EEIST

ENERGY TRANSITION IN BRAZIL: INNOVATION, OPPORTUNITIES AND RISKS

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Contents

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; **Brazil** – Federal University of Rio de Janeiro (UFRJ), University of Brasilia (UNB), University of Campinas (UNICAMP); **EU** – Scuola Superiore di Studi Universitari e di Perfezionamento Sant'Anna (SSSA); **China** – Beijing Normal University, Tsinghua University, Energy Research Institute; **India** – The Energy and Resources Institute, World Resources Institute.

The EU partner SSSA contributed as a leading organisation with focus on Brazil context and research.

Contributors

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The contents of this report represent the views of the authors, and should not be taken to represent the views of the UK government, CIFF or the organisations to which the authors are affiliated, or of any of the sponsoring organisations.

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Executive summary

Brazil has recently re-committed to environmental policy and international cooperation. This enhances the practical value of joint research to accelerate a transition towards a more sustainable economy, in particular in view of its hosting of COP30, which will be held in the port city of Belem, on the Amazon river delta.

This report summarises work performed during the past three years on innovation in the energy sector and the impact of environmental policies on trade and emissions, as part of an international programme on the Economics of Energy Innovation and System Transition (EEIST), with results from the programme in Brazil. It illustrates why (and how) the way in which policy is assessed matters for policymakers: specifically, tools that emphasise interactions between policies and an economy in constant evolution can pinpoint risks and opportunities. It draws on extensive knowledge as published in three main reports under the EEIST programme, which address (i) the theoretical underpinnings and implications for risk-opportunity analysis (ROA),[1] from which follow (ii) ten principles for policymaking in the energy transition;[2] and (iii) frames the modelling science around new economic modelling, with 15 case studies emerging from the interaction between modellers and policy engagement across Brazil, China and India.[3]

This report provides insights on how unique dimensions of the Brazilian landscape and financial situation give scope for effective action towards a low-carbon re-industrialisation. Written for technical and policy teams in Brazil, with particular relevance to the ministerial, development banks and energy regulators, it illustrates in particular that the dynamic nature of low-carbon re-industrialisation offers opportunity, with **ROA a more useful tool than traditional (but impractical) cost-benefit analysis (CBA) to assess the green transition** via empirical case studies. It supports this with **four additional modelling case studies** implementing the learning from this work in policy-relevant modelling. An appendix summarises the **engagement strategy built upon communities of practice in Brazil**, as a potential example to future science-policy interface collaboration.

[1] Grubb, M., Drummond, P., Mercure, J.-F., et al. (2021) The new economics of innovation and transition: Evaluating opportunities and Risks. Economics of Energy Innovation and System Transition. Exeter University, Exeter, UK. Available at: eeist.co.uk/eeist-reports.

[2] Anadón, L.D. et al. (2023) Ten policy principles for policy making in the energy transition: Lessons from experience. Exeter University, Exeter, UK. Available at: eeist.co.uk/eeist-reports.

[3] Barbrook-Johnson, P. et al. (2023) New Economic Models of Energy Innovation and Transition: Addressing New Questions and Providing Better Answers. Exeter University, Exeter, UK. Available at:eeist.co.uk/eeist-reports.

Table 1. Policy questions addressed and key findings in this report.

Policy questions	Key findings
Effects of combined policies for low-carbon transition: Can combined public financing and auctions policies for solar and wind generate opportunities for development that outweigh those generated by applying the policies in isolation?	Financial constraints severely affect transition processes in the private sector, and these can be overcome by public financing. Reducing cashflow risks through auctions associated with power purchase agreements can induce faster transitions, with limited effects. Coordination of both policies together can accelerate the energy transition without additional cost, and specifically the combination of auctions with public financing can achieve 'more than the sum of their parts'.
Cost of solar and expansion of solar industry: How do different power sector technology mixes and models compare in terms of cost effectiveness and wider economic impacts? Would more solar power, compared to the likely current trajectory, be a good or bad thing for Brazil?	Scenarios with higher deployment of renewables tend increase GDP and employment. Measures that accelerate the deployment of both solar and wind may be beneficial, but with the emphasis on supporting solar in the near term (since it has a much smaller share of generation than wind at present), and with a greater emphasis on supporting wind over the longer term. The power generation technology mix calculated by the cost-optimising models may not be the least-cost one. Lower electricity prices could be achieved by either boosting or limiting solar deployment, due to the dynamic interplay between the greater deployment of solar that can reduce the costs of generation; and with a better balance between solar and wind reducing the costs of energy storage.
Domestic energy demand: How much can innovation in energy intensity contribute to the reduction in energy demand and associated GHG emissions for Brazil by 2050? What is the combined effect of policies on energy efficiency and energy substitution to low-carbon sources for the energy transition in Brazil?	Firm-led innovation accelerates declining energy intensity and plays a key role in reducing energy demand and its associated carbon emissions. The current speed of advancements in energy-saving technologies may reduce mid-century energy demand and carbon emissions by about 15% by 2050. The current speed of energy transition in the power sector can also contribute about 15%. Such 'dynamics-as-usual' trends are too slow to meet national emission and sustainable development goals, which is still unlikely to meet the sustainable development targets by 2050. A combination of firm-led energy-efficiency innovations and government policies that accelerate the transition to low-carbon energy sources can best achieve climate and energy targets by 2050.
Export and re-industrialisation: From which parts of the economy should the government seek to reduce emissions? How important will international trade be in the decarbonisation of Brazil's economy?	Most polluting industries seem to be reducing the intensity of their GHG emissions (except for electricity, water and gas), and the household sector has also reduced its emissions intensity. Agriculture, electricity generation and transport are responsible for most of Brazil's emissions. Exports accounts for almost one third of total emissions, while representing only 16% of gross output. Therefore, exports are more intensive in emissions by 9 tCO_2/R$ in comparison to the average of the economy. Reducing national emissions by replacing domestic production with imported products, whether for final or intermediate consumption, is unlikely to help either reduce global emissions, or Brazil's economic development. Brazil has a strong interest in coordinating with other countries to establish conditions in foreign markets that enhance the competitiveness of its export industries as they decarbonise while eliminating emissions from their production processes.

From policy questions to better answers

The engagement between scientists and policy workers as part of the EEIST project in Brazil identified a number of questions to be addressed. *These informed the work in this report, as well as Brazil-focused studies in the previous report 'New Economic Models of Energy Innovation and Transition', and may continue to shape the research agenda going forwards.* These include:

- What are the green investment needs for the Brazilian economy? Which are the key sectors that demand the biggest efforts?
- What are the policy and technological paths with lower decarbonisation costs (both financial and social) and higher sustainable growth potential?
- Which industrial policies should be pursued and why?
- What are the possible side-effects of policies (e.g. subsidies) on financial variables (e.g. inflation)?
- Which investments have the higher benefit for job creation in terms of level and quality?

In order to provide meaningful answers to these questions, this report supports enhancing capability by policy institutions around developing:

- **A systemic perspective.** There is huge potential to accelerate existing renewable energy sources expansion and new electrification projects would also have potential spillovers to other sectors as well as the macroeconomic implications.
- **Complex toolboxes.** There is a need for the joint creation of a stakeholder-driven analytical toolbox: analysis of government databases, policy modelling and evaluation, and domestic and international macro assessment.
- **Dedicated training programmes.** There is a need to develop training activities for Brazilian students and policymakers across different regions, to enable the use of a more diverse set of analytical tools.

The application of such new tools and thinking could support answering the above policy problems in their wider context. Some examples include:

- **Jobs and technologies to be analysed together.** Technological trajectories should be mapped for key sectors and associated job-creation opportunities on entire supply chains.
- **Public mobility in its wider context.** There is a need to convert the public transportation fleet to be compatible with electric vehicles while considering the wider implications on the supply chain linked with the bus industry.
- **The mutual impacts of land use and land use changes alongside industrial and transport sectors.** Economically viable alternatives for the development of deforested regions need to consider both adaptation and mitigation approaches, and possibly stimulating reforestation of degraded areas.

All of these require a strong engagement of science and policy, and interministerial coordination to support systems transformation for a low-carbon economy.

Policy highlights

The EEIST team in Brazil has extended the concept of ROA and applied it to four modelling case studies. The combination of all the case studies forms a picture of Brazil from its role in the national aspects of the energy transition to the wider foreign policy landscape, taking into account the unique characteristics of the national economy.

Here, we present a selecti ies in this report. The purpose of this section is not to provide a summary, but to give some examples that illustrate the potential of new economic models to address new questions and provide better answers to the policy problems of energy innovation and transition. Readers can refer to the case studies to find more detail on the methods, results, limitations and policy implications of each of these pieces of analysis.

Combined policies for low-carbon transition

The case study *Positive non-linear change from combining low-carbon energy policies from a polycentric governance perspective: An agent-based analysis* finds that the combination of auction policies based on power purchase agreements and public financing can achieve an effect on renewable energy deployment that is more than the sum of the effects of the policies implemented individually (Figure 1). This opportunity would not be discovered by analysis that follows the traditional approach of assessing the expected net present value of each policy individually. The study benefits from a realistic representation of policies that might be implemented by public authorities operating in the energy sector and, by simulating their interactions, suggests how different parts of governments could achieve better outcomes by coordinating their efforts.

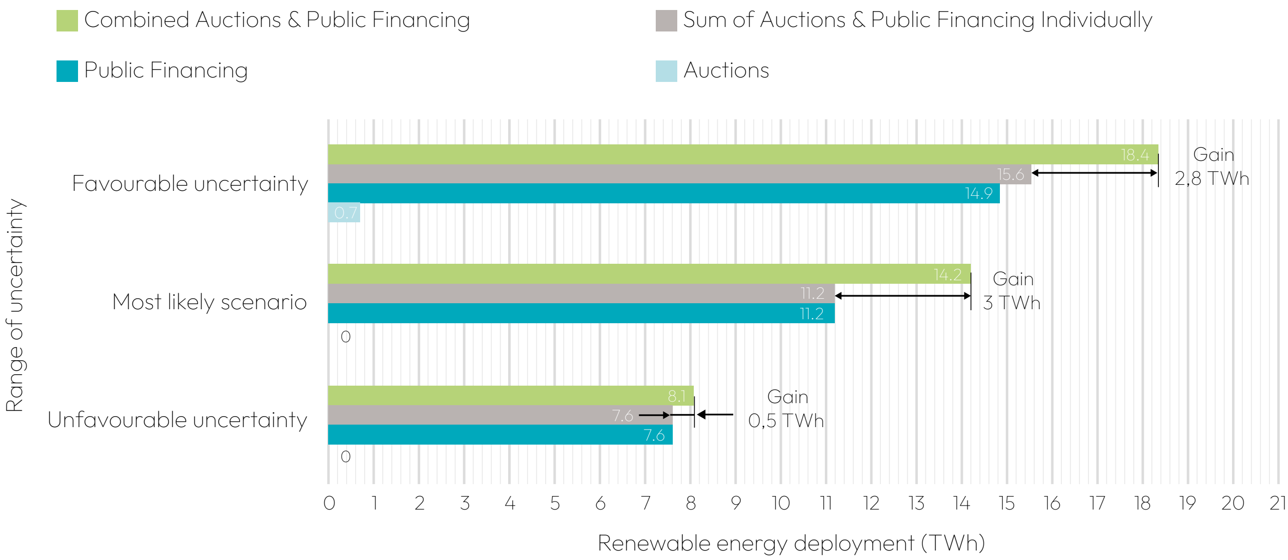


Figure 1. Gain in effectiveness of energy generation from renewables through policy combination in 2040, accounting for uncertainty in scenarios.

Cost of solar and expansion of solar industry

The case study *Power sector technology choices and economic outcomes: A comparative analysis using optimising and simulating models* highlights the opportunity for near-term policies that facilitate faster deployment of renewables to lead to lower electricity prices over the longer term (Figure 2). This arises from the inclusion within the simulating model of dynamics of endogenous cost reduction: innovation and learning lead to lower cost and greater expansion of solar power in the long run. This contrasts with the findings of the cost-optimising model in which technology cost projections are an input.

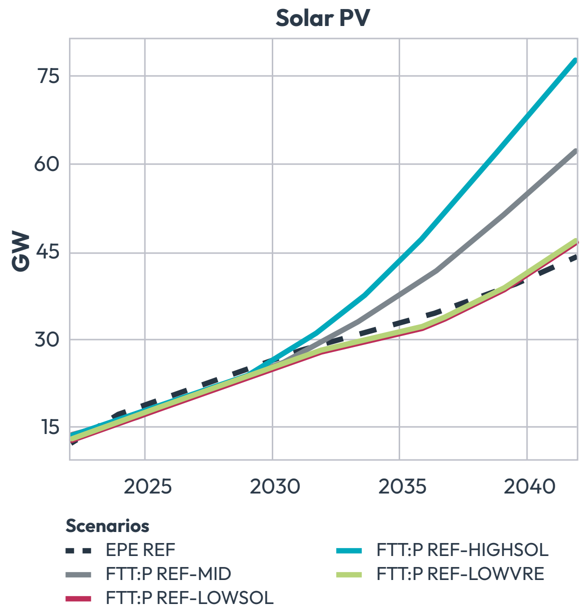


Figure 2. Power generation capacities of solar PV power for all scenarios in both cost-optimising (see EPE Ref) and new economic models (FTT scenarios).

Domestic energy demand

The case study *Firm-led innovations in energy efficiency and its contributions to carbon emissions in Brazil* finds that a combination of firm-led energy efficiency innovations and government policies that promote a transition to low-carbon energy sources is the most effective approach to achieve climate and energy targets by 2050 (Table 2). The model benefits from a representation of how firms invest in R&D innovation, and how they imitate each other to lower cost and decrease energy demand via improvements in energy efficiency.

	Scenarios						
	Base – no innovation	**Energy efficiency innovation – Current Brazil Trends**			**Energy Efficiency innovation – Brazil follows trend as in the UK**		
Variables	**Sc1**	**Sc2**	**Sc3**	**Sc4**	**Sc5**	**Sc6**	**Sc7**
Scenario inputs							
Energy efficiency innovation trend	-	Brazil rate	-	Brazil rate	-	Brazil rate	UK rate
Energy source substitution trend	-	-	Brazil rate	Brazil rate	UK rate	UK rate	UK rate
Scenario outputs (Montecarlo average)							
Avg. annual growth of CO_2 emissions	4.84%	3.16%	3.16%	1.83%	0.45%	-0.31%	-1.54%
Avg. annual growth of energy demand	4.84%	3.16%	4.84%	3.16%	4.84%	3.16%	0.45%
Total CO_2 emissions (as a ratio of Sc1)	100%	85%	85%	73%	59%	51%	36%
Total energy demand (as a ratio of Sc1)	100%	85%	100%	50%	100%	85%	59%

Table 2. Results of model simulations with Monte Carlo analysis by combining 'Energy efficiency innovation' and 'Energy Source Substitution' in the year 2050. The combination of policies assumes different input data based on no policy in place, policies in line with historical trend in Brazil and policies that are in line with historical trend in the UK (which is higher than in Brazil).

Exports and re-industrialisation

The case study *Identifying the sources of structural changes of greenhouse emissions in Brazil: An input-output analysis from 2000 to 2020* finds that in the last two decades, the increase in Brazilian GHG emissions has occurred mainly by an increase in the level of final demand from households and by increasing exports of high-carbon products. Agriculture, transport, distribution and production of electricity, water and gas and industrial commodities were the sectors most responsible for this increase (Figure 3). The study highlights Brazil's interest in international cooperation to achieve conditions in global markets that support the decarbonisation of energy-intensive sectors, so that the government's goals of emissions reduction and re-industrialisation of the Brazilian economy can be successfully pursued in parallel.

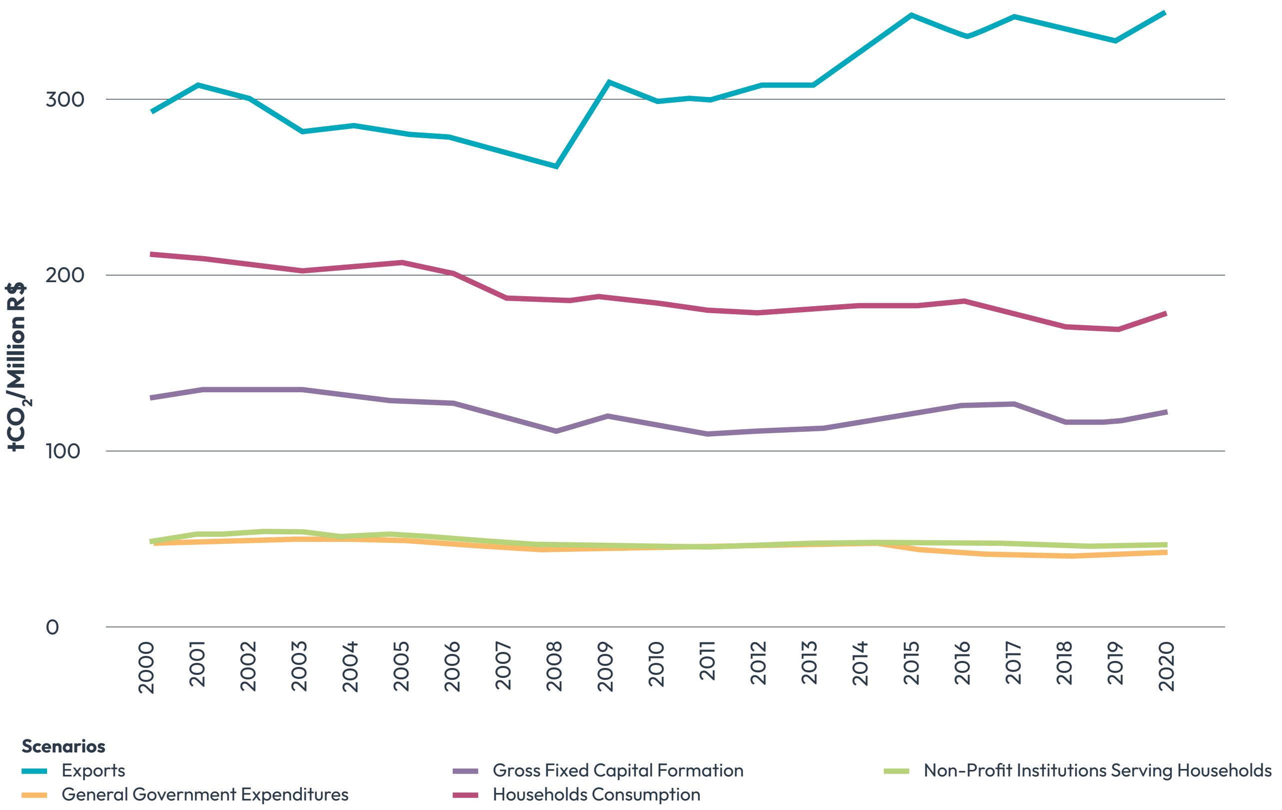


Figure 3. The emissions intensity by final demand component (tCO_2 per million R$).

Introduction

The aim of this report and the key audience

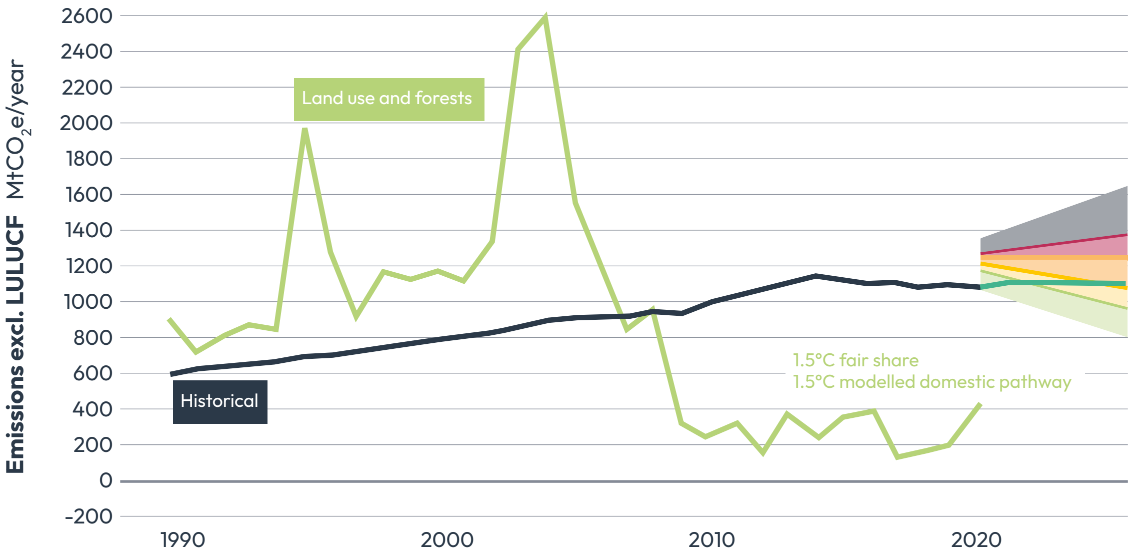
The environmental, economic and political context of Brazil is a perfect ground for research and collaboration as part of the EEIST programme and future cooperation. This report summarises the state of the work performed during the past three years of the programme in Brazil and draws extensive knowledge from the previously published and publicly available reports. These are Grubb et al. (2021),[4] Anadon et al. (2022)[5] and Barbrook-Johnson et al (2023).[6] This report also builds new knowledge, including an analysis of the engagement strategy in Brazil, which it frames as an example for future science-policy interface collaboration. It provides insights on the Brazilian energy-transition landscape and financial situation in the country, which makes it a unique ground for effective action. Finally, it includes four additional modelling case studies implementing the learning from this work in practical modelling to use in policy.

The aim of this report is to bring to light the insights from the EEIST project and build an even stronger relationship with technical and policy teams in Brazil, with particular focus on the ministerial, development bank and energy regulators.

The unique case of the Brazilian energy transition landscape

Unlike many countries, the main source of GHG emissions in Brazil is not the energy and industry sectors, but land use. In turn, the share of emissions coming from each sector is highly dependent on deforestation control policies. Emissions from deforestation fluctuate wildly in response to how stringently controls are enforced (see Figure 4). Under lax policies, total emissions are expected to increase this decade.[7] Beyond land use, the largest sources of energy-related CO_2 emissions are transport (43%), industry (27%) and power (11%).[8] There are also large emissions of methane from agriculture, mainly livestock.

Figure 4. Instability of sources of emissions in Brazil.



[4] Grubb, M., Drummond, P., Mercure, J.-F., et al. (2021) The new economics of innovation and transition: Evaluating opportunities and Risks. Economics of Energy Innovation and System Transition. Available at: eeist.co.uk/eeist-reports.

[5] Anadón, L.D. et al. (2023) Ten policy principles for policy making in the energy transition: Lessons from experience. Available at: eeist.co.uk/eeist-reports.

[6] Barbrook-Johnson, P. et al. (2023) New Economic Models of Energy Innovation and Transition: Addressing New Questions and Providing Better Answers. Exeter, UK: Exeter University. Available at: eeist.co.uk/eeist-report/.

[7] climateactiontracker.org/countries/brazil

[8] www.climate-transparency.org/countries/americas/brazil

Brazil's largest exports are agricultural products, iron ore and oil.[9] The environmental debate is dominated by the contest between those in favour of protecting the forests and those who favour further exploitation for agriculture and mining.[10] The intensity of this contest can mean that the need to reduce emissions in other sectors – and to prepare for the changes in global markets that the low-carbon transition could bring – are relatively overlooked. Brazil is a significant exporter of steel and vehicles. The government aims to 'reindustrialise' the economy as a growth strategy, reversing the trend of recent decades that has seen manufacturing's share of GDP fall while that of raw materials has risen. However, this needs to be done in a sustainable way, considering the traditional industrial sectors in Brazil are typically strong GHG emitters. The government needs to meet rising energy demand and improve access and affordability in rural areas, while electrification infrastructure and the automotive industry lag behind.

Policy landscape in Brazil: change of administration

Brazil presents an interesting opportunity for climate change initiatives, particularly after the change of administration, with the election of President Luis Inácio Lula da Silva in late 2022. Lula's agenda supports innovation and energy transition initiatives, in contrast with the priorities of the previous administration. This has led to the strengthening of government structures that support transformative policies, including the Ministry of Environment and Climate Change and its National Secretary of Climate Change. Their main goal is to propose and evaluate national policies, norms and initiatives that influence climate change and strengthen initiatives related to the Interministerial Committee on Climate Change and Green Growth (Comitê Interministerial sobre Mudança do Clima e Crescimento Verde – CIMV).

