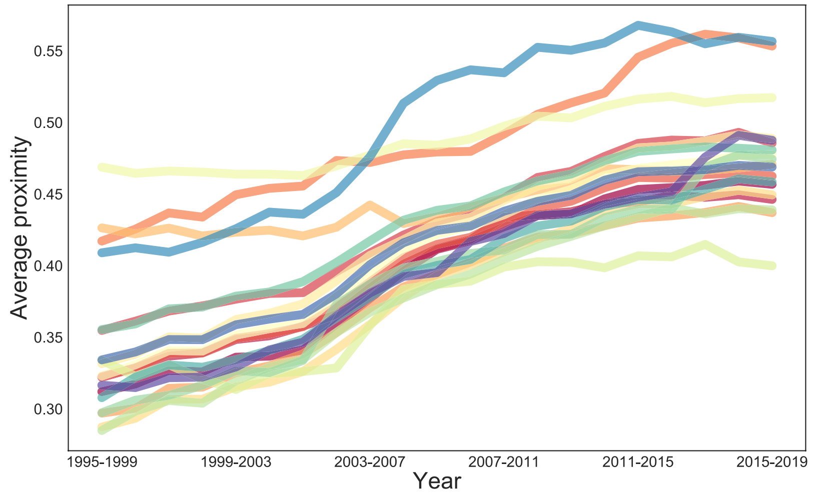


Figure 82: Average proximity to products by environmental product category.



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[255] Mealy, P and Teytelboym, A. (2020). Economic Complexity and the Green Economy. Research Policy: 103948.

[256] https://www.inet.ox.ac.uk/publications/predictors-of-success-in-a-greening-world/

[257] Mealy, P and Teytelboym, A. (2020). Economic Complexity and the Green Economy. Research Policy: 103948.

[258] State Council of The People's Republic of China. (2015). Made in China 2025. <http://english.www.gov.cn/policies/latest_releases/2015/05/19/content_281475110703534.htm>

[259] Mallapaty, S. (2021). China's Five-Year Plan Focuses on Scientific Self-Reliance. Nature: 353-54. <https://doi.org/10.1038/d41586-021-00638-3>.5.

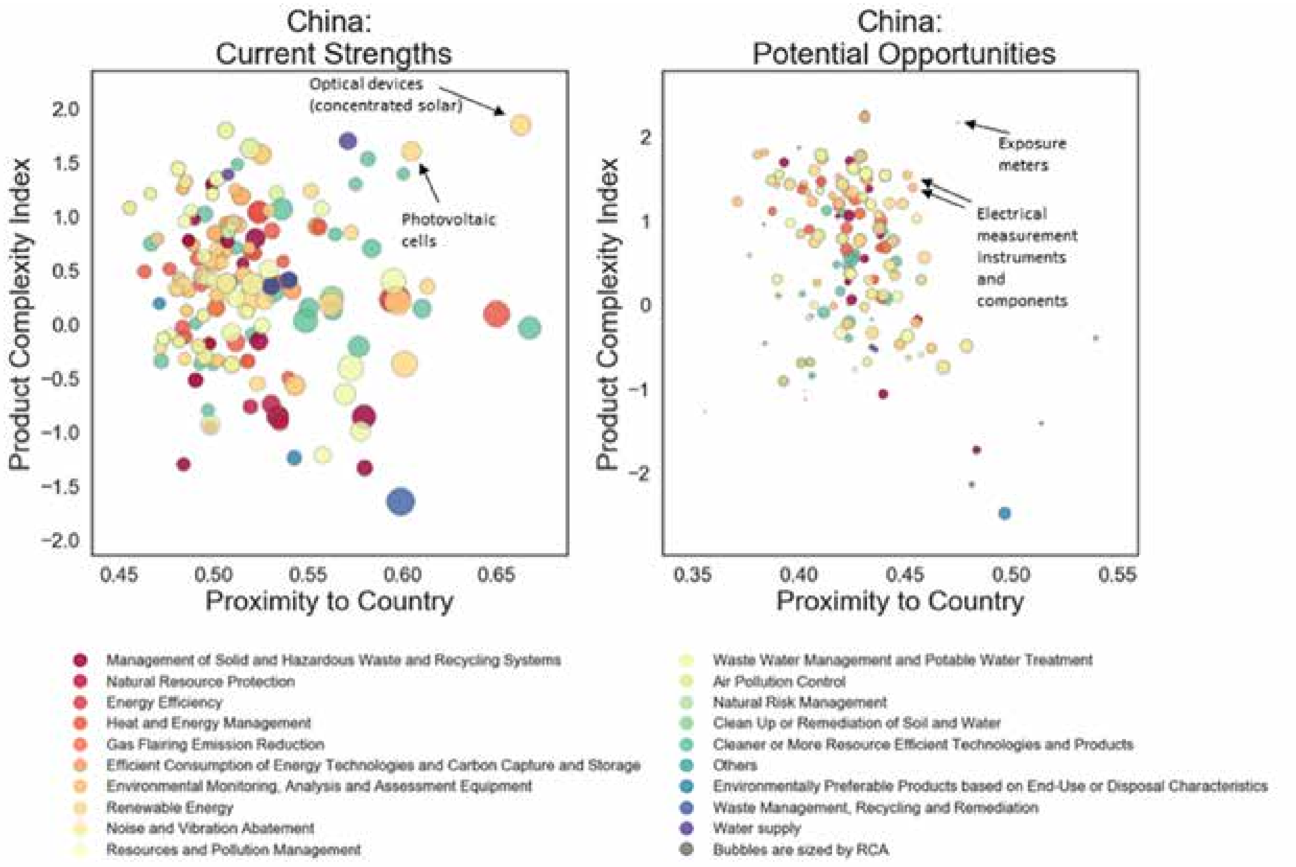
China's green strengths and opportunities

China's first NDC submission called for further R&D spending in renewable energy and related technologies, including desalination and climate change risk assessment methodology.[260] Some environmental monitoring technology is highly complex and close to China's current strengths, such as exposure meters or electrical measurement instruments and their components, both of which can be used in environmental monitoring.