CIMV is composed of a council of ministers, including the Chief of Staff of the Presidency of the Republic (who acts as a chair of CIMV) and the ministers of Foreign Affairs (MoFA), Economy (MoE), Infrastructure (MoI), Agriculture, Livestock and Supply (MoALS), Mines and Energy (MoME), Science, Technology and Innovations (MoSTI), Environment and Climate Change (MoECC), Regional Development (MoRD) and Labour and Social Security (MoLSS). Besides the council of ministers, it also counts on a technical committee of the Inter-ministerial Committee on Climate Change and Green Growth.

The combined efforts of these institutions are trying to bring climate change to the centre of the national debate and inform effective policymaking in this area. The cascading effect would influence climate policies at the state and municipal administrative levels. However, significant opposition remains in place at the National Congress as well in many state and city governments.

[9] OEC (2023). Country profiles database. Available at: oec.world/en/profile/country/bra#:~:text=Exports%20The%20top%20exports%20of,and%20Chile%20(%247.14B)

[10] The Amazon rainforest is the largest but not the only natural biome at risk. The Cerrado and Atlantic forests are also significant targets to deforestation, and so are an important source of land-use emissions.

Learning from the Risk-Opportunity Analysis and Ten Policy Principles reports

Why ROA?

The uncertainty in the results of economic policy demands alternative means of policy appraisal to the more traditional cost-benefit analysis (CBA). The need is particularly pressing for long-term initiatives aimed at structural transformation, whose effects have many externalities that are difficult to quantify as marginal gains of a static objective function.

ROA is conceived to address the limitations of CBA in the context of transformative policies,[11] focusing on the systemic effects of the policy under analysis. The basic idea is to incorporate nonlinear effects, path-dependence and both positive and negative feedback in the analysis of economic policy, defining its aim in terms of the desired structural change instead of marginal gains in the existing economic structure.

The ROA model regards the economy as in constant evolution, where fundamental uncertainty makes it difficult to predict the outcomes of policy in exact terms, and where economic equilibrium is the exception instead of the rule. Based on this view, the effects of policies can have conflicting or synergic effects due to the multiple feedbacks that interact in the system. Box 1 shows the operational steps of ROA.

[11] Grubb, M., Drummond, P., Mercure, J.-F., et al. (2021) The new economics of innovation and transition: Evaluating opportunities and Risks. Economics of Energy Innovation and System Transition. Available at: eeist.co.uk/eeist-reports.

Step 1: Establish objectives, options, key system characteristics and system feedbacks.

- Define the objective within the target system (e.g. improving a specific technology within a given sector).
- Decide if the option being examined is 'mission-critical' to this objective.
- Establish the main characteristics, feedbacks and boundaries of the system and identify models available for analysing the system.

Step 2: Identify the impacts of policy options on processes of innovation and system change.

- Consider how policy options might affect innovation, infrastructure or other factors which may strengthen, weaken, create or eliminate reinforcing or balancing feedbacks, and whether or how this might change structural relationships between components of the system.
- Where historical data are available, assess the outcome of related past initiatives to inform the evidence based on system dynamics.

Step 3: Assess risks and resilience.

- Stress test the resilience of the system and the influence of the proposed policies regarding extreme, if unlikely, circumstances.
- Probe the most important ways in which the system could fail and the potential consequences with attention to cascading failures and tipping points, and the existence of low-likelihood, high-impact outcomes.

Step 4: Assess innovation and opportunity creation.

- Explore the ability of the policy to create or enhance options that could help the system evolve towards the goals established, in ways that capture economic and other opportunities.
- Large-scale programmes may also assess trade impacts, productivity improvements and resources and institutional implications.

Step 5: Engage decision makers concerning the impacts and uncertainties in multiple dimensions.

- Impacts, degrees of uncertainty or confidence, and resilience estimates for each of the metrics adopted in Step A can inform decisions, with specific reference to strategic goals of the overarching policy and legal frameworks.
- The preferred strategy is determined by the appropriately appointed decision maker.

Source: EEIST report, The New Economics of Innovation and Transition: Evaluating Opportunities and Risks.

In the context of economic transformation, the traditional principles that dominate policy thinking do not hold true any more, requiring to be reframed in this domain.

The Ten Policy Principles for Policy Making in the Energy Transition[12] report uses empirical evidence from case studies to propose how 10 traditional principles for policymaking can be substituted with 10 principles for the transition, as in agreement with ROA. Table 3 outlines these principles.

	Traditional principle	Principle for the transition	
1	*Policy should be 'technology neutral'*	**Technology choices need to be made**	In a context of innovation and structural change, policies will almost always advantage some technologies more than others. It is better to choose deliberately rather than accidentally, supporting innovation in low-carbon directions. Some policies intended to be neutral can have a bias towards incumbents, and incremental change.
2	*Government interventions raise costs*	**Invest and regulate to bring down costs**	Well-designed investment and regulation policies can bring down the cost of clean technologies, by creating a 'demand pull' for innovation that complements the 'supply push' of research, development and demonstration, strengthening learning-by-doing feedbacks in technology development, deployment and diffusion.
3	*Markets on their own optimally manage risks*	**Actively manage risks to crowd-in investment**	Low-carbon transitions involve many sources of uncertainty. Efforts to reduce the risks of private investment in clean technologies, including public finance acting as a lead investor, can reduce technology risk and financing costs and greatly increase rates of investment and deployment.
4	*Simply price carbon at a level that internalises the damages of climate change*	**Target tipping points**	Well targeted interventions can activate tipping points in technology competitiveness, consumer preference, investor confidence, or social support for transitions, where a small input leads to a large change. This can inform the targeting and level of subsidies and taxes, as well as the stringency of regulations.
5	*Consider policies individually based upon distinct 'market failures'*	**Combine policies for better outcomes**	A combination of policies will be needed to drive each low-carbon transition. Since the effect of each policy depends on its interactions with others, assessing policies individually can be misleading. Assessing policies as a package can identify those that are mutually reinforcing, generating outcomes 'greater than the sum of the parts'.
6	*Policy should be optimal*	**Policy should be adaptive**	There are many paths along which economies can develop over time. It is often impossible in practice to identify which is 'best' in terms of public goals, or even 'least cost' economically, which implies there may be no single 'optimal' policy. Given also the potential to learn from experience, policy should be designed to be adaptive, so that it can more easily respond to unforeseen changes, exploit opportunities and manage risks.
7	*Act as long as total benefits outweigh the costs*	**Put distributional issues at the centre**	Low-carbon transitions inevitably involve transfers of economic resources. Distributional issues should be central to policy analysis, since they are important for environmental, economic and social goals, and are likely to have a strong bearing on social support for the transition.
8	*Link carbon markets to minimise current costs*	**Coordinate internationally to grow clean technology markets**	Countries should coordinate internationally to grow clean technology markets in each of the emitting sectors of the global economy. This can lead to faster innovation and larger economies of scale, accelerating the cost reduction of clean technologies, with benefits for all countries.
9	*Assess aggregate costs and benefits*	**Assess opportunities and risks**	Policy appraisal should consider risks and opportunities, not just costs and benefits, when unquantifiable or very uncertain factors are likely to be important. Where the aim is transformational change, appraisal should consider the effects of policies on processes of change in the economy, alongside their expected outcomes.
10	*Policy models and assessment are neutral*	Know your biases	The construction of economic models unavoidably involves many choices that will influence their outputs, in which there are no 'correct' answers. We should be aware of our biases, make model choices transparently and, where possible, use a range of models instead of a single one.

Table 3. Ten policy principles for the transition, contrasted with traditional principles. Source Anadon et al. (2023).

[12,13] Anadón, L.D. et al. (2023) Ten policy principles for policy making in the energy transition: Lessons from experience. Available at: eeist.co.uk/eeist-reports.

The following section briefly summarises three case studies from the *Risk-Opportunity Analysis* and *Ten Policy Principles* reports that demonstrate how transformative policies were applied in Brazil, despite (not because of) the dominance in the use of static (not dynamic) modelling tools to inform policy. The adoption of these principles would promote a more mission-oriented government attitude to climate policy, which can be beneficial to the adoption of transformative policies in Brazil.

Wind turbines in Brazil (for additional background see [14])

The Brazilian electricity system has been operating at its full capacity for decades. This means supply is particularly vulnerable to droughts, as the main generation source is hydroelectric power plants (70% of total supply). In 2001, a major drought caused electricity supply restrictions in the country and acted as a tipping point for diversifying the energy mix with wind power so as to increase resilience.[15] The Incentive Programme for Alternative Sources of Electric Energy (Proinfa) was created in 2002, while empowering the role of the Brazilian Electricity Regulation Agency (ANEEL). The incentive system was based on feed-in tariffs, auctions specific for the wind energy sector and other market regulations. The effect of this strategy kicked off the dynamics of learning-by-doing, led to major cost and price reduction for wind generation (from US$1826/MWh t in 2004 to US$59.5/MWh in 2013[16]), making it competitive against other sources, and led to the expansion of wind energy especially in the northeastern part of the country (see Figure 5).

These polices could not easily have been justified by cost benefit analysis, since the cost per tonne of emission avoided by the Proinfa subsidies in 2002 was far higher than most estimates of the 'social cost of carbon', and also higher than many other options for Brazil to marginally reduce emissions, such as blending biomass in transport fuel, and reducing deforestation[17]. They could more reasonably have been justified by an ROA that considered the opportunities for rapid cost reduction, deep emissions cuts over time, a power system more resilient to drought, and job creation in the manufacturing and installation of wind power technologies. While these opportunities are undoubtedly clearer with hindsight, it is useful to consider the different conclusions that CBA and ROA could have led to, given that similar choices may arise in other sectors, or around other technologies, now and in the future.

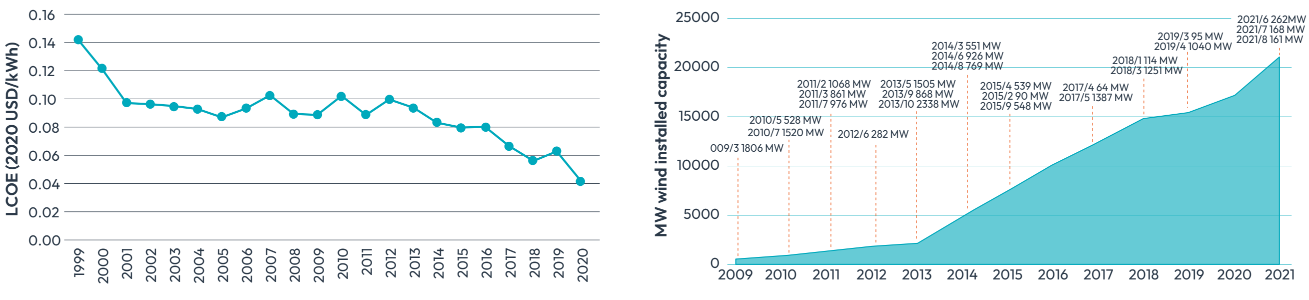


Figure 5. Onshore wind power expansion and LCOE reduction in Brazil.

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[14] Grubb et al. (2021). The New Economics Of Innovation And Transition: Evaluating Opportunities And Risks. EEIST Report. November 2021. eeist.co.uk/eeist-reports. Wind Energy in the UK and Brazil Annex.

[15] Nogueira, L. P. P. (2011). Estado atual e perspectivas futuras para a indústria eólica no Brasil. Dissertação de Mestrado. Universidade Federal do Rio de Janeiro.

[16] Ferreira, A. C., Blasques, L. C. M., & Pinho, J. T. (2014). Avaliações a respeito da evolução das capacidades contratada e instalada e dos custos da energia eólica no Brasil: do PROINFA aos leilões de energia. Revista Brasileira de Energia Solar. 5(1).

[17] Ramirez Camargo, L., Castro, G., Gruber, K., Jewell, J., Klingler, M., Turkovska, O., Wetterlund, E. & Schmidt, J. (2022). Pathway to a land-neutral expansion of Brazilian renewable fuel production. Nature communications, 13(1), 3157.

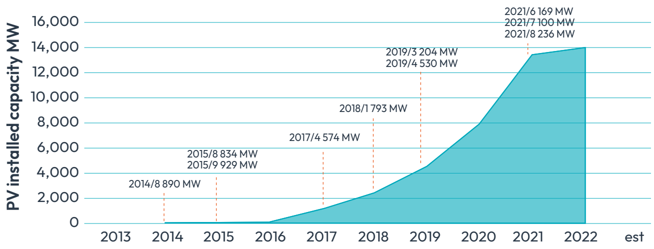
Solar PV in Brazil

Diversification in the energy mix has also advanced through the use of photovoltaic (PV) energy. Brazil's solar resource is both more intense, and much bigger, than in some other countries that have invested heavily in PV projects.[18] Yet In 2021, solar's share of the generation mix in Brazil was only 1.7% – significantly lower than in Germany (9%), France (3%) and Spain (6%).[19] This was due to a much later adoption of policy instruments in Brazil.

The situation has changed in the last decade due to a mix of favourable regulations and auctions introduced to accelerate the expansion of solar while decreasing cost (see Figure 6). The country's first large PV plant was installed only in 2011, in Tauá, Ceará. PV growth accelerated following a new regulation in 2012, which allowed small suppliers to access the grid at low or zero cost, enabling distributed generation,[20] with a growing number of households and firms investing in solar power to both reduce their bills and sell their surplus electricity to the public grid.

Centralised power generation gained force later, in 2014, when solar power plants were included in public auctions (with demand guarantees) at favourable prices for producers[21]. Therefore, this is a case of adaptive policy creating incentives for the adoption of clean and sustainable technologies after a slow start. Solar PV Capacity is growing exponentially in Brazil having reached 25GW in 2022[22], with forecasts estimating that Brazil will have almost 900k grid-connected solar power systems installed in 2024. [23,24]

As in the wind example, the first subsidies for solar deployment could not easily be justified through cost benefit analysis, since they achieved marginal emissions reductions at high cost. But those policies now appear well justified by their contribution to building up Brazil's capacity to accelerate installation as costs declined - both in terms of international modules, and domestic balance-of-system costs. Solar is becoming the cheapest source of power globally as well as in Brazil, and its cost advantage compared to all other generation technologies continues to widen[25].



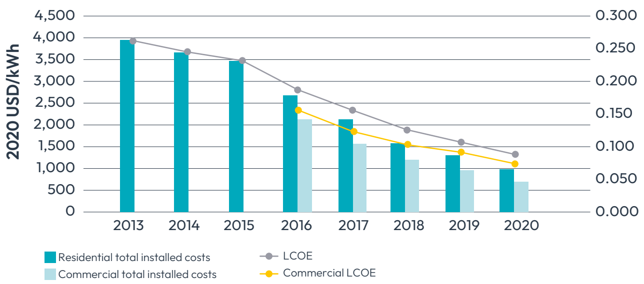


Figure 6. Solar PV expansion and LCOE reduction in Brazil.

[18] A Daily Direct Normal Irradiation in Brazil is mostly between 4-5 kWh/m2, compared to 2.5-3.5 in Northern Europe. It is also less variable (particularly seasonally) and of course Brazil has vastly bigger land area.

[19] IEA. (2021). Electricity Information. www.iea.org/data-and-statistics/data-product/electricity-information.The percentage of solar PV energy over the country's electricity generation for Germany, France and Spain is from 2020.

[20] Esposito, A., Fuchs, P. (2013). Desenvolvimento tecnológico e inserção da energia solar no Brasil. web.bndes.gov.br/bib/jspui/handle/1408/1421

[21] Pereira, N. (2019). Desafios e perspectivas da energia solar fotovoltaica no Brasil: geração distribuída vs geração centralizada. UNESP

[22] IRENA (2023). Renewable Power Generation Costs in 2022, International Renewable Energy Agency, Abu Dhabi. Avaiable online at: https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf?rev=cccb713bf8294cc5bec3f870e1fa15c2

[23] ANEEL. (2022). Resultados dos leilões de expansão da geração. Relatório interativo. Dados por Empreendimento. Accessible at: app.powerbi.com/view?r=eyJrIjoi-YmMzN2Y0NGMtYjEyNy00OTNlLWI1YzctZjI0ZTUwMDg5ODE3IiwidCI6IjQwZDZmOWI4LWVjYTctNDZhMi05MmQ0LWVhNGU5YzAxNzBlMSIsImMiOjR9.
Last accessed November 2023.

[24] ESFC Investment Group (2023). Solar power plants in Brazil: financing and construction. Available online at: https://esfccompany.com/en/articles/solar-energy/solar-power-plants-in-brazil/. Last accessed November 2023.

[25] Nijsse, F. J., Mercure, J. F., Ameli, N., Larosa, F., Kothari, S., Rickman, J., Vercoulen, P. & Pollitt, H. (2023). The momentum of the solar energy transition. Nature Communications, 14(1), 6542.

Ethanol in the transport sector in Brazil

Another powerful example of policy-driven expansion of energy supply is that of ethanol. The Brazilian investment in ethanol as an alternative fuel for vehicle propulsion dates to 1979, when the first alcohol-powered car was launched in the country. The initiative was part of the 'Proálcool' programme – the government's response to the 1973 oil shock. Despite some initial problems with the technology, such as difficulty in starting engines at low temperatures and the lower energy efficiency in comparison to gasoline, both ethanol vehicles and gas stations began to proliferate in the country during the mid-1980s.

It then took off in the 2000s, when the development of flex-fuel engines allowed consumers to choose the best fuel based on market prices.[26] Today, almost every light duty vehicle produced in Brazil has a flex-fuels engine. The current rule of thumb is that ethanol pays off when its price is less than 70% of the price of gasoline at the pump.[27] Such an extensive adoption of flex-fuel technology in the 2000s was only possible thanks to the large-scale government investments and subsidies on ethanol production from sugarcane in the 1970s and 1980s. This allowed for the development of scale in ethanol distribution and gave consumers the opportunity to make a choice between fuels even for the cheapest vehicles in the market.

More recently, in the 2020s, the country's industry is starting to develop hybrid (electric) flex-fuel engines, which can increase consumers' choice and the country's energy resilience even further.

Any CBA undertaken to inform the decision in the 1970s to invest in creating an ethanol market in road transport would have had to estimate cost savings of ethanol compared to petrol, based on assumptions about future oil prices. Crude oil prices have fluctuated wildly since then: from barely US$30 per barrel during the COVID-19 crisis in 2020 to well over US$100 per barrel in June 2008.[28] Even a central estimate that was fortunately accurate would have failed to capture the true benefit of the policy for Brazilian consumers: the greater resilience it provided against oil price spikes.

Looking ahead, CBA based on the value of marginal emissions reductions would still be a poor guide to technology choices for the future of road transport. In turn, the large role of ethanol (and domestic oil production) could impede accelerated adoption of EVs where they may be beneficial. In policy decisions that influence the balance between ethanol fuels and EVs, the government will need to consider opportunities and risks related to future technology costs, jobs and competitiveness in auto manufacturing and exports, the implications for electricity grids of large numbers of EVs, and competing needs for the finite supply of genuinely sustainable biofuels.

From empirical evidence to policy engagement

This section has provided evidence of use of policy instruments that supported the expansion and technology diffusion of low carbon technologies in Brazil, providing both theoretical underpinning from ROA and real-world examples for the case of onshore wind, solar PV and ethanol diffusion. Box 2 and the Appendix give insights on how EEIST's engagement strategy was performed in Brazil in line with the evidence summarised in the project's policy reports.

[26] Lopes, M.L., Paulillo, S.C.D.L., Godoy, A., Cherubin, R.A., Lorenzi, M.S., Giometti, F.H.C., Bernardino, C.D., Amorim Neto, H.B.D. and Amorim, H.V.D., 2016. Ethanol production in Brazil: a bridge between science and industry. Brazilian journal of microbiology, 47, pp.64-76.

[27] Pacini, Henrique, Arnaldo Walter, and Martin Kumar Patel. 'Is ethanol worth tanking only when it costs 70% of the price of the equivalent in volume of gasoline?' Biofuels 5, no. 3 (2014): 195-198.

[28] U.S. Energy Information Administration (2023). Statistics available online at: www.eia.gov/dnav/pet/hist/RWTCD.htm. Accessed in October 2023.

Engagement strategy built around communities of practice

The engagement strategy in Brazil illustrates the importance of a clearly conceived structure centred around communities of practice (CPrs), and proceeding from more general to more targeted engagement. This case demonstrates both the robustness and the effectiveness of a strong strategy that can be applied to every other country in international research projects that focus on policy impact. A clear overall design guiding the selection of country partners and relying on their leadership was a decisive factor, with the bottom-up engagement strategy played at the local level being determinant in the success of the entire programme. This, aligned with the overarching international-impact engagement strategy, supported highlighting peculiarities and barriers in those systems of governance helping to understand regulatory bottlenecks even further.

Figure 4 shows the number of events that were run along the CPr thread, and their alignment between national and international CPr approaches. Table 2 shows some of the organisations that engaged with EEIST in Brazil.

Figure 7. The engagement strategy in Brazil highlighting the cross-learning international motives, and the persistency aspects via the community of practice events in the local context. The EEIST academic partners involved were Federal University of Rio de Janeiro (UFRJ), State University of Campinas (UNICAMP), University of Brasilia (UnB), Sant'Anna School of Advances Studies (SSSA), University of Cambridge (UCAM), University of Exeter (UEX), University of Oxford (UOX), Anglia Ruskin University (ARU) and University College London (UCL).

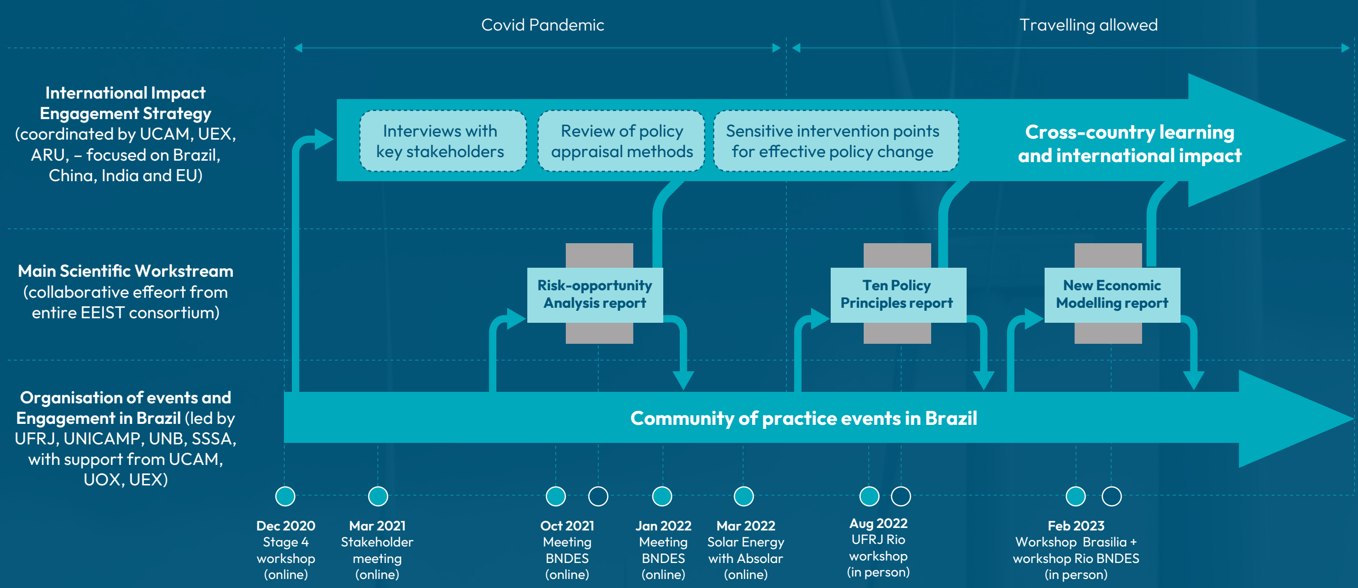


Table 4. List of some organisations engaged with EEIST in Brazil.

Organisation	Stakeholder type
Senate Commission on the Environment	Congress
Chamber of Representatives	Congress
Ministry of Public Management and Innovation	Federal administration
Ministry of Agriculture and Livestock	Federal administration
Ministry of the Environment	Federal administration
Ministry of Finance	Federal administration
Ministry of Mining and Energy (MME)	Federal administration
Ministry of Mining and Energy (MME)	Federal administration
BNDES	Federal public agency
BNDES	Federal public agency
Energy Planning Company (EPE-MME)	Federal public agency
National Agency for Electric Energy (ANEEL)	Federal regulatory agencies
UN ECLAC	International agency
Brazilian Solar Energy Association (ABSOLAR)	National associations
Brazilian Wind Energy Association (ABEOLICA)	National associations

Finance situation in Brazil

Decarbonising the Brazilian economy

Brazil has been undergoing a process of deindustrialisation since the 1990s that has deepened in the last decade. Industry's share of GDP dropped from 36% in 1985 to 11% in 2021 and policymakers are concerned about a return to reliance on the export of primary materials, associated with lower productivity gains.

In general, the government sees investment in clean technologies across all sectors as an opportunity to reindustrialise the economy and add value to Brazil's exports. This may be a long-term effort, but the government wants to show as much short-term progress as possible. This is reflected in new senior official positions created by the current administration across ministries, such as the Secretary for the Green Economy, Decarbonisation and Bioindustry at the Ministry of Development, Industry and Trade. Recent industrial policy has targeted components of wind and solar power supply chains, including subsidising semiconductor manufacturing, in an attempt to develop a local industry supplying the fast-growing deployment of distributed solar generation.

But there are also risks. The oil and gas industry employs around 340,000 workers directly, and around 1.6 million across the supply chain, and in 2021 it generated more than US$19bn in tax revenue. More than 80% of national oil and gas production is in the state of Rio de Janeiro, where lower oil prices since 2014 have caused a fiscal crisis. Brazil's oil production is relatively high-cost, making it more vulnerable to the global transition. The government must also worry about what will happen to the more than 860,000 people employed in biofuel supply chains if a different technology path is chosen.

Macroeconomic aspects of financing the transition to sustainable energy in Brazil

From the perspective of macroeconomic and financial stability, the Brazilian economy is facing a number of challenges.[29] The drop in commodity prices combined with the rise in exchange rates in the international currency market is expected to generate pressures for reducing inflation. It is also expected that the SELIC rate (the risk-free rate), i.e. the basic interest rate applied to the government in Brazil) will fall during the second semester of 2023, resulting in incentives for more investment from the private sector. As a result, the country's economic situation in 2024 is expected to be characterised by uncertainty and instability.

In terms of public deficit, the efforts to control public finances using a fixed cap were frustrated by the COVID-19 pandemic, which forced the expansion of income support programmes. However, the effort to control public deficit should eventually benefit from the expected growth in GDP and reduction in interest rates.[30]

One of the most important components of aggregate demand is the investment in fixed capital. It is frequently used to forecast short-term changes in Brazil's GDP, considering household and government consumption is significantly more stable. In this respect, the recent recovery in fixed investment presented in Figure 5 may signal good prospects for the coming years. If investment in clean energy projects is added to this trend, a longer period of growth becomes more likely.

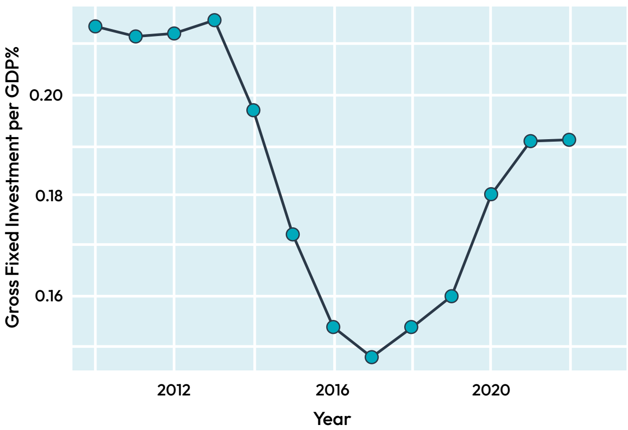


Figure 8. Gross fixed investments as a fraction of GDP in Brazil. Source: elaborated by the authors from SIDRA (2023).[31]

[29] https://www.ipea.gov.br/cartadeconjuntura/wp-content/uploads/2023/07/230705_cc_59_nota_33_visao_geral.pdf

[30] www.scielo.br/j/rep/a/w6bJQyLcz39bhzhsgbYyccr

[31] sidra.ibge.gov.br/pesquisa/cnt/tabelas

Indeed, one reason for the recent recovery in investment may be found in the country's gradual institutional realignment to support sustainability commitments, including new investments in sustainable energy generation. The Banco Nacional de Desenvolvimento Econômico e Social (BNDES), by means of the FINEM program, approved almost R$ 3.5bn in investment in renewable energy at the beginning of 2023. These include three new renewable energy generation complexes to be installed in the states of Minas Gerais and Bahia.[32]

There are five main public institutions that provide finance for energy transition projects in Brazil: (1) BNDES; (2) Banco do Nordeste (BNB)[33]; (3) Banco da Amazonia (BASA)[34]; (4) Banco de Desenvolvimento de Minas Gerais (BDMG)[35] and, (5) Financiadora de Estudos e Projetos (FINEP)[36]. Although directed by common sustainability objectives, each of these institutions has different strategies, conditions and eligibility criteria for financing projects.

As part of the strategy to promote green investments, the government sought to attract greater private participation in the market for 'green' bonds issued mainly by public institutions. However, between 2015 and 2022, just a little less than US$22m in such bonds were issued. Figure 9 shows the issued bonds from 2016 to 2022, demonstrating how the Sustainability Linked Bonds (SLB) took dominance against all others (GB: Green Bond, STB: Sustainability Transition Bond, SB: Sustainability Bond, S: Social Bond). SLBs were launched for the first time in September 2019 by ENEL[37] as a complement to green bonds, so as to enable more issuers to access the sustainable financing market. This lowers the barriers for access as the bonds are not restricted to be used in green projects, but requires the issuers to have an overall sustainability strategy in place, or demonstrate previous ESG target achievements.

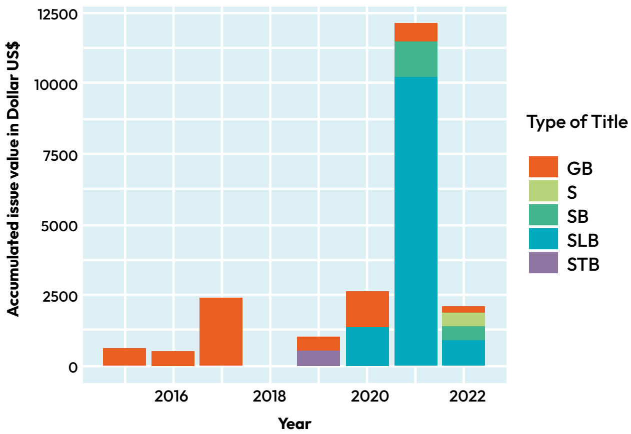


Figure 9. Issuance of green bonds by Brazilian entities. Source Natural Intelligence (NINT).[38]

The increase in green bonds (mainly SLBs) seems to indicate that the country has an opportunity to gain greater domestic and international confidence from private agents through sound and transparent economic policies that support the green transition[39,40], By building trust in the green bond markets, it is possible to stimulate the diversification of the financial instruments available for financing transition projects. This reinforces the country's reputation on the international stage, and allows Brazil to raise funds for investments in environmentally responsible projects and initiatives, boosting sustainable development and contributing to a more prosperous and ecologically balanced future. The 30th Conference of Parties on Climate Change (COP30), to be hosted in Brazil, may be an important venue to exploit this opportunity.

[32] https://www.bndes.gov.br/wps/portal/site/home/financiamento/produto/bndes-finem-distribuicao-energia-eletrica

[33] www.bnb.gov.br

[34] www.bancoamazonia.com.br

[35] www.bdmg.mg.gov.br

[36] www.finep.gov.br

[37] www.nortonrosefulbright.com/en-br/knowledge/publications/8a104da8/sustainability-linked-bonds#section4

[38] www.nintgroup.com

[39] Markowitz, H. M. (2015). Portfolio theory. Personal Finance: An Encyclopedia of Modern Money Management: An Encyclopedia of Modern Money Management, 321.

[40] KÖLBEL, Julian F.; LAMBILLON, Adrien-Paul. Who pays for sustainability? An analysis of sustainability-linked bonds. An Analysis of Sustainability-Linked Bonds (January 12, 2022). Swiss Finance Institute Research Paper, n. 23-07, 2022.

Modelling case studies

Overview

This section presents four case studies of new economic modelling being applied to the national context and policy questions relevant to Brazil. These case studies can be read alone or in combination. They each cover key points such as the policy topic at hand, methodological details, findings and implications. Such modelling work relies on insights from *Risk-Opportunity Analysis* and the case studies of successful transition policies in Brazil as indicated in the *Ten Policy Principles* report. For a broader review of the modelling principles underlying these models, see EEIST's report *New Economic Models of Energy Innovation and Transition.*[41]

These new case studies are complementary to previous modelling work undertaken by the Brazil team as part of EEIST. These include three national case studies on the application of system mapping to understand the impact of the energy transition on the sustainable development goals (SDGs)[42] and on jobs,[43] and analysis of investors' choice in hindering energy transition to renewables based on exit-options analysis;[44] and two global case studies that analyse farmers' behaviours in adopting sustainable practices,[45] and policies that can accelerate decarbonisation while preserving economic stability and growth.[46]

[41] Barbrook-Johnson, P. et al. (2023) New Economic Models of Energy Innovation and Transition: Addressing New Questions and Providing Better Answers. Exeter, UK: Exeter University. Available at: eeist.co.uk/eeist-reports.

[42] de Moura, F.S. and Barbrook-Johnson, P. (2023) Data-Driven Systems Mapping of SDGs and Energy Transition Interactions, pp. 150–155. Available at: eeist.co.uk/eeist-reports.

[43] Berryman, A. et al. (2023) Modelling labour market transitions: the case of productivity shifts in Brazil, pp. 120–126. Available at: eeist.co.uk/eeist-reports/ (Accessed: 1 June 2023).

[44] Martins, A.C., Pereira, M. de C. and Pasqualino, R. (2023) 'Renewable Electricity Transition: A Case for Evaluating Infrastructure Investments through Real Options Analysis in Brazil', Sustainability, 15(13), p. 10495. Available at: doi.org/10.3390/su151310495.

[45] Coronese, M., Occelli, M., Lamperti, F., Roventini, A. (2023) Supporting sustainable agriculture intensification: a system-wide agent-based modelling approach. Exeter: University of Exeter, pp. 112–119. Available at: www.eeist.co.uk/eeist-reports.

[46] Lamperti, F. and Roventini, A. (2023) Policy options for rapid smooth decarbonisation and sustainable growth. Exeter: University of Exeter, pp. 46–51. Available at: www.eeist.co.uk/eeist-reports.

The main findings from the novel modelling case studies presented in this report are reported in the following table:

Table 5. Modelling case studies applied to Brazil context.

Policy questions	Key findings	Topic (Method)	Title
Can combined public financing and auctions policies for solar and wind generate opportunities for development that outweigh those generated by applying the policies in isolation?	Financial constraints severely affect transition processes in the private sector, and these can be overcome by public financing. Reducing cash flow risks through auctions associated with power purchase agreements can induce faster transitions, with limited effects The interplay between auctions and public financing is crucial for the entry of renewables in Brazil. Coordination of multiple policies might be able to accelerate the energy transition beyond the application of each taken in isolation and without additional costs for policy. When auctions and public financing are used together, they achieve more than the sum of their parts.	Combined policies for low-carbon transition (agent-based model).	Positive nonlinear change from combining low-carbon energy policies from a polycentric governance perspective: an agent-based analysis.
How do different power sector technology mixes compare in terms of cost effectiveness and wider economic impacts? **Would more solar power, compared to the likely current trajectory, be a good or bad thing for Brazil?**	Scenarios with higher deployment of renewables tend to achieve more positive results for GDP and employment. These findings are likely to be an understatement, since the model used does not explicitly represent the jobs created around new technologies such as solar and wind power. It may be beneficial to take measures to accelerate the deployment of both solar and wind, but with the emphasis on supporting solar in the near-term (since it has a much smaller share of generation than wind at present), and a greater emphasis on supporting wind over the longer term. It appears that the power generation technology mix calculated by the cost-optimising models may not be the least cost one. Lower electricity prices could be achieved by either boosting or limiting solar deployment, due to the dynamic interplay between the greater deployment of solar and reduced costs of generation; and with a better balance between solar and wind reducing the costs of energy storage. The differences between these models' respective outputs of most likely and cost-optimal solar deployment increase with time.	Cost of solar and expansion of solar industry (comparison between dynamic and cost-optimising models).	Power sector technology choices and economic outcomes: A comparative analysis using optimising and simulating models.

Policy questions	Key findings	Topic (Method)	Title
How much can innovation in energy intensity contribute to the reduction in energy demand and associated GHG emissions for Brazil by 2050? **What are the prospects for low-carbon energy transition scenarios based on the current trends of energy efficiency and energy supply in Brazil?** **What is the combined effect of policies on energy efficiency and energy substitution to low-carbon sources for the energy transition in Brazil?**	Firm-led innovation is one of the main determinants of a long-run trend of declining energy intensity and plays a key role in reducing energy demand and its associated carbon emissions. The current speed of advancements in energy saving technologies can contribute to a 15% approximate reduction of total energy demand and associated carbon emissions by 2050, but Brazil is unlikely to sustainable development targets without a transition in energy supply. The current speed of energy transition in the power sector can also contribute to a 15% approximate reduction of carbon emissions, which is still unlikely to meet the sustainable development targets by 2050. A combination of firm-led energy efficiency innovations and government policies that promote the transition to low-carbon energy sources is suggested as the best approach to achieve climate and energy targets by 2050.	Domestic energy demand (agent-based model).	Firm-led innovations in energy efficiency and its contributions to carbon emissions in Brazil.
From which parts of the economy should the government seek to reduce emissions? **How important will international trade be in the decarbonisation of Brazil's economy?**	Most polluting industries seem to be reducing the intensity of their GHG emissions (except for electricity, water, and gas). Agriculture, electricity generation and transport are responsible for most of Brazil's emissions. Exports accounted for almost a third of national emissions in recent years, but their production only represented 16% of gross output. Therefore, exports are more intensive in emissions by 9 tCO_2/R$ in comparison to the average of the economy. Despite still being a key source of national GHG emissions, household consumption has achieved improvements in the intensity of emissions. Reducing national emissions by replacing national products with imported products, whether for final or intermediate consumption, is unlikely to be helpful either for reducing global emissions, or for Brazil's economic development. Brazil has a strong interest in coordinating with other countries to establish conditions in global markets that would allow its export industries to remain competitive while eliminating emissions from their production processes.	Exports and re-industrialisation (Static input-output analysis).	Identifying the sources of structural changes of greenhouse gas emissions in Brazil: an input-output analysis from 2000 to 2020.

Positive nonlinear change from combining low-carbon energy policies from a polycentric governance perspective: An agent-based analysis

Authors: Gustavo Andreao, Jose Maria da Silveira, Miguel Vazquez, Roberto Pasqualino.

Policy questions

Can combined public financing and auctions policies for solar and wind generate opportunities for development that outweigh those generated by applying the policies in isolation?

Method

Agent-based model.

Key findings

- Financial constraints severely affect transition processes in the private sector, and these can be overcome by public financing.
- Reducing cashflow risks through auctions associated with power purchase agreements can induce faster transitions, with limited effects. The interplay between auctions and public financing is crucial for the entry of renewables in Brazil.
- Coordination of multiple policies might be able to accelerate the energy transition beyond the application of each taken in isolation and without additional costs for policy. When auctions and public financing are used together, they achieve more than the sum of their parts.

Summary

The authors use an agent-based model to analyse the interplay between public financing and auctions for the expansion of solar and wind in Brazil. The main objective of the study is to demonstrate how a mix of policies towards energy transition produces positive nonlinear change in comparison to both policies applied in isolation. The study advocates for improving coordination of multiple systems of governance that, if combining their efforts, might be able to accelerate the energy transition considerably without additional costs for policy.

Introduction

Climate change is a reality that we must face.[47] The overreliance on fossil fuels only increases the need for collective actions requiring multiple institutions that apply policies at the same time.[48]

This case study focuses on the challenge of renewable energy transition in Brazil, with particular attention to combined use of public financing and auctions policies.[49] This was a particularly important case for the Brazilian economy because auctions associated with power purchase agreements were the main policy used to prompt the expansion of the electricity mix in Brazil towards renewables (e.g. wind energy) since the early 2000s.[50] In fact, as a continental country, the use of centralised auctions alongside long-term power purchase agreements have been used to successfully increase Brazil's electricity capacity while avoiding an overreliance on natural gas.[51] Since 2010 there have been plans to insert more solar PV into the electricity mix[52] and auction contracted projects were awarded special public funds by the development bank of Brazil (BNDES), at first to expand the electricity mix in order

[47] Intergovernmental Panel on Climate Change IPCC, Climate Change 2022: Mitigation of Climate Change, Assessment Report of the Intergovernmental Panel on Climate Change, VI (Geneva: United Nations, 2022), report.ipcc.ch/ar6/wg3/IPCC_AR6_WGIII_Full_Report.pdf.

[48] Valeria Constantini, Francesco Crespi, and Alessandro Palma, "Characterising the Policy Mix and Its Impact on Eco-Innovation in Energy-Efficient Technologies," Sustainability Environmental Economics and Dynamic Studies Working Paper Series 11 (2015).

[49] Kathryn Hochstetler and Genia Kostka, "Wind and Solar Power in Brazil and China: Interests, State–Business Relations, and Policy Outcomes," Global Environmental Politics 15, no. 3 (August 2015): 74–94, doi.org/10.1162/GLEP_a_00312.

[50] Paolo Mastropietro et al., "Electricity Auctions in South America: Towards Convergence of System Adequacy and RES-E Support," *Renewable and Sustainable Energy Reviews* 40 (December 2014): 375–85, doi.org/10.1016/j.rser.2014.07.074.

[51] R. R. Timponi, "Leilões Como Mecanismo de Planejamento Da Expansão de Geração Elétrica: O Caso Do Setor Elétrico Brasileiro" (Master's thesis, Rio de Janeiro, Universidade Federal do Rio Janeiro, 2010), www.gee.ie.ufrj.br/index.php/component/cck/?task=download&file=dissertacao_tese_arquivo&id=94.

[52] EPE, "Análise Da Inserção Da Geração Solar Na Matriz Elétrica Brasileira," *Nota Técnica EPE*, May 2012.

to avoid blackouts,[53] but later with a deliberate local content requirement policy aimed at internalising industries.[54] Nevertheless, even with solar projects entering auctions, there was a slow start to the solar expansion in Brazil.[55]

This case study therefore focuses on a relatively simple scenario to test the potential impact of combining auctions and public financing on the uptake of solar power in Brazil. The specific policy question addressed is: Can combined public financing and auctions policies for solar and wind generate opportunities for development that outweigh those generated by applying the policies in isolation?

The Tefe model

In order to address this problem, we develop a simulation model, Technology, Financing and Energy model (TeFE) (see Figure 10). This is an agent-based model (ABM),[56] newly developed at the University of Campinas, that models the dynamic interplay of public and private institutions in Brazil. TeFE values the understanding of heterogeneous agents playing a policy role for the context of the energy transition. As a result, it is designed to capture a number of different policies, i.e. public financing, guarantees by a public bank, feed-in tariffs, auctions, carbon-tax and cashflow incentives to technology firms.

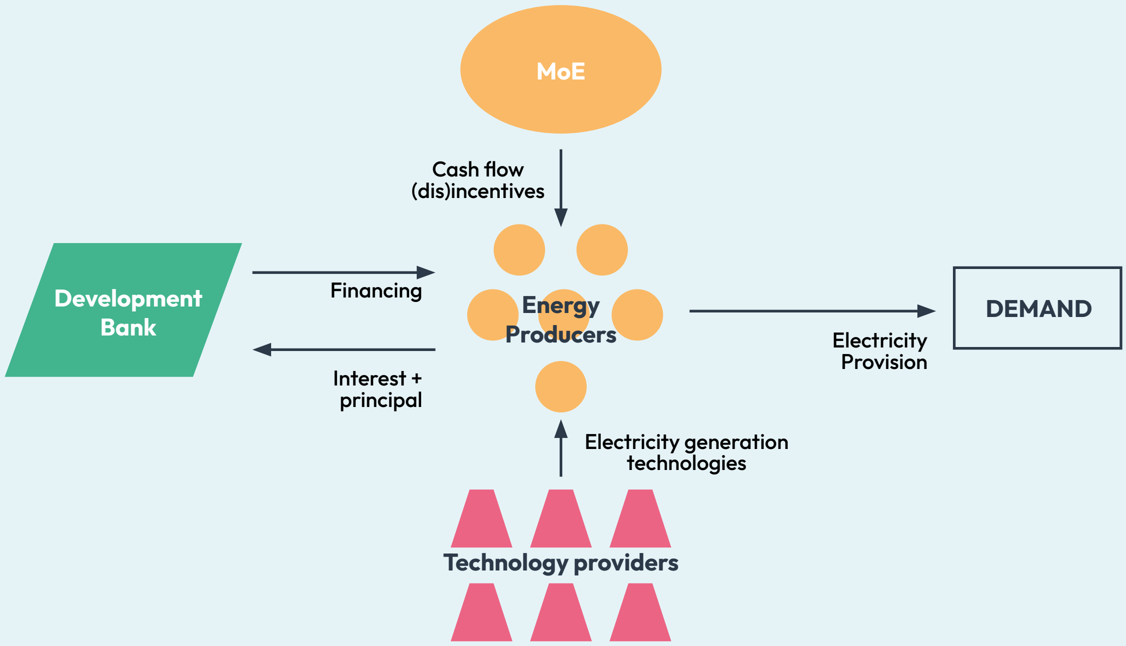


Figure 10. Diagram of the TeFE model. Energy producers acquire electricity generation assets from technology producers, being financed either by a development bank or through reinvestment. The Ministry of Energy (MOE) provides cashflow incentives to energy producers. Electricity is produced to meet demand.

The TeFE model consists of two classes of industrial agents and two classes of public organisations. On the industrial side, we consider energy providers and technology producers. Technology producers invest in productive capacity or in R&D and manufacture energy provision assets, focusing on either wind or solar technologies. Energy providers acquire assets from technology producers in order to provide electricity; they choose between solar, wind and gas. All agents pursue a satisficing heuristic where private agents attempt to catch up with competitors when lagging behind, but will accommodate themselves when in front of competition.[57] Two hypothetical ministries govern on top of the industrial agents and act as policymakers on different domains and based on separate budgets. These are (a) a Ministry

[53] João Carlos Ferraz and Luciano Coutinho, "Investment Policies, Development Finance and Economic Transformation: Lessons from BNDES," *Structural Change and Economic Dynamics* 48 (March 2019): 86–102, doi.org/10.1016/j.strueco.2017.11.008.

[54] M. G. Podcameni, "Sistemas de Inovação e Energia Eólica: A Experiência Brasileira." (PhD Thesis, Rio de Janeiro, Universidade Federal do Rio Janeiro, 2014).

[55] Miguel Vazquez and Michelle Hallack, "The Role of Regulatory Learning in Energy Transition: The Case of Solar PV in Brazil," *Energy Policy* 114 (March 2018): 465–81, doi.org/10.1016/j.enpol.2017.11.066.

[56] L. Tesfatsion, "Agent-Based Modeling and Institutional Design," *Eastern Economic Journal* 37, no. 1 (January 2011): 13–19, doi.org/10.1057/eej.2010.34.

[57] Herbert A. Simon, "Theories of Decision-Making in Economics and Behavioral Science," *The American Economic Review* XLIX, no. 3 (June 1959): 253–83.

of Energy (MoE), which decides between auctions, carbon tax and feed-in tariffs, thus supporting the development or decline of energy technologies in the longer term (e.g. solar, wind or fossil fuels); and (b) a development bank (DB), which decides between direct lending and guarantee provision. In the experiment reported here, these policy choices are inputs to the model. The focus on polycentric governance of the TeFE model addresses the simultaneous policies of complementary public organisations that act in a constantly changing policy landscape driven by socio-technical transition and heterogeneous interests of their agents.

The model in use agrees with the newly developed policy assessment framework of risk-opportunity analysis (ROA)[58] in different ways: equilibrium is not an assumption, agents are heterogeneous, and path dependency and nonlinear change can occur as a result of policy decisions due to the interaction between agents. The model accounts for the cumulative effect of past decisions, and the use of satisficing heuristics instead of optimal behaviour of agents (i.e. profit maximisation or cost minimisation),[59] that generates path dependence in the model outcome. For example, in the Tefe model, the expansion of the energy supply follows the demand, but these do not have to match one to another at every point in time during a simulation, i.e. not all new generation will be contracted if the demand is met with less than 100% of capacity utilisation.[60]

Results

We run an experiment based on Brazilian data from the 2000s until mid-2010s. The model is inspired by the slow entry of solar PV capacity in Brazil, which was a result of auction-contracted capacity growing, but with constructors not being able to access the DB's subsidised financing over this decade because the domestic content requirements were too difficult to meet.[61]

The experiment consists of building three scenarios: (i) only auctions are considered, mimicking the slow start of solar and wind in Brazil (Auction scenario); (ii) only public financing from available DB funds are considered (Financing scenario); (iii) both policies are applied together (Combined scenario). These scenarios are also compared to the base run scenario, where neither policy is implemented (No Policy scenario).[62] Agents may choose between onshore wind, solar PV and a fossil power plant that uses natural gas as fuel. Table 6 summarises the inputs in the scenarios from the respective governing agents.