Figure 83 divides all green products into those which China exports competitively (based on Revealed Comparative Advantage,[261] and labelled 'Current Strengths') and those which it currently does not (labelled 'Potential Opportunities'). The horizontal axis shows the products' proximity to China's current productive capabilities, which is an indication of how quickly China could develop competitiveness in those products in the future where it does not already have it.

Figure 83 shows that, for China, the most proximate products tend to have a lower PCI score, indicating that there is a trade-off between transitioning into 'proximate' versus 'complex' new products. High-complexity products are more likely to add value and open up greater diversification opportunities, but if products high in complexity tend to be relatively further away from existing capabilities, transitioning into those will be riskier.

Figure 83: China's green export products divided into current strengths (left) and potential opportunities (right). Size of product circle indicates China's current RCA; colours represent product categories.



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[260] NDRC. (2015). China's Intended Nationally Determined Contribution: Enhanced Actions on Climate Change.

[261] Revealed Comparative Advantage is a measure of the relative advantage of a certain country in exporting a certain product. An RCA of a country-product pair of 0.5 means that country exports half of what is expected given the global average exports of that product and the country's total export value. A country exports a product with competitive advantage or capabilities if it has an RCA of >1 for that product.[247] Mallapaty, S. (2021). China's Five-Year Plan Focuses on Scientific Self-Reliance. Nature: 353-54. <https://doi.org/10.1038/d41586-021-00638-3>.5.

Low-emission vehicles

One of China's 'Made in China 2025' target industries is green vehicles. There have been policies in place for Chinese consumers to buy hybrid and electric cars since 2009, and in 2035 all new vehicles sold must be electric, hybrid or fuel-cell driven, according to a Ministry of Industry and Information Technology guided report.[262] Electric and hybrid vehicles represent about 5 per cent of new car sales in 2020 and perhaps 20 per cent in 2025, making it the world's largest EV market in absolute numbers.[263]

In our analysis, China's share of global export of new energy vehicles (which includes natural gas-powered vehicles besides electric, hybrid and hydrogen-powered ones), is only about 1 per cent for 2015-2019, compared to 12-25 per cent for Germany, Japan and the US – all three countries with large automotive sectors. China had not yet developed competitive export capabilities in this area in 2015-2019, with an RCA of 0.06 and proximity to productive export capabilities comparatively low at about 0.4.

However, since 2017 EVs have their own export code (separated from other 'new energy' vehicles), but this is not included in our longitudinal data covering the period of 1995-2019. Tracking this new export code, it can be found that China was the third-largest net exporter of EVs in 2021, with exports up fourfold from 2020, capturing 13.7 per cent of the global export markets for EVs,[264] which means that China had only gained export capabilities (RCA = 1.02 > 1) in EVs in 2021.[265]

Separately, we can find in the dataset that China already had export capabilities (RCA = 1.1 > 1) in the 2015-2019 period in buses that are non-diesel-powered and thus often less polluting[266] and is a major player in that export market. But those are a different product with a lower complexity (PCI of 0.43) from new energy vehicles (PCI of 1.87).

Conclusion

This case study presented two relatively new measures of economic complexity – the Green Complexity Index and Green Complexity Potential – that can be used by policymakers to understand fine-grained areas of current and future comparative advantage as the transition to net zero plays out. These measures were applied to China, with a view to understanding China's evolution over time and where China stands in the race to benefit from the energy transition. It was found that China has achieved a dramatic transformation of its economy in the form of world-leading increases in green complexity over recent decades, and in the final period of the study (2015-2019) China ranked fifth in green complexity and first in green complexity potential.

From earlier research it is clear that this success did not happen by accident and is driven by China's targeted industrial policy, which included industry-specific subsidies, preferential credit and measures which aggressively target technology transfer. We discussed the 'Made in China 2025' strategy, which targets sustainability and some key green technologies such as electric vehicles, where China has gained export capabilities in 2021, as well as digitalisation and high-tech industries. But not every country will find adopting such interventionist industrial policy feasible or desirable. China's experience demonstrates what is possible, and other countries will observe that leaving the evolution of the economy exclusively up to market forces can mean that opportunities to exploit increasing returns are missed.

Looking forward, policymakers can use their country's green complexity index and green complexity potential to signal areas of likely future comparative advantage. Strategic long-term policies – whether heavily or lightly interventionist – can help steer nations towards areas of potential comparative advantage. In China's case, our analysis suggests that it is already strong in such a large number of areas that doubling down and maintaining comparative advantage in many of those areas is likely to make sense. For instance, given the disruption underway in the automotive sector and the scale of the value at stake, it may be sensible for China to continue to strengthen their investment in EVs. Policymakers in other countries may draw different conclusions from the analysis of their own economy's green complexity potential.

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[262] Tabeta, S. (2020). China Plans to Phase out Conventional Gas-Burning Cars by 2035. Nikkei Asia. < https://asia.nikkei.com/Business/Automobiles/China-plans-to-phase-out-conventional-gas-burning-cars-by-2035>

[263] IEA. (2020). Reports: Electric Vehicles.

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[265] Taking China's percentage of world trade at 13.5% using 2020 data from https://wits.worldbank.org/CountryProfile/en/WLD

[266] This category includes electric and hydrogen buses, but also those that run on non-diesel fossil fuels such as natural gas or petrol.

EEIST

Economics of Energy Innovation and System Transition

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.

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