Table 6. Combination of policies from Development Bank and Ministry of Energy for the scenario analysis.

Agent	Development Bank (DB)	Ministry of Energy (MoE)
Policy	Public financing for wind and solar	Auctions for wind and solar
Requirements to receive funds	Plants above the threshold of local content requirement have a higher chance of accessing the subsidised funds (0.5% per month of interest rate) and 25 years to amortise the plants	Lower-cost plants have a higher chance of being awarded power purchase agreements for the duration of 20 years of operations
Aim of the policy	Foster the internalisation of the value chain of the energy technology	Foster the entry of renewables in the market
Policy variables	Interest rate reduced from 0.11% (No Policy scenario) to 0.05% per month (Public Financing and Combined scenarios) Local content requirements reduced from 100% (No Policy) to 0% (Public Financing and Combined scenarios)	Auction size increases from 1 GW (No Policy) to 5 GW (Auctions and Combined scenarios)[63]

[58] Michael Grubb et al., *The New Economics of Innovation and Transition: Evaluating Opportunities and Risks*, 02 November 2021 The Economics of Energy Innovation and System Transition (EEIST) Consortium (EEIST, 2021), eeist.co.uk/download/557; Jean-Francois Mercure et al., "Risk-Opportunity Analysis for Transformative Policy Design and Appraisal," *Global Environmental Change* 70 (September 2021): 102359, doi.org/10.1016/j.gloenvcha.2021.102359.

[59] Herbert A. Simon, "Theories of Decision-Making in Economics and Behavioral Science," The American Economic Review XLIX, no. 3 (June 1959): 253–83.

[60] Starting values are 3% of the Brazilian electricity demand (around 15 TWh).

[61] Gustavo Onofre Andreão, "The Dawn of Solar in Its Dusk: An Agent-Based Model for the Impaired Utility-Level Solar Photovoltaic Expansion in Brazil" (Master's thesis, Niterói, Universidade Federal Fluminense, 2018); G. O. Andreão, M. C. M. Hallack, and M. Vazquez, "Rationales for Technology-Specific RES Support: The Impaired Brazilian Solar Expansion," *Bocconi IEFE Working Paper* 99 (2017): 33

[62] The absence of a MOE means that there is no active energy policy in the scenario, not that there is no energy regulation or no wholesale Market for electricity.

[63] Wind turbines have 1.5 MW of capacity, solar panels have 100 kW of capacity and natural gas plants have 50 MW of capacity. That capacity encompasses the minimum investment in watts per source, in other words, the minimum lump of investment. Energy providers may invest in several lumps: multiple solar panels at a solar farm, multiple wind turbines at a wind farm or multiple generators at a large fossil power plant.

In the Auction scenario there is a MoE that opens auctions with power purchase agreements that last 20 years, starting from the entry of the plant into the energy mix. This ensures a consistent cash inflow, thus reducing the risks of renewable plants not being contracted. In other words, these contracts assure that energy providers receive a stable monthly income from the government that is enough to make a profit while paying the investment back in the long run. In the Financing scenario, there is a DB financing renewable plants with reduced interest rates, thus reducing the risks of an energy producer not having enough funds to invest in new capacity (this scenario is in line with the observed data from Brazil[64]).

In the No Policy scenario there are no policies in force, leading to a slow and uncertain expansion of renewable plants (Figure 11). The median simulation[65] for the generation contracted for renewables remains below 1 TWh at the end of the simulation. A decrease in generation may happen if the price is not enough to cover costs, or if plants are decommissioned and agents do not have enough funds to replace the decommissioned capacity. This explains the instability of the natural gas plants in Figure 2 as the sector could have difficulties in meeting cash balances without any public support.

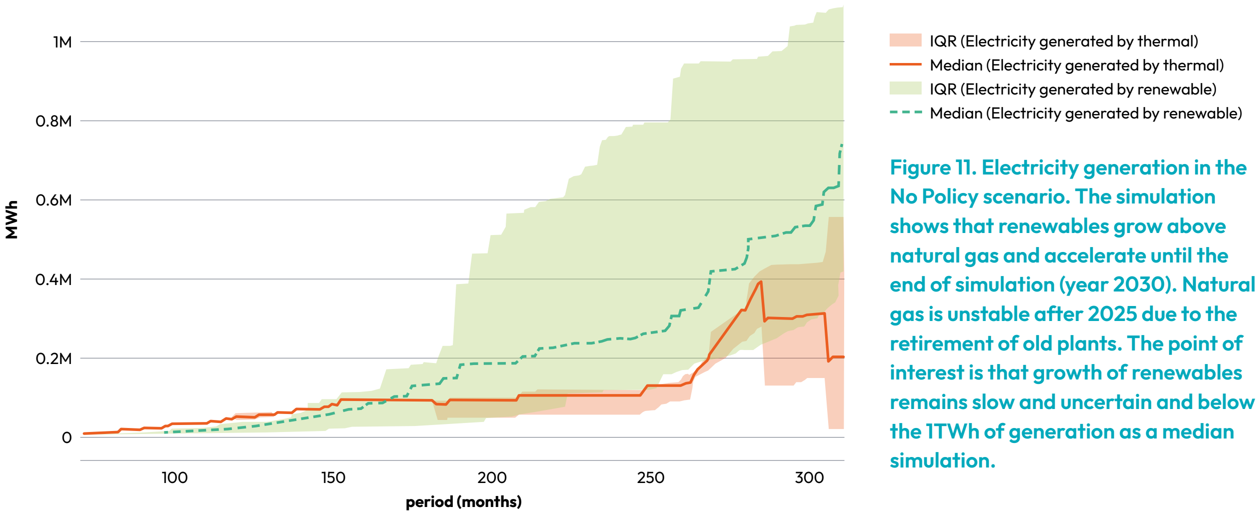


Figure 11. Electricity generation in the No Policy scenario. The simulation shows that renewables grow above natural gas and accelerate until the end of simulation (year 2030). Natural gas is unstable after 2025 due to the retirement of old plants. The point of interest is that growth of renewables remains slow and uncertain and below the 1TWh of generation as a median simulation.

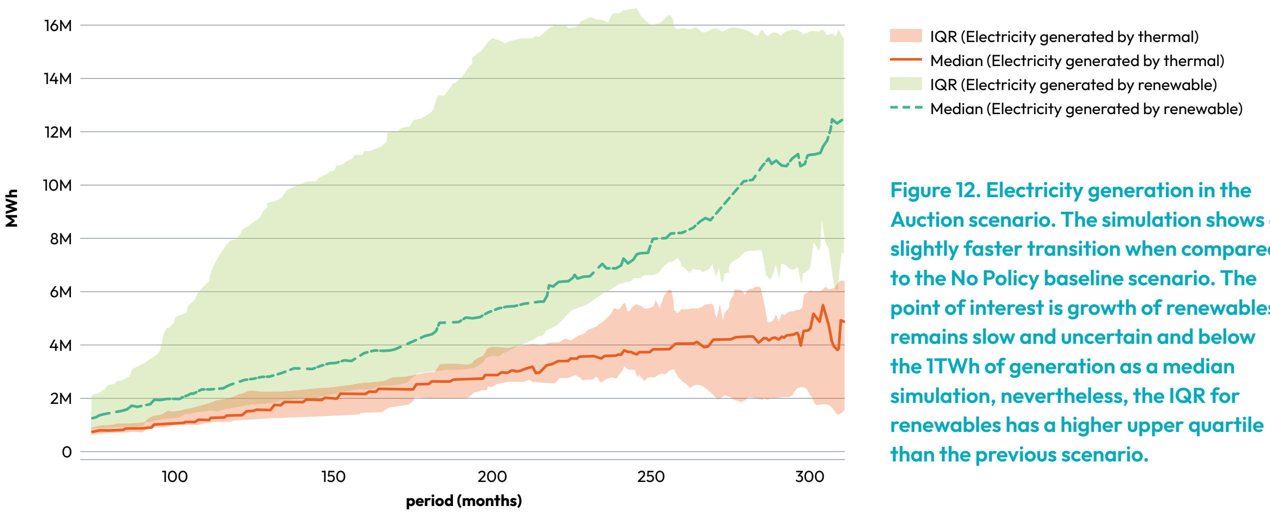


Figure 12. Electricity generation in the Auction scenario. The simulation shows a slightly faster transition when compared to the No Policy baseline scenario. The point of interest is growth of renewables remains slow and uncertain and below the 1TWh of generation as a median simulation, nevertheless, the IQR for renewables has a higher upper quartile than the previous scenario.

[64] Miguel Vazquez et al., "Financing the Transition to Renewable Energy in the EU, Latin America and the Caribbean," *EU-LAC Reports*, 2018, eulacfoundation.org/en/system/files/renewenergpublish.pdf.

[65] The scenarios are presented in terms of electricity generation by summing up solar PV and onshore wind together (green colour – labelled as 'renewables' in the chart) and natural gas plants (red colour – labelled as 'thermal' in the charts). The simulations are run based on 100 Monte Carlo simulations and presented in terms of median (simulation at the 50th percentile in every time period – represented as a dark curve in the charts), and Interquartile (IQR) range (i.e. the difference between the 25th and the 75th percentile per period represented in light colour as a range around the median). Time 0 represents data until year 2010, and time 120 corresponds to the data 10 years later. This approach is important because the uncertainties of the parameters of the TEFE model are large. We remember here that we seek to understand the possible dynamics of the system instead of providing precise forecasts. The base run simulation is not meant to replicate historical data, and is used as a reference simulation to explain the non-linear change due to the combination of policies.

In the Auction scenario (Figure 12), the expansion is still slow, but the larger interquartile range (IQR) for renewable generation at the end of the simulation shows that it is possible to expand renewables further. It is important to note that the growth of fossil generation means that the incentives are enough to prompt more entry of renewables but not enough to move energy producers away from fossil fuels, as they are investing in both technologies.

In the Financing scenario (Figure 13), it becomes clear that the financial aspects are a significant bottleneck for capacity expansion in renewable projects. The generated electricity from renewables grows from around 1 TWh from the previous scenarios to almost 12 TWh (50th percentile). While there is a significant expansion of renewables, there is also a steady growth of fossil fuels, which increases by 10 times (from 0.4TWh to 4TWh) in comparison to the previous simulation. This is due to the fact that private energy providers would invest in renewable plants thanks to the public incentives, but still divert a fraction of their profit to reinvest in gas plants to meet the demand. In other words, the TeFE model helps explaining how the use of a single policy is enough to prompt more renewables into the system, but not enough to move energy providers away from the fossil source due to the inherent behaviour of the private sector in reinvesting financial resources where most convenient.

The Combined scenario (Figure 14) shows a greater expansion of renewables and a contraction of natural gas plants. The main differences between the Combined and Financing scenarios are that, with the auction scheme, there is a clear signal of reduction of fossil use and that the entry of renewables occurs faster and in a more sustained way (the lower bound of the interquartile range[66] for renewables grows sustainably). This is due to the fact that the combination of policies increases the opportunities for renewable power plants while reducing their risks.

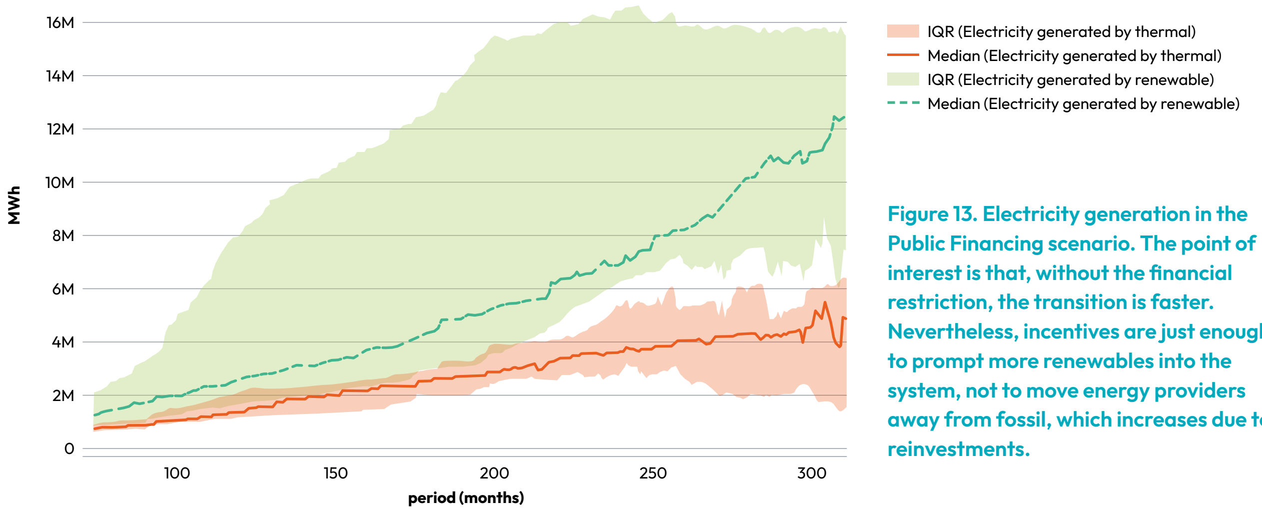


Figure 13. Electricity generation in the Public Financing scenario. The point of interest is that, without the financial restriction, the transition is faster. Nevertheless, incentives are just enough to prompt more renewables into the system, not to move energy providers away from fossil, which increases due to reinvestments.

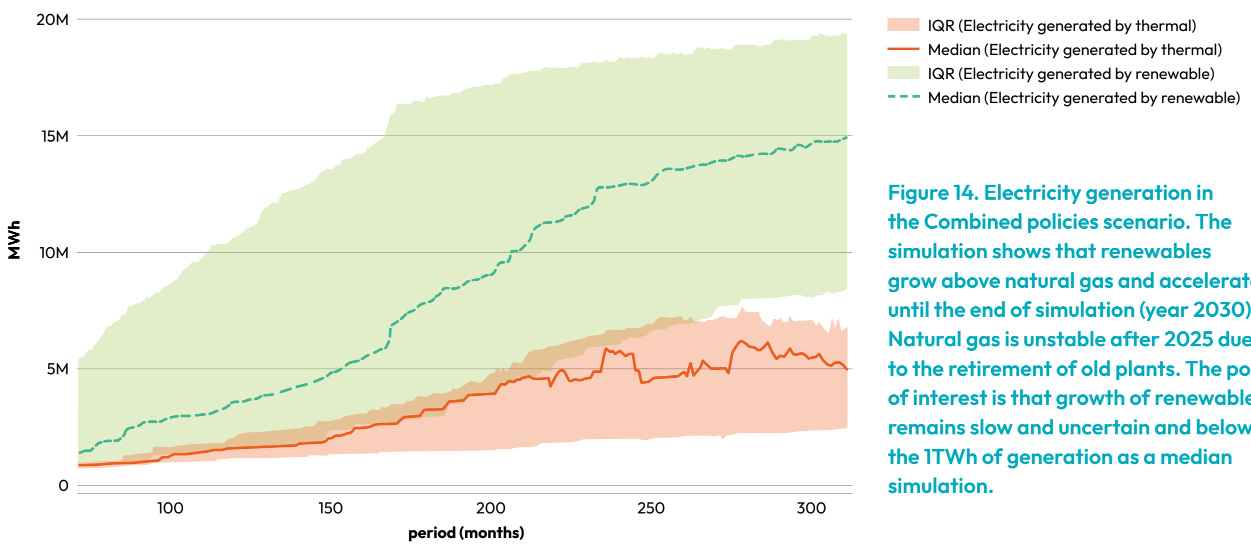


Figure 14. Electricity generation in the Combined policies scenario. The simulation shows that renewables grow above natural gas and accelerate until the end of simulation (year 2030). Natural gas is unstable after 2025 due to the retirement of old plants. The point of interest is that growth of renewables remains slow and uncertain and below the 1TWh of generation as a median simulation.

[66] 3rd quarter of the data – 1st quarter of the data, i.e. space between 25% and 75% of the observed data.

The same effect happens at the Financing scenario, but with a reduced magnitude. It is worth noting that, as the expansion closes its gap with the demand towards the final periods of the simulation (with about 20 TWh of demand for electricity), the increase of renewable capacity in the combined scenario stabilises. This effect does not happen to the median of the Financing scenario due to the fact that, with a slower median increase, there is still demand to be met at the end of the simulation. Consequently, the Combined scenario shows fossil fuel power plants that are not being contracted in favour of renewable energy power plants towards the end of the simulation. The Combined scenario also shows that there are 3 TWh of additional renewable energy generation in comparison to the financing scenario, while contracting 1.2 TWh less of fossil energy. The pace of the transition follows S-shaped curve in terms of the renewable energy, indicating a smoother and faster transition in comparison to the Financing scenario, and highlighting the nonlinearity of the model.

Conclusion

In this experiment, it becomes clear that combining policies leads to transition results that surpass those from scenarios with only one policy. The result of the auction and financing policies when used in combination is more than the sum of the results of each used individually. This gives strong evidence in favour of the combination of policies into a policy mix. In other words, an active auction scheme from a MoE, together with the presence of subsidised public funds with lower interest rates by a DB, may lead to a transition process that is faster and more sustainable over time.

The relevance of public financing for solar is due to the fact that Brazil, similarly to other developing countries, has a local banking sector averse to high-risk and long-term investments in sectors other than oil and gas, farming and mining. As a result, the expansion of renewables relied on public funds in the past decades. Nevertheless, the energy policy structure, in the form of the auction scheme, is also responsible for fostering the entry of renewables in the country. The conclusion is that, even though both policies are relevant, it is their combination that is able to significantly foster the entry of renewables.

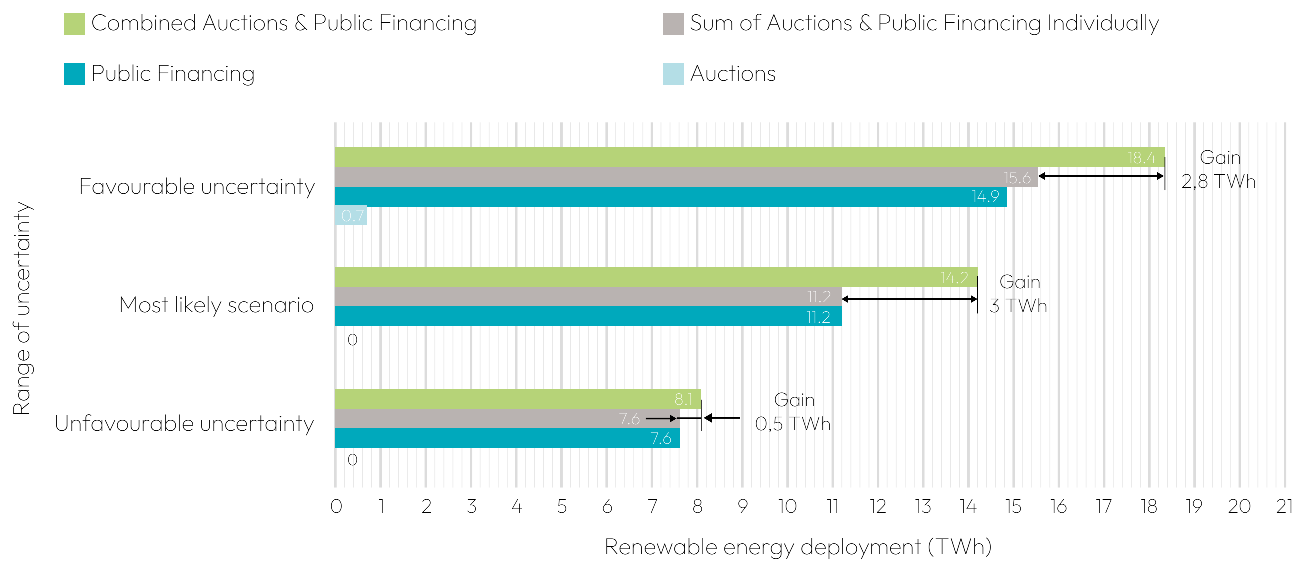


Figure 15. Gain in effectiveness of energy generation from renewables through policy combination in 2040. The figure shows the resulting gain in additional renewable generation for every policy in isolation and in combination as an increased gain to the No Policy scenario, and using the values of the Most likely scenario (median), Unfavourable uncertainty scenario (low interquartile), and Favourable uncertainty scenario (high interquartile) in 2040. The results show that the combined results of Auctions and Financing policies is more than the sum taken in isolation in every uncertain scenario.

Such results are in line with has happened in Brazil since the electricity market liberalisation (2000s on), especially regarding the slow start of solar in the country, when the auction scheme was in full force but the financing scheme was not at first.[67]

The development of the TeFE ABM allows us to produce and compare different alternative scenarios in a systematic way, focusing on the interplay between a MoE and a DB in fostering renewable energy. Despite the experiments showing some preliminary results, it is vital to note that the change due to the two policies in combination leads to a nonlinear increasing effect of the auction policy for solar on electricity generation (from 0.8TWh at the end of simulation in Auction scenario, to around 12TWh in the finance scenario, and around 15TWh in the scenario of auction in combination with public financing). This is due to the fact that the combination of policies increases opportunities and reduces risks of renewables to a larger extent than each policy alone. Such magnitude of effects proves itself to be enough to not only foster the entry of renewables, but also to move energy providers away from the fossil source. Figure 15 compares the levels of renewables generation reached at the end of each scenario against the No Policy scenario and accounting for the uncertainty in the analysis, so that the gain in effectiveness that arises from combining policies can be easily seen.

The model is based on Brazilian data for its starting values and is able to reproduce some trends in data, but the outcome of future simulation remains uncertain due to the design of the model. Making precise forecasts is not the focus of the model – rather, it is to analyse the interplay between public entities in the context of energy transitions in a developing country. The findings have implications at three levels. For policy, they suggest that combinations of policies might produce better results than individual policies, with combinations achieving more than the sum of their parts. For analysis, this implies it is useful to compare the likely effectiveness of different policy packages, not just different individual policies. And for governance, it highlights the value of coordination between different ministries, so that the most effective policy packages can be identified and implemented.

[67] Podcameni, "Sistemas de Inovação e Energia Eólica: A Experiência Brasileira."; W. Ferreira, "O Estado Atual e Os Incentivos Ao Desenvolvimento Da Indústria Eólica Brasileira: O Caso Da Política de Conteúdo Local Do BNDES" (Master's thesis, Niterói, Universidade Federal Fluminense, 2013); Gustavo Onofre Andreão, "The Dawn of Solar in Its Dusk: An Agent-Based Model for the Impaired Utility-Level Solar Photovoltaic Expansion in Brazil" (Master's thesis, Niterói, Universidade Federal Fluminense, 2018); G. O. Andreão, M. C. M. Hallack, and M. Vazquez, "Rationales for Technology-Specific RES Support: The Impaired Brazilian Solar Expansion," *Bocconi IEFE Working Paper* 99 (2017): 33; Vazquez and Hallack, "The Role of Regulatory Learning in Energy Transition"; Miguel Vazquez et al., "Financing the Transition to Renewable Energy in the EU, Latin America and the Caribbean," EU-LAC Reports, 2018, https://eulacfoundation.org/en/system/files/renewenergpublish.pdf.

Power sector technology choices and economic outcomes: A comparative analysis using optimising and simulating models

Authors: Roberto Pasqualino, Pim Vercoulen, Simon Sharpe, Femke J.M.M. Nijsse.[68]

Policy questions

- How do different power sector technology mixes compare in terms of cost effectiveness and wider economic impacts?
- Would more solar power, compared to the likely current trajectory, be a good or bad thing for Brazil?

Engagement

The work proposed in this case study had been developed in close collaboration with the Brazilian Energy Research Office (EPE). EPE is a public company that develops studies to assist the Ministry of Mines and Energy in formulating Brazil's energy policy. To this end, it prepares the technical studies for the country's main sectoral energy plans, developing medium and long-term energy demand and supply scenarios (the two main products are the Ten-Year Energy Plan and the National Energy Plan). EPE uses a series of models with detailed and granular information on the country's economic and energy structure and believes that comparing figures from different models is a natural practical exercise. Still, it should be noted that, as these are scenarios (and not forecasts), many of the differences observed can be derived from the scenario process. EPE saw the partnership with EEIST as a way of sharing knowledge and learning about different types of modelling that have been developed in world-leading academic centres.

Methods

- Comparison between Future Technology Transformation (FTT) provided by Cambridge Econometrics and cost-optimisation models provided by EPE.

Key findings

- Scenarios with higher deployment of renewables tend to achieve more positive results for GDP and employment, and these findings may be an understatement due to not explicitly modelling new energy industries in the FTT.
- It may be beneficial to take measures to accelerate the deployment of both solar and wind, but with the emphasis on supporting solar in the near term (since it has a much smaller share of generation than wind at present), and a greater emphasis on supporting wind over the longer term.
- Based on the FTT analysis, it appears that the power-generation technology mix calculated by the cost-optimising models may not be the least-cost one.
- Modelling suggests, counterintuitively, that lower electricity prices could be achieved by either boosting or limiting solar deployment. This is due to the dynamic interplay between the greater deployment of solar and reduced costs of generation; and the better balance between solar and wind, that can reduce the need for energy storage.
- The differences between these models' respective outputs of most likely and cost-optimal solar deployment increase with time.

Summary

The authors compare the FTT and cost-optimising models to demonstrate how the dynamic of learning-by-doing can impact solar technology expansion over the long term. This shows how the dynamics of endogenous cost reduction can surpass the expectations of cost-optimising models, and highlights the opportunity for near-term policies that facilitate faster deployment of renewables to lead to lower electricity prices over the longer term.

[68] The authors are grateful to Gustavo Naciff de Andrade, Gustavo Pires da Ponte, and Gabriel Konzen from the EPE team for their support and availability, as well as sharing insights and data from their models to make this case study possible.

Introduction to the study

The EEIST project consortium and the EPE team agreed to compare model projections on power sector technology choices and economic outcomes, to see whether insights could be gained from the comparison of findings from structurally different models. Initial findings were discussed at a workshop in Rio de Janeiro in August 2022. Following further exchanges of information, this case study summarises the findings.

The policy questions this study aims to inform are:

- How do different power sector technology mixes compare in terms of cost effectiveness and wider economic impacts?
- Would more solar power, compared to the likely current trajectory, be a good or bad thing for Brazil?

Within the general question of 'what is a desirable power sector technology mix?', the specific question about solar power was raised for two reasons. Firstly: when we compare the outputs of the Cambridge Econometrics FTT model used by the EEIST project with the outputs of cost-optimising models more commonly used by governments and international organisations, we typically find the greatest difference to be in relation to solar power. For example, our projection that solar will account for over 50% of global electricity generation by 2050 contrasts markedly with the International Energy Agency's baseline scenario of 20%.[69] Secondly, in earlier workshops held by the EEIST project in Brazil, some stakeholders had argued that Brazil's exceptionally good solar power resources were relatively underexploited compared to wind power, where Brazil is a world leader in rapid deployment. It has been suggested that national content requirements, which the solar industry in Brazil is not yet able to meet, are constraining the ability of BNDES to provide financial support for faster solar deployment.

Comparison of different model projections for power generation technology mix

In this section we compare power sector technology mix projections from different economic models, with fundamentally different structures and assumptions. The models used are set out in Table 7.

	CE	EPE	
	FTT	IDM[70]	4MD[71]
Type	Evolutionary simulation	Cost-optimal	Data fitting simulation
Time horizon	2030 & 2050	2030	2030
Representation of solar energy and storage	Aggregated solar and grid-scale storage	Centralised solar and grid-scale storage	Decentralised solar

Table 7. Description of the models used for the scenario comparison.

[69] For details see the EEIST policy brief, 'Is a solar future inevitable?' eeist.co.uk/policybriefs

[70] IDM is an acronym for Investment Decision Model

[71] 4MD is an acronym for Micro- and Mini-generation Distributed Market model. This is translated from the portuguese of 'Modelo de Mercado da Micro e Minigeração Distribuída'.

Key differences between the models are as follows:

i. **Optimising vs simulating:** IDM estimates the cost-optimal technology mix within given constraints, which can include policy targets. 4MD fits bass diffusion curves to all industrial sectors (including household decentralised data) and simulates most likely futures based on curve trends. FTT simulates the most likely technology mix resulting from given conditions, which can include policy actions and accounts for various sources of uncertainty.

ii. **Technology costs:** In IDM, technology costs are inputs to the model, assumed to vary as a function of time. In FTT, technology costs are endogenous to the model, assumed to vary as a function of cumulative global deployment (through the process of learning-by-doing).

iii. **Agents:** In IDM, power producers are assumed to be homogeneous. In FTT agents are heterogeneous, with varying perceptions of cost components.

iv. **Solar power:** IDM models utility-scale solar only, and 4MD models decentralised (distributed) solar. FTT models solar deployment in aggregate.

v. **Energy storage:** In IDM: energy storage can be grid-scale or distributed, and its level of deployment is determined by a cost comparison with other technologies that can ensure grid stability. In FTT, energy storage deployment is computed as a function of the deployment mix of power generating technologies, and storage costs are assumed to be distributed among the variable renewable technologies according to their respective contributions to causing demand-supply mismatches.

The outputs of the comparison are shown in Figure 16 below. This compares the baseline projections of FTT and IDM+4MD for all power technologies between 2020 and 2031.

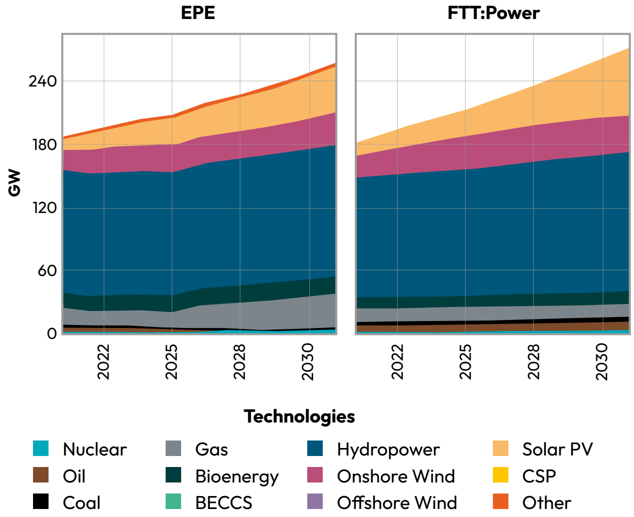


Figure 16. Baseline comparison for the energy mix between FTT and the IDM+4MD models until 2031.

In IDM and 4MD combined, the total cost-optimal solar deployment by 2031 is estimated to be 44 GW (of which 10 GW is utility-scale and 34 GW is distributed). In FTT, the total likely solar deployment by 2031 is projected to be 62 GW (40% higher). Apart from solar, the next most significant difference is in relation to gas, with IDM estimating 32 GW as cost optimal in 2031, and FTT calculating only 12 GW as likely. Gas power provides the back-up role in both IDM and FTT. The latter also includes grid-scale storage that can provide back-up.

Both suites of models show a rapid growth in deployment of solar PV, despite major differences in the model logic. This is because the fall in solar PV costs over the past 10 years mean it can already outcompete all other technologies on cost. This is reflected in both simulation and optimisation models. However, the difference between the models increases over time, and is substantial by the end of the simulation period. This is because FTT contains a positive feedback loop between global cumulative capacity additions and the falling cost of solar, while in IDM the cost of solar is an exogenous assumption. Figure 17 shows the divergence between solar costs in the two models over the period of time.

The models also differ in their representation of how grid stability is guaranteed. In the optimisation models, the economic performance of back-up capacity trumps that of electricity storage, while in FTT the falling costs of batteries give storage a bigger role.

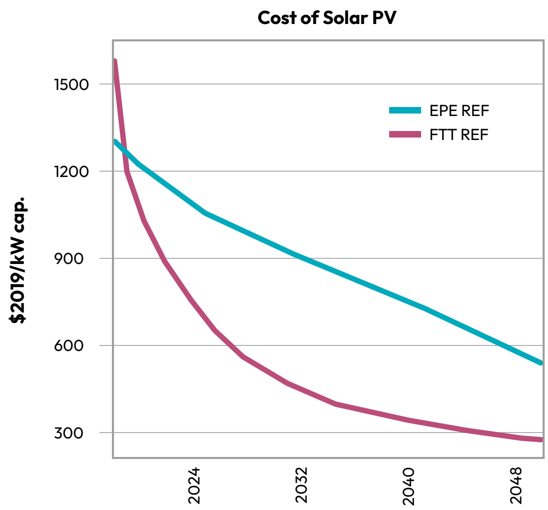


Figure 17. Cost of solar PV panels over time.

Modelling cost in E3ME-FTT

E3ME-FTT is a global model of 71 regions with major economies represented individually and distinguishes 70 economic sectors in European countries and in non-European countries. It combines two models (E3ME and FTT) that work on different principles, thus creating synergies in terms of scope and boundaries.

E3ME[72] is a computer-based macro-econometric model of the world's economic and energy systems and the environment. E3ME is demand-led and determines the components of demand using time-series econometrics to solve components of final demand and various other indicators (e.g. commodity prices, labour, wages, incomes, production). Because of its reliance on past data, E3ME is not suitable to model novel technologies and costs which require to ingest dynamic assumptions into future forecasts. This is where the 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 (FTT:Power)[73], iron and steel (FTT:Steel),[74] household heating (FTT:Heat)[75] and passenger vehicles (FTT:Transport).[76] FTT:Power models the energy mix supply and determines the technology configuration to meet the demand which is calculated elsewhere in E3ME-FTT.

The cost of technologies is among the building blocks of the model as it builds on a positive feedback loop of learning-by-doing based on global cumulative technology capacity additions (leading to endogenous exponential decay in cost). Based on this, investors' decisions are integrated in the positive loop based on a Lotka-Volterra replicator function, where they compare all technologies on a pair-wise basis. In so doing, at every year the investors make a choice based on a cost-parity heuristic that allows them to invest in the lowest-cost technology. The costs include the Levelised Cost of Energy (LCOE) and grid storage costs paid by investors in variable renewables. These investment dynamics close the feedback of learning-by-doing, as the increased capacity typically lowers the cost further, leading to exponential expansion of low-cost technologies.[77] The positive cost-capacity feedback gives rise to a potential positive tipping point, which can be activated by a policy mix of subsidies, taxes and regulations.

Comparison of different technology mix scenarios using E3ME-FTT

Here we use the FTT model in combination with the macro-econometric E3ME model to compare different power sector technology mix scenarios. Since E3ME-FTT simulates what is likely, its projections should not be seen as representing an 'optimal' case. The likely outcomes of different policy choices can be compared in terms of several economic variables of interest.

We define three scenarios that represent different policy choices compared to the baseline:

i. **Low Solar** imposes an exogenous trajectory of solar PV that is 25% lower in levels by 2030 compared to the endogenous baseline. This represents any additional hurdles to the expansion of solar PV capacity.

ii. **Low VRE** imposes exogenous trajectories of solar PV, and of onshore and offshore wind power that are 25% lower in levels by 2030 compared to the endogenous baseline. This extends the hurdles to wind power as well.

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

[73] 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.

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

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

[76] 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.

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

iii. High Solar imposes an exogenous trajectory of solar PV that is 25% higher in levels by 2030 compared to the endogenous baseline. This represents that solar PV uptake is met with little resistance from the system.

Figure 18 shows the outcomes in terms of the power generation technology mix. In the Low Solar scenario, more wind power is deployed (an additional 70% compared to the baseline) to make up for the shortfall in solar. This indicates that, if solar PV uptake is met with additional hurdles, it is likely there will be additional growth in wind power to compensate. In the Low VRE scenario, where both solar and wind are constrained, the model projects that more hydropower (+7% by 2031) and gas power plants (+36% by 2031) will be deployed to compensate. In the High Solar scenario, there is significantly more solar by design but, perhaps surprisingly, more solar PV also leads to more wind power. In FTT, the storage costs are allocated to VRE technologies proportional to the amount of back-up storage demand each technology is responsible for.[78] In the High Solar scenario, a small amount of extra wind power reduces the demand for storage because – to some degree – solar and wind power show complementarity in their hourly load profiles.

If we compare the deployment of solar PV and onshore wind power of these scenarios and the FTT baseline to the baseline of EPE's suit of models, then it becomes clear that – in terms of VRE uptake – the Low VRE scenario comes closest to the baseline produced by IDM and 4MD (see Figure 19).

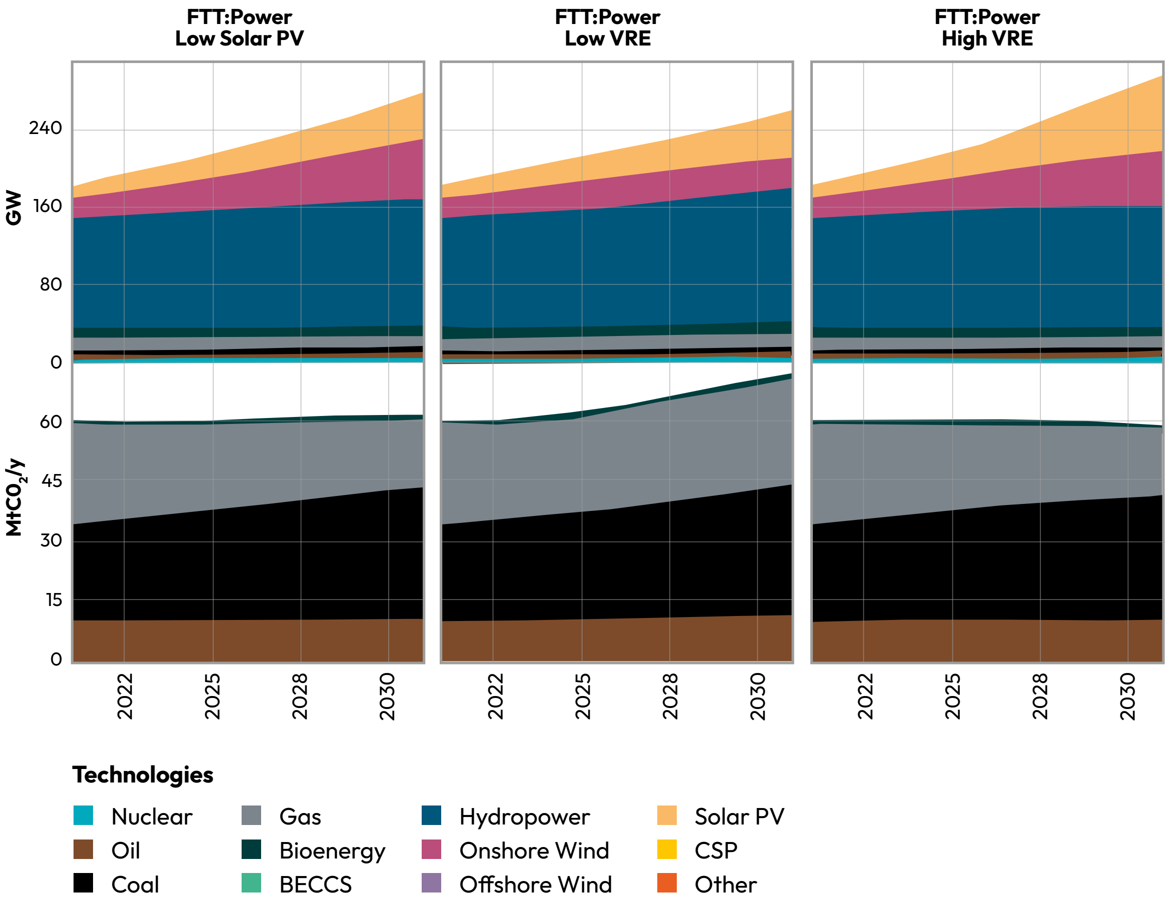

Figure 18. Power generation capacity and CO_2 emissions by technology in alternative scenarios using FTT.

[78] We have used this method of allocating the costs of energy storage for this exercise. FTT also allows for other methods of allocating storage costs.

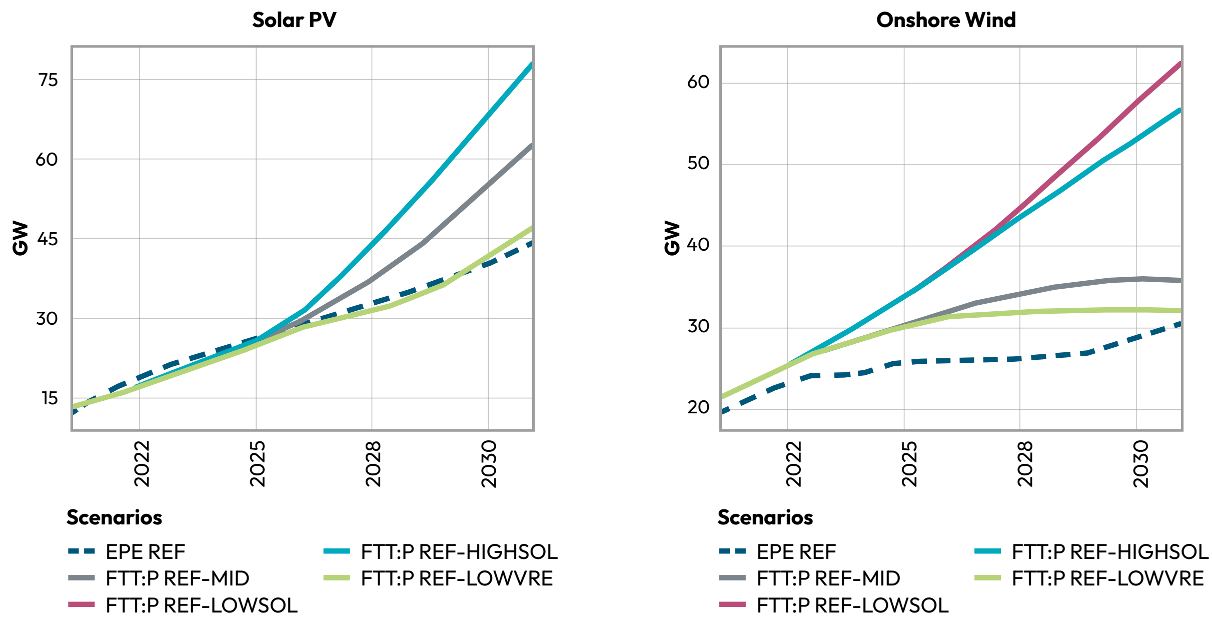

Figure 19. Power generation capacities of solar PV and onshore wind power for all scenarios. Note that the lines FTT:P REF-LOWSAL and FTT:P REF-LOWVRE overlap in the left panel.

Figure 20 shows the outcomes of these three scenarios as compared to the baseline scenario in terms of electricity prices, GDP, employment, and power-generation emissions.

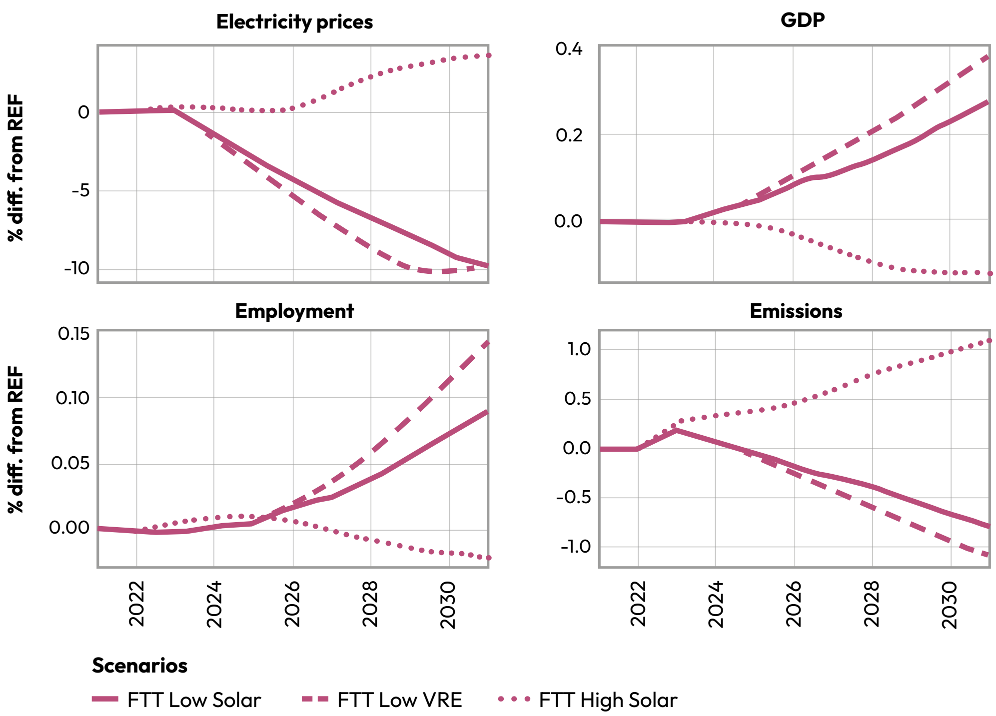

Figure 20. High-level impacts on electricity prices, GDP, employment and emissions.

Electricity prices

In the Low VRE scenario, electricity prices gradually become higher than in the baseline (Figure 20). This reflects the expectation that solar and wind will be increasingly cheaper than fossil fuel generation over the course of this decade, even when the cost of energy storage is factored in.

Electricity prices are lowest in the High Solar scenario, for most of the period. This reflects the advantage of greater deployment of what is likely to be the cheapest source of generation.

In the Low Solar scenario, electricity prices are significantly lower than in the baseline, and converge with those of the High Solar scenario by 2030. This is because this scenario deploys more wind power than the baseline, which improves the overall balance of power supply and demand and reduces the costs of energy storage.

GDP

Lower electricity prices boost demand for goods and services across a range of sectors, which is notable in the consumer expenditure and investment results as shown in Figure 21. The Low VRE scenario misses out on both cheap solar PV and cheap onshore wind power and, as a result, the inflated electricity prices suppress consumer expenditure and investments. Ultimately, electricity prices have a sizeable effect on effective demand.

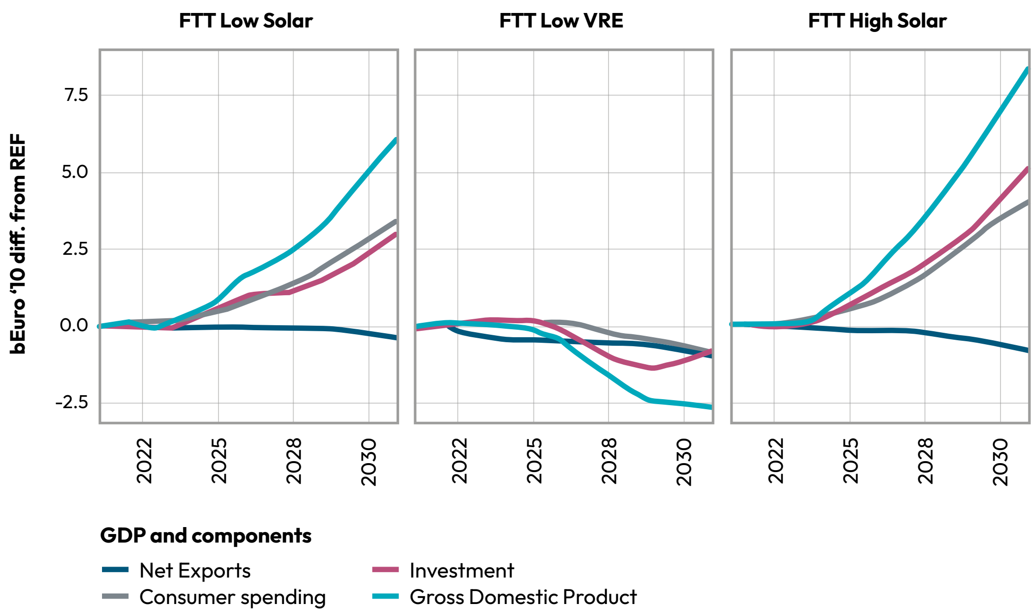

Figure 21. Gross domestic product and its components in each scenario compared to the baseline.

Employment

Cheaper electricity prices reduce operating costs across the whole economy and unlock spending by households on other goods and services that would otherwise be spent on electricity bills. This creates additional demand and leads to additional employment. This is mainly noticeable for employment in the services sector, as shown in Figure 22. Services have a relatively high level of domestic content, so additional spending here leads to higher employment.

Changes in employment follow from changes in GDP, so the model projects an overall decrease in employment compared to the baseline in the Low VRE scenario, and the greatest increase in overall employment in the High Solar scenario.

An important point to note is that the model simulates employment outcomes within 43 sectors. These include the coal, oil and gas, and electricity sectors, but do not include the more detailed level within industries for the manufacture and installation of individual energy technologies, such as solar PV

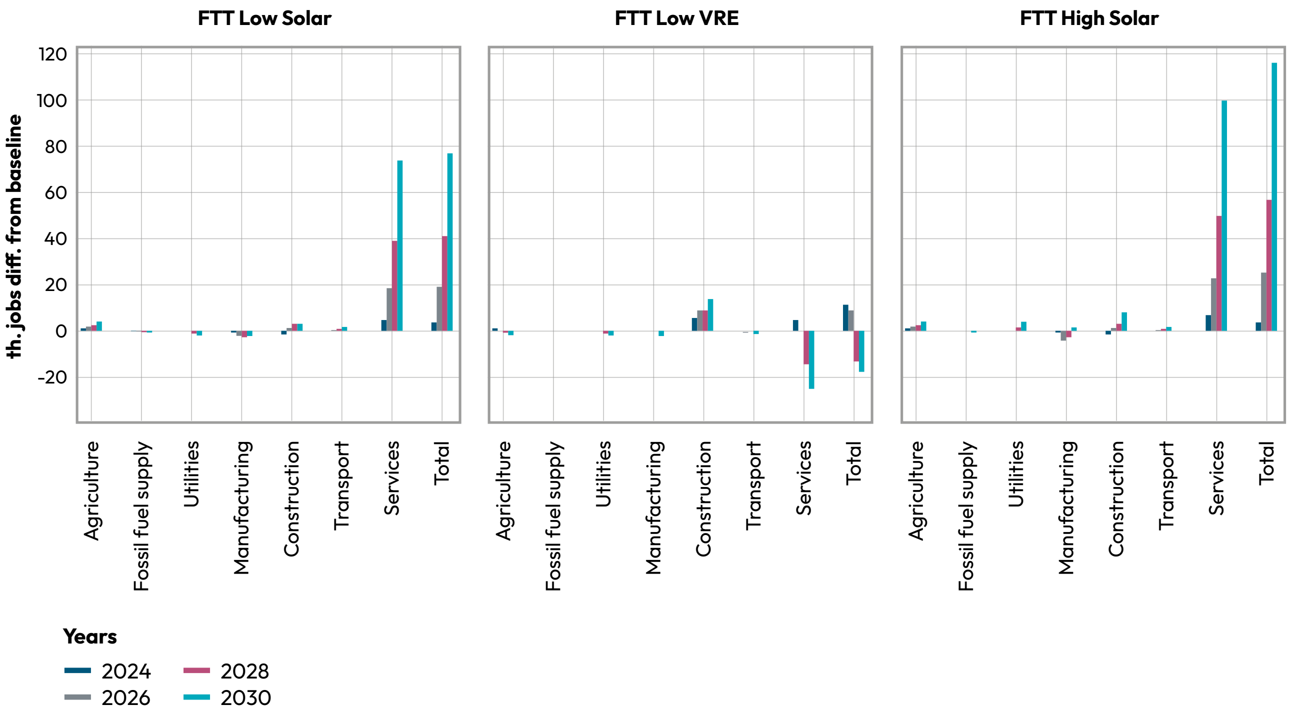

Figure 22. Absolute employment differences by sector from baseline.

production by the electrical engineering sector. Consequently, the potential for additional jobs to be added by the development of new industries in Brazil, such as solar or wind, is not represented.

Another limitation is the lack of skills tracking in the model. E3ME is not able to account for demand and supply mismatches in skills of the labour force, which may limit the ability of workers to move from occupations in sectors where jobs are lost to occupations in sectors where jobs increase (an agent-based model of the labour market developed by Oxford University as part of the EEIST project addresses this issue).[79]

Emissions

While our scenarios are revolving around the already largely decarbonised power sector in Brazil, we note some effect on emissions due to their different technology mixes (see graph of emissions gaps in Figure 20). Both the Low Solar and High Solar scenarios show lower emissions due to electricity generation compared to the baseline (5% and 8% respectively), as their additional deployment of renewables displaces some fossil fuel technologies within the power sector. Again, in the Low Solar scenario that is due to wind power deployment increasing to compensate for the lower deployment of solar PV. We have seen that both scenarios lead to a reduction in electricity prices, and this has the additional effect of final energy users preferring electricity over other energy carriers, helping to further reduce emissions (a 1% decrease in the High Solar scenario and a 0.75% decrease in the Low Solar Scenario). The Low VRE scenario prevents both solar PV and wind power uptake and therefore shows the opposite effect (1% increase).

Concluding discussion

The comparison of scenarios using E3ME-FTT suggests that the power-generation technology mix calculated by the cost-optimising models may in fact not be the least-cost one. While FTT shows the Low VRE scenario technology mix in 2030 to be similar to that calculated by the combination of IDM and 4MD, we have identified two alternative scenarios that each achieve lower electricity prices over this period. This, at least, is the finding to a first approximation.

[79] Berryman, A. et al. (2023) Modelling labour market transitions: the case of productivity shifts in Brazil, pp. 120–126. Available at: eeist.co.uk/eeist-reports (Accessed: 1 June 2023).

The FTT model's finding that lower electricity prices could be achieved by either boosting or limiting solar deployment appears counter-intuitive at first. It arises from the interaction of two factors: on the one hand, greater deployment of solar reducing the costs of generation, and on the other, a better balance between solar and wind reducing the costs of energy storage (see Figure 17 for cost of solar). Because the costs of solar are falling at a faster rate than those of wind (20% with each doubling of global deployment, compared to 13% for wind), as solar deployment accelerates in future years, wind will need extra help to 'keep up' – to maintain a solar-wind balance that is efficient for the system. A tentative conclusion for policy is that it may be beneficial to take measures to accelerate the deployment of both solar and wind, but with the emphasis on supporting solar in the near-term (since it has a much smaller share of generation than wind at present) and wind over the longer term.

Some limitations of the model, and of the scenarios we have tested, may be relevant to this tentative policy conclusion:

a. The FTT model assumes that finance is available whenever it is needed for investments in new power generation. If investments in solar power (or wind) are limited in any way by the availability or cost of finance, then it is likely that deployment will be lower than suggested by the 'most likely' (baseline) scenario. Measures that reduce the cost of capital, such as auctions for long-term contracts, or low-interest loans from public institutions, could be important to achieving scenarios with high renewables deployment and low electricity costs.

b. The FTT model assumes that energy storage is deployed as needed (with its costs allocated to variable renewables), and that grid connections are available as needed. In reality, the level of storage deployment will depend on how the market rewards storage services, which will depend on policy and regulatory choices. The cost of energy storage may vary by its geographical location. The availability of grid connections may also depend on public investment decisions. The cost of grid expansion, which may be larger in high VRE scenarios, is included in the IDM model but is not included in the FTT simulation.

c. In these FTT model scenarios we have assumed that electricity prices are formed through the merit order approach, reflecting the cost of the marginal unit of supply. As variable renewables take up a larger share of generation, different electricity prices could be yielded by different market designs.

The models' assumptions about future costs of solar and wind are also important. The FTT model assumes that their costs will continue to reduce by 20% and 13% respectively with each doubling of their global deployment, for all of the time period simulated. This is consistent with the trend from 1979 to 2020.[80] However, there have been fluctuations around this trend in the past, and the pace of cost reduction in future may be influenced negatively by materials supply constraints, or positively by innovation. This is not a limitation of the model, but is a fundamental uncertainty relevant to our understanding of the model's outputs.

The comparison between FTT and the combined IDM-4MD shows that differences between these models' respective outputs of most likely and cost-optimal solar deployment increase over the course of time. If reality turns out to be close to the FTT projection, then all the considerations above become more important: larger deployment of the cheapest source of power generation (solar) represents an opportunity for low-cost electricity, but realising this opportunity may depend greatly on the availability of grid connections and energy storage, and on the extent of deployment of wind power.

The E3ME model's finding that scenarios with higher deployment of renewables tend to achieve more positive results for GDP and employment may be an understatement, for the reason mentioned above (new energy industries are not explicitly modelled). However, a limitation of E3ME is that it assumes people have the necessary skills to fill new jobs that are created. In reality, as the transition to clean energy increases jobs in some sectors and decreases them in others, the need for skills of different kinds will change, and policy interventions (such as retraining) may be needed to maximise the opportunities of growth sectors and limit the risk of skills gaps being a constraint.

[80] Way, R. *et al.* (2022) 'Empirically grounded technology forecasts and the energy transition', *Joule*, 6(9), pp. 2057–2082. Available at: **doi.org/10.1016/j.joule.2022.08.009**.

Firm-led innovations in energy efficiency and its contributions to carbon emissions in Brazil

Authors: Matheus Trotta Vianna, Esther Dweck, Carlos Eduardo Young.[81]

Policy questions

- How much can innovation in energy intensity contribute to the reduction in energy demand and associated GHG emissions for Brazil by 2050?
- What are the prospects for low-carbon energy transition scenarios based on the current trends of energy efficiency and energy supply in Brazil?
- What is the combined effect of policies on energy efficiency and energy substitution to low-carbon sources for the energy transition in Brazil?

Methods

Agent-Based, Stock-Flow Consistent, Input-Output dynamic simulation model.

Key findings

- Firm-led innovation is one of the main determinants of a long-run trend of declining energy intensity and plays a key role in reducing energy demand and its associated carbon emissions.
- The current speed of advancements in energy-saving technologies can contribute to a 15% approximate reduction of total energy demand and associated carbon emissions by 2050, but Brazil is unlikely to meet sustainable development targets without a transition in the energy supply.
- The current speed of energy transition in the power sector can also contribute to a 15% approximate reduction of carbon emissions, which is still unlikely to meet the sustainable development targets by 2050.
- A combination of firm-led energy-efficiency innovations and government policies that promote the transition to low-carbon energy sources is suggested as the best approach to achieve climate and energy targets by 2050.

Summary

This case study explores the role and the contributions of innovation in energy efficiency as one of the many factors in the whole energy transition process. We employ a multisectoral micro-macro agent-based model, which allows us to run simulations and compare different scenarios. The scenarios combine policies linked with firm-led energy efficiency innovations and energy source substitution. The aim is to investigate how much innovation in energy intensity can contribute to reduce energy demand and associated GHG emissions by 2050, what are the prospects for low-carbon energy transition scenarios based on the current trends of energy efficiency and energy supply in Brazil, and what is the combined impact of promoting both innovations in energy efficiency and energy substitution on the energy transition. The study suggests that a stronger combination of firm-led energy-efficiency innovations and government policies that promote the transition to low-carbon energy sources is the best approach to achieve climate and energy targets by 2050.

Introduction

Energy efficiency plays a pivotal role in achieving sustainable energy transition and climate change mitigation goals worldwide. As countries strive to reduce their carbon emissions and transition to cleaner energy sources, optimising energy efficiency emerges as a key strategy to meet energy demands while curbing environmental impacts. According to the IEA in its *2022 Global Energy and Climate Model Report*, to reach net-zero emissions by 2050, energy-intensity improvements need to increase to 4% from 2020 to 2030 on a global average. Slow improvements in energy intensity against increasing economic activities raise GHG emissions and harm environmental sustainability.

From 1965 to 2015, carbon intensity reduced on average 1.22% per year and energy intensity reduced on average 1.03% per year on a global level.[82]

[81] The authors would like to express the valuable and voluntary support of Rui Zhao, student at the University of Manchester, which helped with the data collection and analysis.

[82] Hannah Ritchie, Max Roser and Pablo Rosado (2022) - "Energy". Published online at OurWorldInData.org. Retrieved from: '**ourworldindata.org/energy**' [Online Resource]

In the same period, Brazil has economically grown faster in comparison to the world's average, however, its reduction in carbon intensity has been slower, with an average decline of 0.22% per year and increased energy intensity at 0.32% per year on average. These results are reflected by the rapid and strong economic expansion that the country experienced during the 1970s, despite the improvement in performance due to recent trends and commitments to sustainable development over the past decade. If we look from 2000 to 2015, we find an average annual decline in carbon intensity of 1.23% and an average annual decline of energy intensity of 1.62%.

According to the Brazilian National Energy Plan 2050 (PNE2050[83]), there are **two key aspects in the process of energy transition:** more efficient use of energy resources and reduction of share of carbon-intense energy sources. In order to meet the targets proposed in the PNE2050, the key challenges for both policymakers and society in general are (i) a redesign of the market, regulatory and institutional framework of the energy supply sector, (ii) the increasing uncertainties involved in the energy supply sector and (iii) the multiplicity of dimensions involved in the energy transition process, demanding efforts to coordinate the economic, scientific-technological, educational, industrial and environmental spheres and policies. Brazil has a long history of policies and incentives to promote energy efficiency, stretching back to the 1980s, with a series of policies and plans to measure, promote and regulate energy-efficiency activities.

This case study aims to contribute to the **third challenge:** studying the role and the contributions of innovation in energy efficiency as one of the many factors in the whole energy transition process.

To explore the complex role of energy intensity, we employ a multisectoral micro-macro agent-based model, which allows us to run simulations and compare different scenarios. We explore several scenarios of firm-led energy-efficiency innovations in combination, or not, with energy transition, in the hope to give some relevant insights in the policy debate. In particular, we aim to investigate the following policy questions: How much can innovation in energy intensity contribute to the reduction in energy demand and associated GHG emissions for Brazil by 2050? What are the prospects for low-carbon energy-transition scenarios based on the current trends of energy efficiency and energy supply in Brazil? What is the combined effect of policies on energy efficiency and energy substitution to low-carbon sources for the energy transition in Brazil?

The model

The Multisectoral Micro-Macro Model for the Economy, Energy and Emissions (M3E3)[84] is a dynamic simulation model that combines theoretical foundations from Keynesian, Kaleckian and Schumpeterian approaches and methodological techniques from Agent-Based[85], Stock-Flow Consistent[86] and Input-Output[87] modelling approaches. The model is useful to investigate general dynamic properties of capitalist economies including the relationship between the economy, energy production, energy demand and GHG emissions.[88,89,90] Due to its theoretical foundations, the model shares many concepts with ROA,[91] such as fundamental uncertainty, path-dependency and disequilibrium, all due to complex agent interaction and nonlinear dynamics. For this case study, most of the parameters of the model were calibrated based on empirical data for Brazil. We calibrate the model so that the first 50 years of simulation (from 1950 to 2000) generate behaviour that is comparable to a number of stylised macroeconomic facts

83 Ministério de Minas e Energia and Empresa de Pesquisa Energética (2022)."Plano Nacional de Energia 2050". Available at: www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/Plano-Nacional-de-Energia-2050.

84 The model is fully written in LSD code (Version 8.0). LSD (Laboratory for Simulation Development) is a language and a platform to create, run and test simulation models. LSD is copyrighted by Marco Valente and Marcelo C. Pereira (version 7.x additions) and it is freely distributed according to the GNU General Public License, available at github.com/marcov64/Lsd. The model code is also available for reproduction at github.com/thttnn/UFRJ-MMM_v.3.

85 Fagiolo, Giorgio, and Andrea Roventini (2016). "Macroeconomic policy in DSGE and agent-based models redux: New developments and challenges ahead." Available at SSRN 2763735.

86 Nikiforos, Michalis and Gennaro Zezza (2017). "Stock-Flow Consistent Macroeconomic Models: A Survey". In: Journal of Economic Surveys 31.5, pp. 1204–1239.

87 Wiedmann, Thomas (2009). "A review of recent multi-region input-output models used for consumption-based emission and resource accounting." Ecological economics 69, no. 2: 211-222.

88 Possas, Mario and Esther Dweck (2004). "A multisectoral micro-macrodynamic model". In: Revista EconomiA.

89 Dweck, Esther, Matheus Trotta Vianna, and Arthur da Cruz Barbosa. "Discussing the role of fiscal policy in a demand-led agent-based growth model." EconomiA 21, no. 2 (2020): 185-208.

90 Vianna, Matheus Trotta (2021). "Monetary Policy and Stabilization in a Multisectoral Micro-Macro Dynamic Simulation Model". PhD thesis. Universidade Federal do Rio de Janeiro.

91 Sharpe, Simon, J. F. Mercure, J. Vinuales, M. Ives, M. Grubb, H. Pollitt, F. Knobloch, and F. J. M. M. Nijsse. "Deciding how to decide: Risk-opportunity analysis as a generalisation of cost-benefit analysis." UCL Institute for Innovation and Public Purpose (2021).

linked to key variables in Brazil (e.g. GDP growth, inflation, aggregate energy and carbon intensity) as experienced rates over the selected time period.[92,93]

The M3E3 model describes an economy composed by four productive sectors: a financial sector, the households disaggregated in income classes, the government and the external sector, representing the rest of the world. Each is populated by heterogenous agents: consumption firms, intermediate firms, capital firms and energy firms. The households are represented by four income classes. The financial sector is composed of heterogenous banks. Figure 23 shows the model structure and flows in a stylised way. Every firm in every sector generates GHG emissions due to production, although the majority of total GHG emissions is generated in the energy sector.

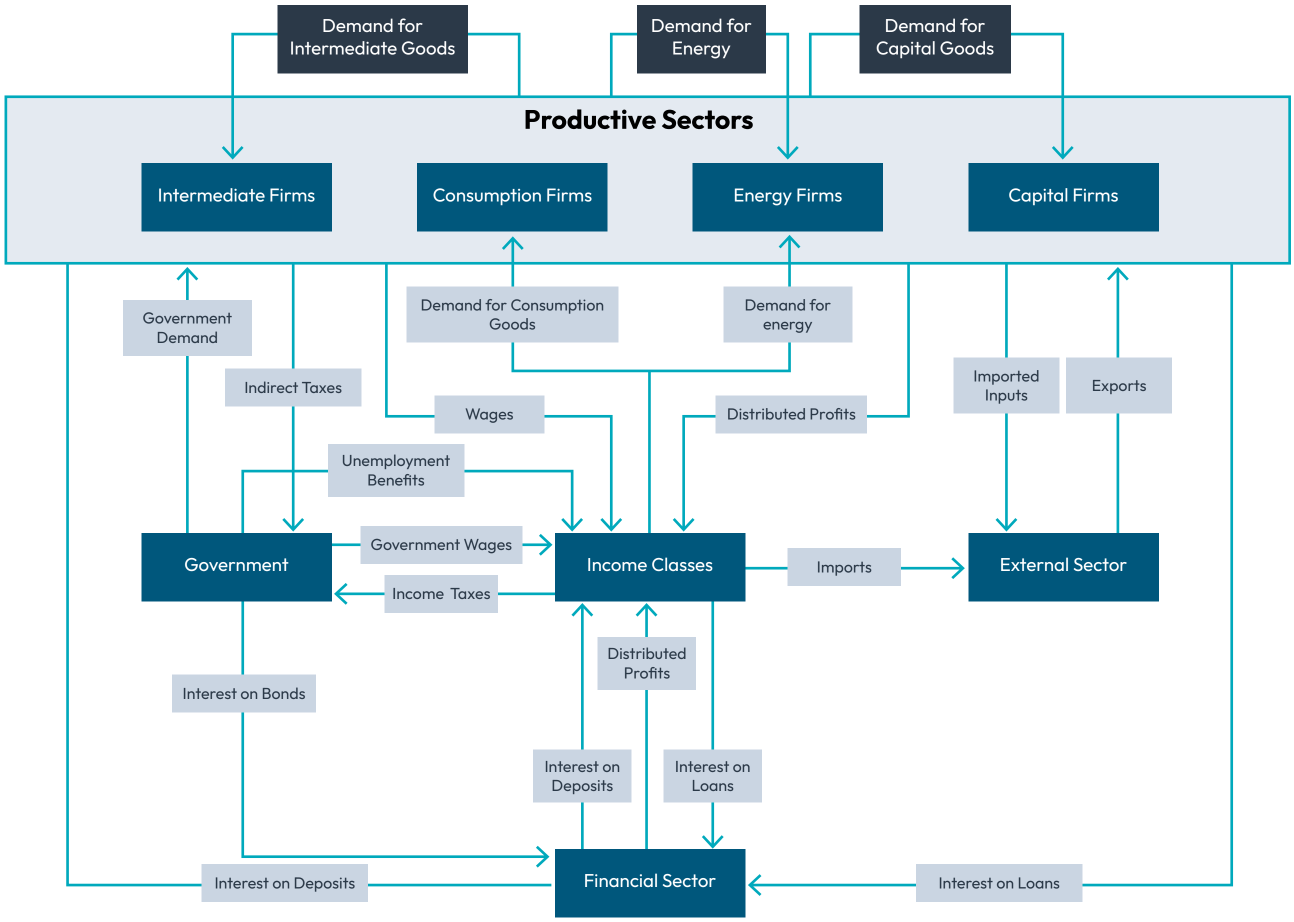

Figure 23. Multisectoral Micro-Macro Model for the Economy, Energy and Emissions (M3E3): structure, agents and flows between agents. The model is composed by consumption goods firms, intermediate goods firms, capital goods firms and energy goods firms. To produce, all firms demand intermediate goods and energy from the respective sectors based on technical requirements. All firms also demand capital goods from the capital sector when deciding to invest and build productive capacity. The household sector, divided into four income classes, demands consumption goods from the consumption firms and the external sector (imports) and energy from the energy sector. The government can demand goods from all sectors, as can the external sector. Production generates income, wages and distributed profits, which goes to the income classes, while a share of profits is retained in the firm to finance investment. If internal funds are not enough, firms can demand loans from the banks in the financial sector. Households can also demand loans to finance consumption decisions. The banks receive interest on the current loans, retain a share of profits to follow regulatory rules and distribute another part back to the income classes.

[92] We run 400 time periods of 3 months each, corresponding to 100 years in simulation (from 1950 to 2050). We run 50 Monte Carlo simulation and compute statistics in every scenario. The model generates endogenous long-run growth and business cycles and endogenous inflation and replicate many other stylised facts, such as the continuous growth of labour productivity, long run stability of the capital-output ratio and the co-movements of aggregate variables and financial variables in the business cycles. This is an indirect calibration procedure. Since the structure of the model and the number of agents does not match the equivalent in real data, we explore the parametric space in a trial-and-error process so the results match some selected stylised facts or empirical data. Therefore, the model is not designed to generate precise forecast, but it is useful to compare policy scenarios.

[93] See Vianna, Matheus Trotta (2021). "Monetary Policy and Stabilization in a Multisectoral Micro-Macro Dynamic Simulation Model". PhD thesis. Universidade Federal do Rio de Janeiro for a full list of stylised facts already reproduced by the previous version of the model.

All firms (both consumer and energy producers) make decisions of how much to produce, at what level to set prices, how much to invest in new assets and how much to invest in research and development (R&D). All firms can innovate and imitate each other in an attempt to improve their energy efficiency, thus reducing costs of production and gain competitiveness.[94]

Results

We run different simulation scenarios and compare the performance of the model against the baseline simulation for a number of variables, including energy demand, energy intensity, total emissions and carbon intensity. Our Scenario 1 (baseline calibration) is set by assuming that firms do not make any efforts to improve their energy efficiency via innovation and that there is no change in carbon intensity of energy sources. Scenario 2 introduces energy efficiency innovations of the firms based on the Brazil historical data from 2000 to 2018. Scenario 3 introduces innovations in the energy sector firms to support substitution from carbon intensive to green technology (e.g. solar). Scenario 4 combines both Scenario 2 and Scenario 3, introducing both energy-efficiency innovation and changes in energy source of the energy firms. This scenario is the closest to the current trend in Brazil.

Scenario 5 explores higher rates in carbon intensity of energy, compatible with the cases of Canada and the United Kingdom, but not innovations in energy efficiency. Scenario 6 builds on Scenario 5 by re-introducing energy-efficiency innovations, as in the current Brazilian trend. Finally, Scenario 7 applies the higher rates in both energy efficiency and carbon intensity of energy compatible with the Canadian and UK data.[95] Table 8 summarises the scenarios and their inputs.

Scenario	Energy Efficiency Innovations	Energy Source Substitution
Sc1 (Baseline)	No Growth	No Growth
Sc2	Brazilian Growth Rates	No Growth
Sc3	No Growth	Brazilian Growth Rates
Sc4	Brazilian Growth Rates	Brazilian Growth Rates
Sc5	No Growth	UK Growth Rates
Sc6	Brazilian Growth Rates	UK Growth Rates
Sc7	UK Growth Rates	UK Growth Rates

Table 8. Simulation scenarios and calibration conditions. All growth rates are averages from the year 2000 to 2018 for Brazil and UK in the different combinations of scenarios.

[94] Although it is possible to introduce technological search to reduce carbon intensity in production in all sectors, we only allow this to happen in the energy sector for simplicity and to limit the scope of the analysis in the context of energy transition. We recognise that emissions in other productive sectors matter, as emissions in household consumption and in agriculture and land use, in the particular case of Brazil, but those emissions remain outside the scope of this case study.

[95] Hannah Ritchie, Max Roser and Pablo Rosado (2022) - "Energy". Published online at OurWorldInData.org. Retrieved from: 'ourworldindata.org/energy' [Online Resource]

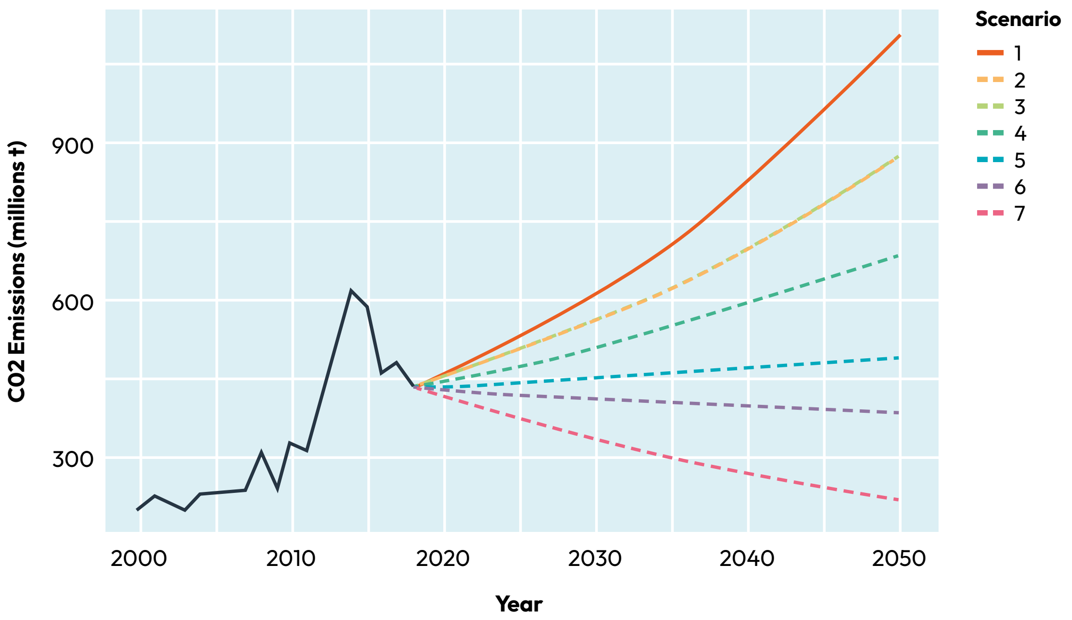

Figure 24. Historical and estimated CO_2 Emissions of Energy in Brazil in every scenario. Estimated series are calculated extrapolating the Brazilian GDP by the historical growth trend, while energy intensity and carbon intensity are represented as the input values in every scenario.

Figure 24 shows the CO_2 emissions from Brazil from the resulting scenarios. These are calculated averages of the Montecarlo simulation in every scenario, based on trend in GDP growth rate of the Brazil economy and showing the estimated growth rates of energy intensity and carbon intensity as input to the simulation.

Table 9 presents some key average results from the fifty Monte Carlo simulations from every scenario.

	Scenarios						
	Base – no innovation	**Energy efficiency innovation – Current Brazil Trends**			**Energy Efficiency innovation – Brazil follows trend as in the UK**		
Variables	**Sc1**	**Sc2**	**Sc3**	**Sc4**	**Sc5**	**Sc6**	**Sc7**
Scenario inputs							
Energy efficiency innovation trend	-	Brazil rate	-	Brazil rate	-	Brazil rate	UK rate
Energy source substitution trend	-	-	Brazil rate	Brazil rate	UK rate	UK rate	UK rate
Scenario outputs (Montecarlo average)							
Avg. annual growth of CO_2 emissions	4.84%	3.16%	3.16%	1.83%	0.45%	-0.31%	-1.54%
Avg. annual growth of energy demand	4.84%	3.16%	4.84%	3.16%	4.84%	3.16%	0.45%
Total CO_2 emissions (as a ratio of Sc1)	100%	85%	85%	73%	59%	51%	36%
Total energy demand (as a ratio of Sc1)	100%	85%	100%	50%	100%	85%	59%

Table 9. Results of model simulations with Monte Carlo analysis. This table presents the Monte Carlo averages cross 50 simulations for each of the seven scenarios (Sc1 to Sc7). Every simulation we compute the average annual growth rate of energy demand and carbon emissions as well as the accumulated energy demand and carbon emissions for the last 100 periods (i.e. 25 years of simulation from 2025-2050).

The results show that firm-led energy-efficiency innovation can contribute to a reduction of approximately 15% of total energy demand, and an equivalent reduction in CO_2 emissions associated to energy production in the scenario where there is no change in the energy sources. When taken individually, neither innovation in energy efficiency nor energy supply transition alone can bring GHG emissions to net zero by 2050. When the scenarios are combined, we find a reduction of accumulated energy demand to half of what it would be without those innovations, assuming the same growth rate of GDP. Total emissions fall by more than 25% in comparison with the baseline scenario. This is still not enough to meet Brazil's targets by 2050. Even stronger policy effects to promote energy transition would be required to reach net zero by 2050.

This shows how innovation in energy efficiency plays a significant role in reducing energy demand. The negative average growth rate in GHG is achieved only in a scenario where a stronger role of the government to support energy transition is combined with a continuous stimulus to energy-efficiency projects. Finally, when we test stronger energy-efficiency innovations in combination with stronger government support for energy transition, we are able to reach a greater negative average growth of GHG emissions with a higher reduction in energy demand.

Conclusion

The case study focuses on how firm-led innovations contribute to improve energy efficiency and therefore the associated carbon intensity of the economy. Although the study focuses only on innovation in energy efficiency in the firm sector and its associated emissions, we provide valuable insights that can be used to inform policy. We would also like to stress that, even though the model was calibrated to the Brazilian case, it is not designed to provide perfect projections and estimates. Rather, its main goal is to provide a robust framework to simulate and compare different scenarios by replicating stylised facts in the context of innovation in energy efficiency.

The experiments showed that (i) Firm-led innovation is one of the main determinants of a long-run trend of declining energy intensity and plays a key role in reducing energy demand. However, although Brazil has a good and long history of policies and projects to promote energy efficiency, (ii) the current speed of advancements in energy-saving technologies are unlikely to accelerate the improvement in energy efficiency that would be required in the short and medium runs to meet sustainable development targets without a proper transition to low-carbon energy sources. Similarly, (iii) the current speed of advancements in low-carbon energy sources are unlikely to meet sustainable development targets without firm-led innovations in energy efficiency. The study suggests that (iv) a combination of firm-led energy-efficiency innovations and government policies that promote energy transition to low-carbon energy sources is the most likely scenario to achieve climate and energy targets by 2050. We suggest that future studies should expand upon this model with other sectors and issues, such as emissions in agriculture and land use and carbon absorption technologies, which would add value to this debate.

Identifying the sources of structural changes of greenhouse gas emissions in Brazil: An input-output analysis from 2000 to 2020

Authors: Kaio Vital da Costa, Lucas Costa, Carlos Eduardo Frickmann Young.

Policy questions

- From which parts of the economy should the government seek to reduce emissions?
- How important will international trade be in the decarbonisation of Brazil's economy?

Methods

Structural Decomposition Analysis based on Input-Output data.

Key findings

- Most polluting industries seem to be reducing the intensity of their GHG emissions (except for electricity, water and gas).
- Agriculture, electricity generation and transport are responsible for most of Brazil's emissions.
- Exports accounted for almost a third of national emissions in recent years, but their production only represented 16% of gross output. Therefore, exports are more intensive in emissions by 9 tCO_2/R$ in comparison to the average of the economy.
- Despite still being a key source of national GHG emissions, household consumption has achieved improvements in the intensity of emissions.
- Reducing national emissions by replacing national products with imported products, whether for final or intermediate consumption, is unlikely to be helpful, either for reducing global emissions or for Brazil's economic development.
- Brazil has a strong interest in coordinating with other countries to establish conditions in global markets that would allow its export industries to remain competitive while eliminating emissions from their production processes.

Summary

The authors use a Structural Decomposition Analysis (SDA) to identify the main effects that were able to increase or mitigate the GHG emissions observed between 2000 and 2020. The objective of the study is to highlight the main effects and the most relevant sectors for the recent trajectory of GHG emissions. The study uses a time series of input-output tables and the country's emissions inventory to build GHG emission vectors so that the decomposition of emissions into economic impacts could be carried out. The approach allows us to identify that, in the last two decades, the increase in Brazilian GHG emissions has occurred mainly by an increase in the level of final demand, an increase in the share of emission-intensive final demand categories (such as exports) and an increase in the share of industries that are more intensive in GHG emissions. Agriculture, transport, distribution and production of electricity, water and gas, and industrial commodities were the industries most responsible for this increase. On the other hand, the total increase in GHG emissions was partially offset by a decrease in the intensity of emissions per unit produced.

Introduction

Brazil presents the highest GHG emissions in Latin America. In 2019 the country emissions per capita were about 5 tCO_2e, accounting for a total of 2,2% of global emissions.[96] Brazil is also one of the biggest suppliers of agriculture and livestock commodities in the world[97] and the emissions of the agriculture sector, including land use and forest change, amount to 73.1% of total GHG domestic emissions.[98] As a developing economy, the country should seek green industrial policies to modernise the production structure and change the international trade pattern. This challenge makes new investments in sectoral and structural linkages of the economy a critical element for the global debate about emissions.

[96] European Parliamentary Research Service (2022). Brazil's climate change policies: State of play ahead of COP27

[97] FAO (2022). Statiscal Yearbook: World food and agricultural.

[98] SEEG (2021). Análise das emissões de gases de efeito estufa e suas implicações para as metas climáticas do Brasil: 1970 – 2020.

Meeting the Paris Agreement's goals requires identifying the main sources of emissions in economies. This case study analyses historical data using a structural decomposition analysis to identify the main effects that raised or mitigated GHG emissions between 2000 and 2020. The key questions that it aims to address are:

1. What are the most polluting sectors in the Brazilian economy?
2. How does the emissions intensity of Brazil's exporting industries compare to the average emissions intensity of the economy? How has this changed over time?

Review of historical trends

Historical data show that exports tend to be more carbon and energy-intensive than other components of final demand in Brazil, which raise a concern about the environmental sustainability of the Brazilian trade pattern and how it has been changing in recent years.[99,100] The already-high share of commodities in the country's export basket has increased (even when discounting the effects of increased commodity prices[101]) as the share of energy-intensive products took off in the last decade.[102,103] From a sustainability standpoint, this seems to be pushing Brazil towards a trade pattern highly specialised in carbon-intensive goods, increasing the country's emissions embodied in trade.

Figure 25 presents the evolution of the gross output and total GHG emissions shares for six final demand categories: households' consumption, gross fixed capital formation, inventory changes, general government expenditures, exports and non-profit institutions serving households. Although the gross output required to meet 'export' demand ranges from 12% to 16% of the total gross output, the total emissions generated due to 'exports' ranges from 20% to 32% – which increased significantly after 2014. On the other hand, the share of emissions generated to meet the demand for 'gross fixed capital formation' and 'general government expenditures' remains throughout the series below the share of gross output driven by these categories. The final demand category with the highest share of emissions and production is 'household consumption'. 'Exports' also have a higher share in total emissions than in gross output, which can be justified by the high demand of this category for emission-intensive sectors such as 'agriculture', 'energy, water, gas' and 'transport'.

[99] Nassif, A.; Castilho, M. R. Trade patterns in a globalised world: Brazil as a case of regressive specialisation. Cambridge Journal of Economics, v. 44, n. 3, p. 671-701, 2020.

[100] Castilho, M.; Costa, K. V.; Torraca, J. F. A importância do mercado latino-americano e da competição chinesa para o desempenho recente das exportações brasileiras de produtos manufaturados. Análise Econômica, v. 37, n. 72, 2019.

[101] Commodity prices increased above the average of total export prices. To illustrate this, if the volume of commodities remained the same, the increase in export prices would have automatically risen the share of exports on total production (same volume × higher prices = higher % in exports). The data show that there was also an expansion of the volume of commodities in relation to total exports, thus explaining that the expansion in production could be registered even if when eliminating relative price effect (commodity prices rising above the average). This explains that Brazil is becoming increasingly more dependent on commodities exports.

[102] Young, C. E. F. (2016). Economia verde no Brasil: desapontamentos e possibilidades. Revista Politika, 4, 88-101.

[103] UNIDO (2017). Structural Change for Inclusive and Sustainable Industrial Development, Vienna.

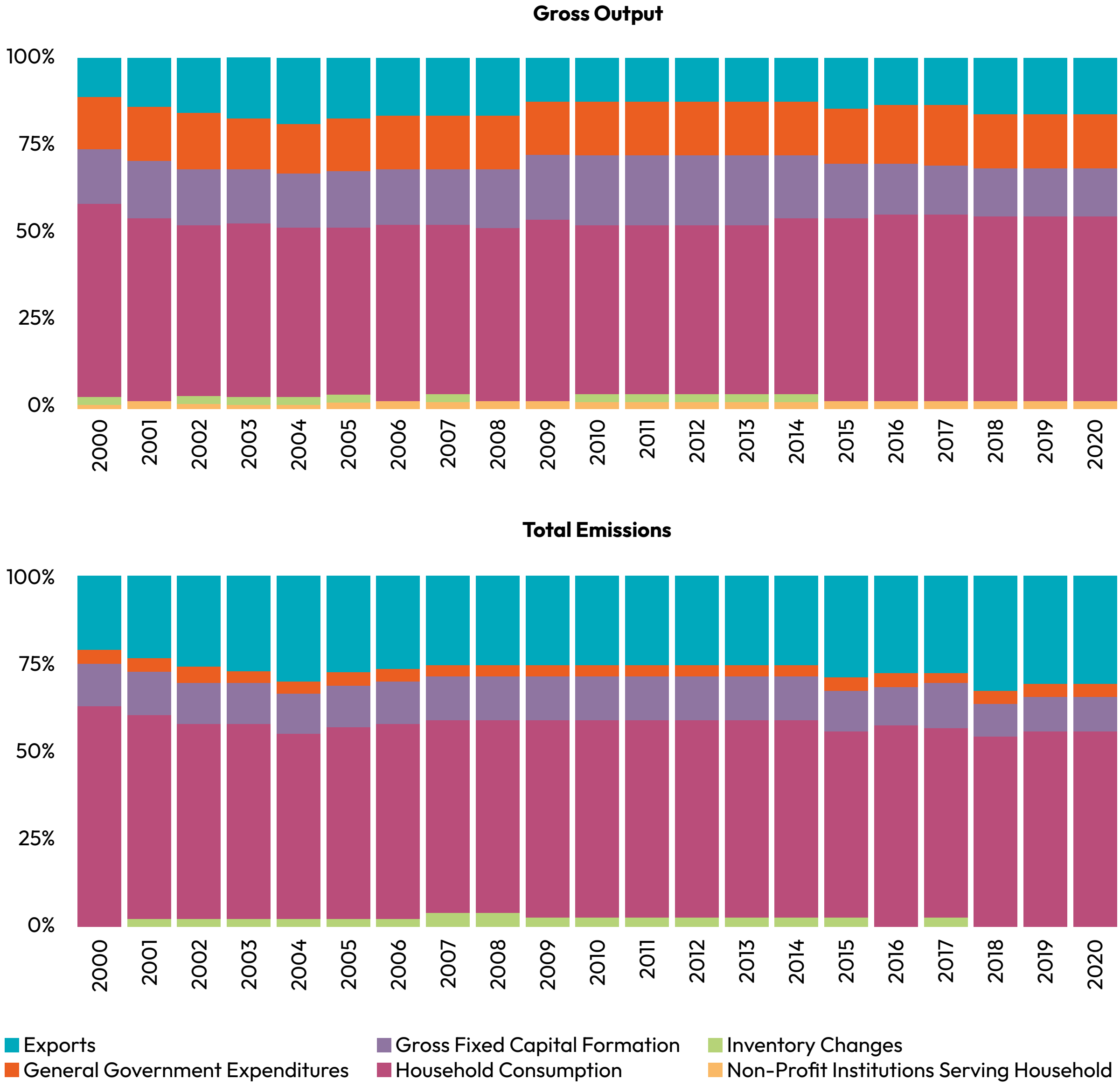

Figure 25. Composition of emissions by final demand component (in % of total emission). Source: own elaboration.

Figure 26 shows the emissions intensity (GHG emission for each million R$ produced) to meet each final demand category. Total output (including intermediate consumption) required for 'gross fixed capital formation', 'household consumption' and particularly for 'exports' are more intensive in GHG emissions than the other final demand categories. Furthermore, while the intensity of emissions from the other categories presents a downward trajectory – emphasising 'household consumption' – the intensity of emissions attributed to 'exports' increased considerably after 2008.

Indeed, the Brazilian trade pattern shifted toward the most carbon-intensive industrial groups. This result supports the country's increasing trade specialisation in natural resource-intensive industries (which often have higher energy intensities) in the period under review. Moreover, the Brazilian economic structure seems to be going in the opposite direction of what would be expected in transitioning to a low-carbon economy, notably since 2010.

Table 10 presents the intensity of emissions by the industrial group between 2000 and 2020.[104] The key sectors showing increases in emissions intensity were 'electricity, water and gas', 'innovative industry' and 'traditional industry'. 'Processed agricultural commodities' remained roughly the same, while 'transport', 'agriculture', 'industrial commodities' and 'other services' decreased emissions intensity.

[104] The groups are based on the perspective of industrial organization. So each group presents a specific type of industrial pattern of competitiveness, which considers factors like production based on scale, products based on natural resources, labor intensity, and technological progress.

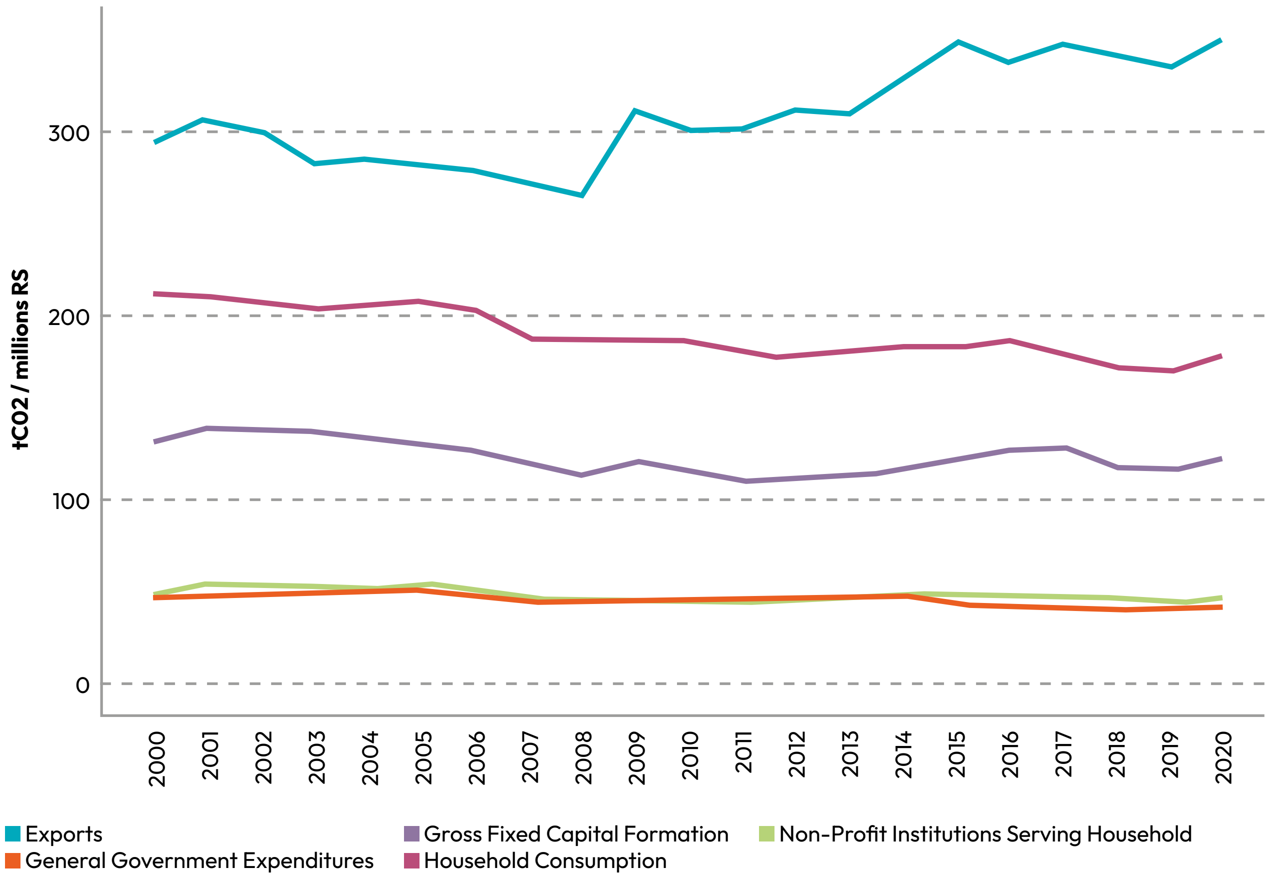

Figure 26. The emissions intensity by final demand component (tCO_2 per million R$). Source: own elaboration from SEEG database and input-output tables.

Industrial group	2000	2005	2010	2015	2020
Agriculture	2,205	2,152	2,019	1,754	1,836
Electricity, water, gas	625	603	615	773	646
Industrial commodities	287	215	232	259	230
Innovative industry	10	12	16	22	25
Other services	2	1	<1	<1	<1
Processed agricultural commodities	72	65	63	73	72
Traditional industry	28	28	35	35	38
Transport, storage and mail	627	582	549	603	551

Table 10. Emissions intensity by industrial group (in tCO_2e per million R$). Source: own elaboration from SEEG database.

However, while industries such as agriculture, industrial commodities and transport – industries that are required to meet export demand – showed a reduction in their GHG emissions intensities, the emission intensity of 'export' production worsened in the period. This trend is due to an increase in the participation of these industries – which, despite reducing emission intensities, are still major GHG emitters – for 'exports'. On the other hand, the production for 'household consumption' decreased in carbon intensity. This is not only because these industries reduced their carbon intensity, but also because their relative share in 'household consumption' required that production was decreased compared to the other sources of demand.

Structural decomposition analysis

A structural decomposition analysis (SDA)[101] was performed from 2000 to 2020, as shown in Figure 27. The SDA consists of the disaggregation of input-output data into the different components (effects) that can explain why the change in sectorial data occurs (such as emissions, employment) between two or more periods. From a time series of input-output matrices and a time series of GHG emissions vectors, the SDA method allows the disaggregation of the increase in Brazilian emissions between 2000 and 2020 into several effects that may be correlated with important economic trends in the period and the public policies observed. The SDA method agrees with the ROA framework as it is a form of system mapping that helps understanding of the structure of a system and can be used to inform more dynamic modelling efforts that focus on the process of change in the economy.

Results

The SDA shows seven distinct effects, which are described as follows:

- **Emissions intensity:** Changes in GHG emissions due to variations in the ratio of tCO_2e per unit of gross output of an industry.
- **Import of intermediate demand:** Emissions changes due to the variations in the share of imports of inputs for a given industry.
- **Technological effects:** Emissions change from changing the amount and share of each input used in the production of an industry.
- **Import effect:** Emissions change due to replacing national production for imports in the final demand.
- **Sectoral composition of final demand:** Emissions change due to a variation in the share of emission-intensive industries in final demand.
- **Final demand composition:** Emissions change due to variations in the share of final demand categories.
- **Final demand level:** Emissions change due to a variation in total final demand.

The 'final demand level' effect is the most critical determinant of emissions in the Brazilian economy, especially in periods of higher economic growth. It is also worth highlighting the positive effects of 'final demand composition' and 'sectoral composition of final demand'. On the other hand, the effect of 'emissions intensity' reduced total emissions in the period, in the same sense as seen in Table 10. The 'technological effect' and 'import of intermediate demand' were responsible for slightly reduced emissions, but less consistently. Finally, no significant changes were observed in GHG emissions due to the replacement of national-produced final demand by imported final demand.

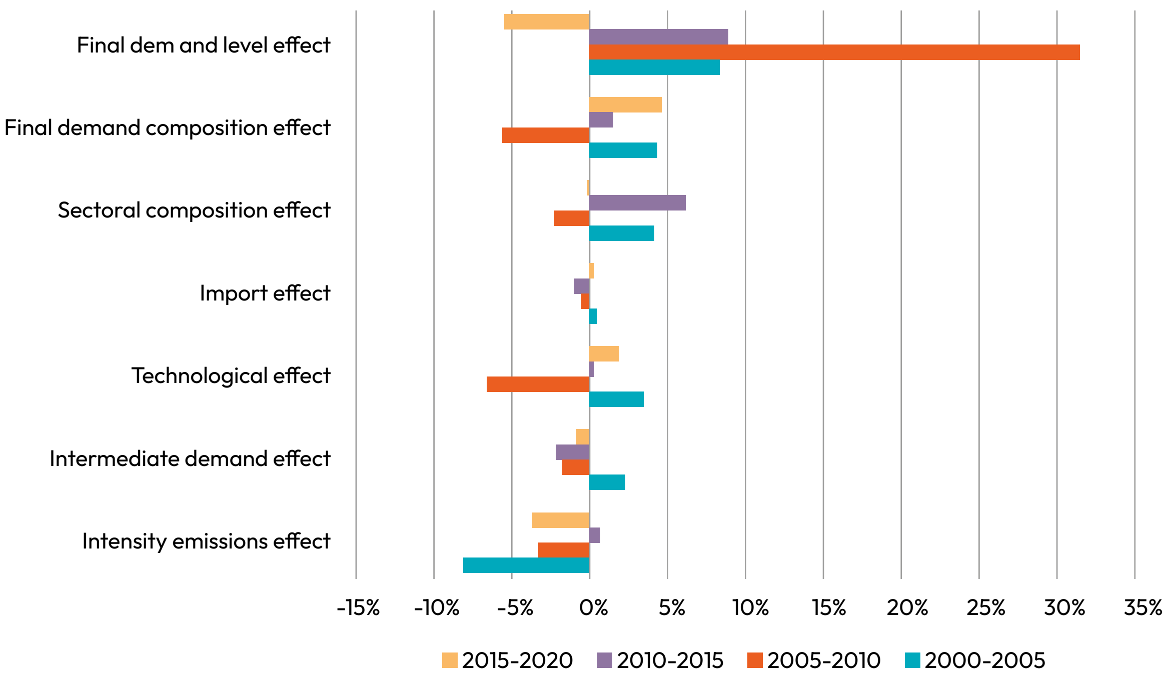

Figure 27. Aggregated results of the structural effects of GHG emissions by component. Source: own elaboration.

Figure 28 shows the evolution of GHG emissions through SDA in Brazilian industries. The most striking results can be seen in the long-run effects of structural changes observed in the agricultural sector. Emissions increased for all industries,[105] especially 'agriculture', 'electricity, water and gas', 'transport, mail and storage', and 'industrial commodities'.[106] However, this growth is mainly due to the 'final demand level' effect, which more than offsets the reduction from other effects.

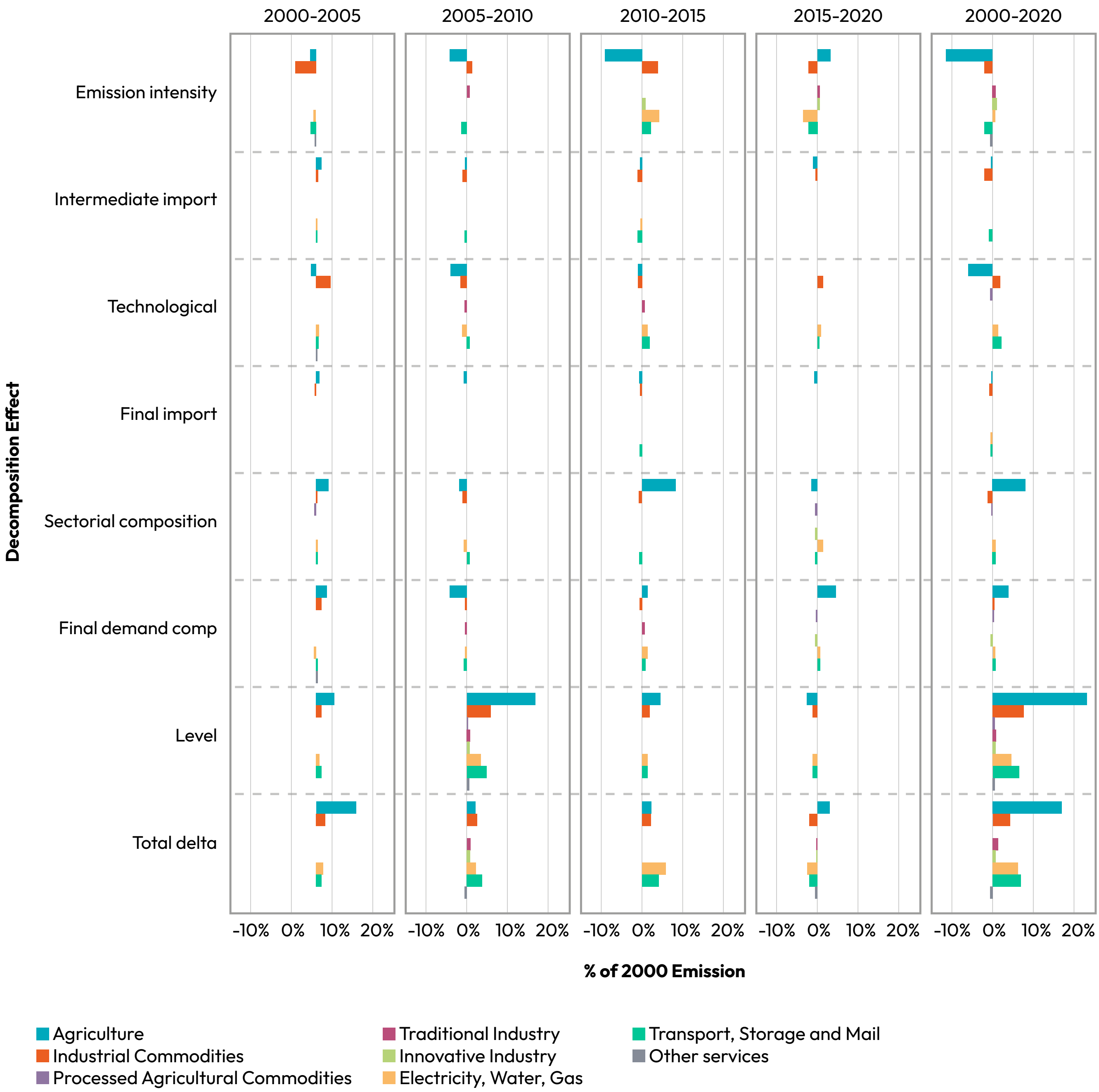

Figure 28. Structural decomposition effects for Brazilian economy (% of 2000 emissions in TCO_2 eq.). Source: own elaboration.

[105] The calculations were carried out at the level of 42 industries and grouped into 8 industrial blocs: Agriculture, fishing, and related; Industrial commodity group; Processed agriculture commodity group; Traditional Industry Group; Innovative Industry Group; Electricity generation and gas and water distribution; Transport, mail, and storage; other services. It may be that the aggregation level of the industries is too high to find a trade effect. In case the more polluting industries within an industry move abroad it is not recognised as a structure effect but as an intensity effect.

[106] More specifically the "oil and gas extraction", "cement" and "steel manufacturing" industries.

On the one hand, the 'final demand level' effect offsets any reduction in emissions that may have occurred through other means, the 'final demand composition' and 'industry composition' effects further deepened the increase in emissions of GHG in the period. The 'agricultural', 'transport' and 'electricity, water, gas' industries showed an increase in emissions through these two effects, which means these emissions-intensive industries increased their shares among other sectors – and the final demand categories that have more outstanding shares of these industries also increased their shares among the different demand categories.

The 'final import' and 'intermediate demand import' seem insignificant for individual industries but can be important in understanding GHG emissions from trading patterns. 'Agriculture' and manufacturing, mainly 'industrial commodities', have a negative import effect on GHG emissions; replacing nationally produced products from these industries with imported ones, whether to meet intermediate demand or final demand, can reduce national GHG emissions. However, regarding public policy to reduce global emissions, this mechanism should only receive attention if the imported product is less carbon-intensive than the domestically produced one. Nevertheless, this decrease is (almost) neutralised by the shift to exports in final demand – as shown by the 'final demand composition' effect.

The most positive result in reducing GHG emissions from the SDA shown in Figure 28 is the 'emissions intensity' effect. Despite the fluctuations in the period, the 'agricultural', 'industrial commodities' and 'transport' sectors were able to reduce total emissions by reducing the intensity of GHG emissions per R$ of output. In terms of public policies, this seems to be one of the most strategic ways to seek to offset emissions that consistently increase with final demand and production growth. In contrast, the 'innovative industry' (production of appliances and electronics), 'traditional industry' (production of food and beverages) and 'electricity, water, and gas', worsened their total emissions due to the increase in emissions intensity. The first two, although minor emitters of GHG per R$ produced, had consistently deteriorated throughout the entire period under analysis; 'electricity, water and gas' declined considerably from the middle of the second decade onwards due to the increase in the share of dirty energies, such as the increase in the use of fossil fuel plants.

Discussion and policy recommendations

Policymakers must consider the role played by technological factors, changes in trade patterns, and final demand growth and composition. The current trade patterns for the Brazilian economy are based on energy-intensive products like soybeans and meat, which impact (direct and indirect) the emissions pattern through the production process and deforestation. One option for transitioning to a low-carbon economy would be to use mission-oriented industrial policies that change the current trade patterns and production away from GHG emission-intensive products (such as livestock, mineral extraction and non-renewable energy generation). Concentrating policy incentives to implement increasingly less carbon-intensive production processes can improve the competitiveness of the export-oriented sectors, which brings both desirable economic development goals and at the same time positive effects to reduce the negative impact of climate change.

From the descriptive statistics shown in this case study, it is worth noting the most polluting industries seem to be reducing the intensity of their GHG emissions (except for electricity, water and gas). This result strengthens the idea that several sectors benefit from increasingly cleaner production processes, such as the intensification of livestock and processes. The adoption of cleaner production processes contributes to reducing and capturing the emitted GHGs, transport that uses less or non-fossil fuels, electric energy generation that does not depend on fossil fuels; investments in the various manufacturing sectors which reduce both GHG emissions in industrial processes and energy consumption in these sectors.

The results also allow us to understand the GHG emissions' origin (industry) and destination (final demand categories). Exports accounted for almost a third of national emissions in recent years, with the production required to generate these exports representing about 16% of total gross output.

For many emissions-intensive exported goods, such as agricultural commodities and metals, eliminating emissions is likely to increase the cost of production, at least in the near term. For Brazilian producers in these sectors to reduce emissions without losing their competitiveness, it will be essential to have the right conditions in global markets. Consequently, Brazil has a strong interest in negotiating with other major producer and consumer countries in these sectors to agree on standards, the pace of the transition, and other measures to ensure low-emission producers are rewarded and not penalised by global markets.

In addition to seeking increasingly less carbon-intensive processes of national output, Brazil must induce the appropriate economic incentives to reduce demand for carbon-intensive sectors, such as 'predatory' agriculture (mainly extensive cattle ranching in deforested areas and plantations with high consumption of pollutant-rich fertilisers) and mineral extraction. On the other hand, despite still forming a key source of national GHG emissions, household consumption achieved a trajectory of improvement in the intensity of emissions. Both are due to the decrease in the intensity of demanded sectors and the relative increase in household demand for services – which are less intensive in GHG.

A deeper structural decomposition analysis suggests the policy recommendations seem even more appropriate. First, it is important to highlight that economic growth, green job creation and reduced inequalities must be pursued as required goals for Brazilian development. On the one hand, expecting a consistent strategy to reduce emissions by replacing national products with imported products, whether for final or intermediate consumption, does not seem appropriate. Both because this may not mean a global reduction in emissions and, as observed in the SDA for 2000-2020, these effects have low potential compared to the scale of national emissions.

On the other hand, three other effects are crucial for informing policymakers. First, we must highlight the importance of the final demand composition effects, mainly the sectoral composition effect.

A path towards a low-carbon economy also involves providing economic incentives and appropriate conditions (e.g. energy-efficiency loans, carbon pricing, energy-efficiency labels and consolidation and dissemination of low-carbon technologies) for sectors with greater potential within a green paradigm (such as transport, energy, livestock breeding, cement, iron and steel, and chemical), one that generates income and jobs that are not harmful to the environment. Brazil has not consciously adopted this path on a large scale in recent years, as shown by the SDA. Second, it is necessary that economic incentives favour, as far as possible, sectors or technologies with high potential for the green economy – not only the existing green industries, but also stimulating new green industries and the bioeconomy.

Third, it is essential for significant gains in reducing the intensity of GHG emissions. In recent years, some sectors such as agriculture, transport and industrial commodities could offset part of the increase in emissions but were far from offsetting the scale effect of final demand. Significant reductions in GHG emissions intensity are much more complex and costly in some cases, such as steel manufacture and extractive industries. However, sectors such as agriculture, transport and electricity generation are responsible for most of Brazil's emissions.

To ensure green growth and development, increased efforts are needed to ensure emissions intensities reduce sufficiently fast, both on the side of technology development and regulations. To induce technological change in the private sector towards a low-carbon economy, governments have a variety of instruments and policies at their disposal, including market-based programmes, regulatory measures, voluntary agreements, targeted development and infrastructure support measures. It is important to adopt a set of measures that are appropriate to national, regional and local conditions. These should also take into account differences in the distribution of financial resources between generations as well as differences in costs of transition across the country.

Conclusion and next questions

The EEIST programme has drawn both from theoretical and empirical evidence to demonstrate how accelerating energy transitions for a low-carbon economy can be achieved. Risk-opportunity analysis[107] represents an umbrella of tools and methods to help the government make meaningful decisions to meet Brazil's SDGs, and to build the required leadership needed in view of COP30. Empirical evidence that demonstrates how the ROA approach has meaning in the context of policy and real-world application is clear.[108] Models that draw on this evidence and agree with the ROA method are available to provide the analytical capacity to compare scenarios and explore impacts of policies.[109]

This report is a step forward in this line of work for the context of Brazil. The main aim is to summarise the output produced by EEIST for the context of Brazilian policy analysts and government. By describing the unique emissions, political and financial context of the country it opens the way for the learning from EEIST programme. These lessons are also integrated as part of novel models that can be used to assess specific policy questions at this very moment and developed by the Brazil team over the course of the project.

The engagement work with BNDES and the government opened the way for a number of pathways and research interests to be pursued as part of the next steps of this line of work. A number of questions arose, such as:

- What are the green investment needs for the Brazilian economy? Which are the key sectors that demand the biggest efforts?
- What are the policy and technological paths with lower decarbonisation costs (both financial and social) and higher sustainable growth potential?
- Which industrial policies should be pursued and why?
- What are the possible side effects of policies (e.g. subsidies) on financial variables (e.g. inflation)?
- Which investments have the higher benefit for job creation in terms of level and quality?

Some recommendations on approaches to analysis that could help answer these questions, and emerging from the continuous discussion with stakeholders as part of the EEIST project, include:

- **A systemic perspective is needed.** There is a need to accelerate existing expansion of renewable energy sources and new electrification projects while at the same time understanding the potential spillovers to the other sectors as well as the macroeconomic implications.
- **Complex toolboxes are necessary.** There is a need for the joint creation of a stakeholder-driven analytical toolbox: analysis of government databases, policy modelling and evaluation, domestic and international macro assessment.
- **Training programmes should be developed.** There is a need to develop training activities for Brazilian students and policymakers across different regions, to enable the use of a more diverse set of analytical tools.

[107] Grubb, M., Drummond, P., Mercure, J.-F., et al. (2021) The new economics of innovation and transition: Evaluating opportunities and Risks. Economics of Energy Innovation and System Transition. Available at: eeist.co.uk/eeist-reports.

[108] Anadón, L.D. et al. (2023) Ten policy principles for policy making in the energy transition: Lessons from experience. Available at: eeist.co.uk/eeist-reports.

[109] Barbrook-Johnson, P. et al. (2023) New Economic Models of Energy Innovation and Transition: Addressing New Questions and Providing Better Answers. Exeter, UK: Exeter University. Available at: eeist.co.uk/eeist-reports.

The immediate application of such new tools and thinking could help answer the above policy problems in their specific context. Some examples include:

- **Jobs and technologies are to be analysed together.** Technological trajectories should be mapped for key sectors and associated job-creation opportunities on entire supply chains.
- **Public mobility should be analysed in its wider context.** There is a need to design the public transportation fleet conversion strategy, considering the effects on the bus industry supply chain.
- **Impacts on land use and land use changes should be framed alongside industrial and transport sectors.** There is a need to explore long-term, economically viable alternatives for the development of deforested regions, considering both adaptation and mitigation approaches, and possibly stimulating reforestation of degraded areas.

All of these recommendations would require a strong engagement of science and inter-ministerial coordination to support systems transformation for a low-carbon economy.

Appendix – Engagement strategy in Brazil built around communities of practice

A clear strategy, a wide and deep network, experience with policy circles, and a structured and persistent progression in establishing and developing a multi-stakeholder dialogue have been key factors determining the success of the engagement strategy of the EEIST project in Brazil. The clear strategy was embodied in a steady stream of EEIST events and meetings with stakeholders in Brazil, even during the pandemic. A wide and deep network and experience in understanding governmental dynamics by EEIST local members helped in defining the correct level of questions to generate interest and impact. Finally, a structured approach to establishing and operating a consortium-wide community of practice (CPr) enabled collaborative work and supported cross-learning from key country players in the energy transition. This appendix describes the approach adopted for engagement in EEIST, integrating a bottom-up and a top-down strategy, and highlighting the results and lessons learned to support international research programmes that work at the interface between science and policy.

Engagement strategy

The foundation of EEIST's engagement strategy in Brazil has been a strong link to government via the country engagement lead and partners operating both in the country (Federal University of Rio de Janeiro – UFRJ, University of Brasilia – UnB, and University of Campinas – UNICAMP) and abroad (Sant'Anna School of Advanced Studies – SSSA). Figure 29 shows the number of events that were run along the CPr thread, and their alignment with the initially challenging and then more favourable mobility context determined by the COVID-19 pandemic.

The EEIST engagement programme started during the COVID-19 pandemic, with no options for organising in-person meeting. Still, the bottom-up strategy proved to be useful and robust against those difficulties, leading to a very positive engagement during the second part of the programme. Over the course of 2022, COVID restrictions were lifted, and a new government was elected, with appointment of key officials set to be better aligned with the main objectives of the EEIST programme. This offered a high-impact window for engagement.

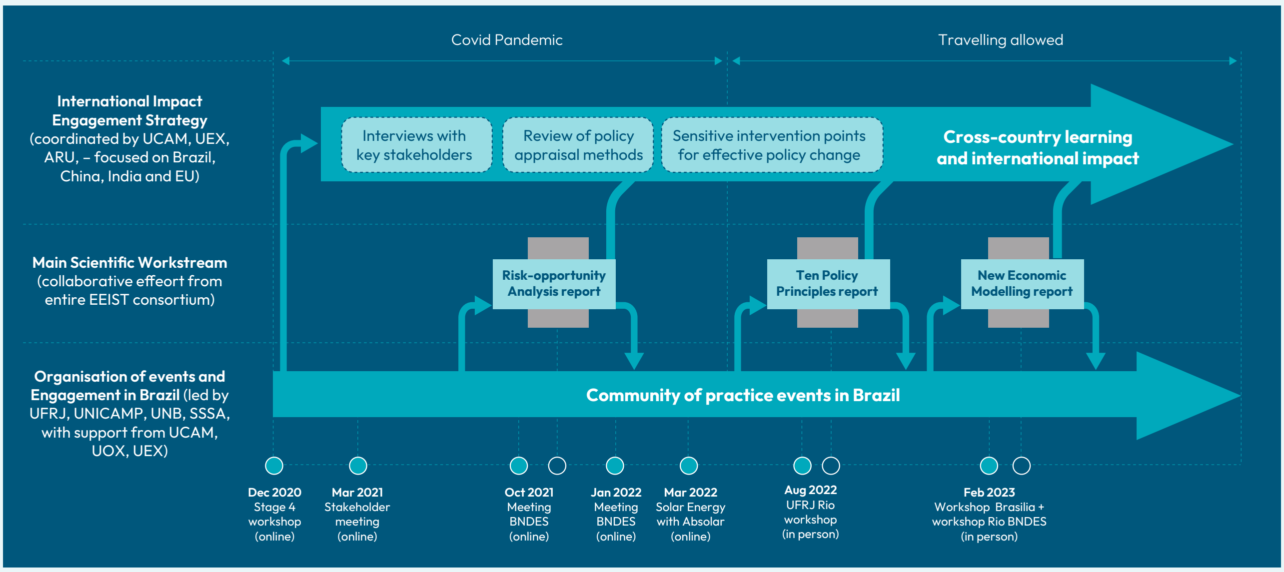

Figure 29. The engagement strategy in Brazil highlighting the cross-learning international motives, and the persistency aspects via the community of practice events in the local context. The EEIST academic partners involved were Federal University of Rio de Janeiro (UFRJ), State University of Campinas (UNICAMP), University of Brasilia (UnB), Sant'Anna School of Advances Studies (SSSA), University of Cambridge (UCAM), University of Exeter (UEX), University of Oxford (UOX), Anglia Ruskin University (ARU) and University College London (UCL).

The academic institutions involved in Brazil were well connected with the government and other key stakeholders, supporting the development of strong relationships with large institutions such as BNDES (the national development bank), the Ministries of Economy, and Mining and Energy, and industry organisations ABSOLAR and ABEEólica (the solar and wind power generators' national associations), thereby providing a good starting point for this programme.

The bottom-up execution of the strategy

There were eight CPr formal events in total, run just over two years. Five of them were online (due to COVID restrictions) and three in person. This was done in parallel to the main workstream and generation of policy-relevant research work outlined in the three major EEIST reports published to date[110,111,112] and alongside the cross-country learning and international engagement strategy led by the University of Cambridge (UCAM), that includes learning from China, India and the EU.

After a first project inception event focused on the wider programme plans and theoretical foundation with the ROA (December 2020 – online), the focus of the CPr events quickly gravitated towards key policy players, including high-level presentation events involving the presidents of ABSOLAR (the solar energy association) and ABEEólica (wind energy association), as well as congressmen and top-rank officers in the Ministry of Economy, and the Ministry of Mining and Energy (25 March 2021 – online). These early conversations informed the content of the EEIST project's first report, by highlighting case studies of wind power generation in Brazil. In parallel to the launch of the *Risk Opportunity Analysis* report in November 2021,[113] engagement work moved closer to the Brazilian Development Bank (BNDES)[114] with a more formal explanation of the ROA method, and proposing early-stage modelling capabilities based on ROA from partners in the University of Exeter (UEX) and SSSA (5 October 2021 – online). This was followed up by an entire event to allow BNDES to present their response, projects and interests for collaboration in the EEIST programme (18 January 2022 – online).

As the main workstream moved towards the design of the *Ten Policy Principles* report,[115] the conversation with institutions in Brazil moved to a stronger focus on solar energy with an event led by the Institute of Economics and the Center for Energy Planning (NIPE) at UNICAMP, and run with ABSOLAR, the Ministry of Mining and Energy and its subsidiary Empresa de Pesquisa Energética (EPE, the energy planning institution), and Agência Nacional de Energia Elétrica (ANEEL, the electric energy regulatory agency), seeking ways to approach solar energy in Brazil (23 March 2022 – online). This led to a case study on solar panel expansion alongside a case study on wind turbines for the EEIST report.

This CPr meeting generated an entry point for the EEIST programme at EPE, which started a close cooperation to compare modelling capabilities within EEIST and EPE normative tools used for the 10-year national development plan reports. A two-month collaboration supported the organisation of the following CPr event, led by the Institute of Economics team at UFRJ, with strong links to government and involving EPE, a former vice-president of BNDES, and a significant BNDES technical group. The understanding of the toolkit proposed in EEIST gradually became clearer.

September and October 2022 were characterised by efforts by EEIST team members in Brazil to anticipate the implications of a shift in governance for the coming elections for the uptake of EEIST approaches and techniques. In line with the launch of the *Ten Policy Principles* report at the Global Clean Energy Action Forum in Pittsburgh, they ran a scientific outreach campaign for the report in Brazil, leading to a launch event at UNICAMP with more than 600 participants, and appearing in some of the major news outlets, strengthening EEIST's relationships with stakeholders. The arrival of a new administration after the elections supported the project's engagement opportunities even further.

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[110] Grubb, M., Drummond, P., Mercure, J.-F., et al. (2021) The new economics of innovation and transition: Evaluating opportunities and Risks. Economics of Energy Innovation and System Transition. Available at: **eeist.co.uk/eeist-reports**.

[111] Anadón, L.D. et al. (2023) Ten policy principles for policy making in the energy transition: Lessons from experience. Available at: **eeist.co.uk/eeist-reports**.

[112] Barbrook-Johnson, P. et al. (2023) New Economic Models of Energy Innovation and Transition: Addressing New Questions and Providing Better Answers. Exeter, UK: Exeter University. Available at: **eeist.co.uk/eeist-reports**.

[113] Grubb, M., Drummond, P., Mercure, J.-F., et al. (2021) The new economics of innovation and transition: Evaluating opportunities and Risks. Economics of Energy Innovation and System Transition. Available at: **eeist.co.uk/eeist-reports**.

[114] BNDES is the leading finance source for green energy investment in Brazil being responsible, directly or not, for over 70% of the funding to large-scale wind and solar power generation projects in the past 10 years.

[115] Anadón, L.D. et al. (2023) Ten policy principles for policy making in the energy transition: Lessons from experience. Available at: **eeist.co.uk/eeist-reports**.

The next step was again driven by the creation of the third major report of the EEIST programme, which focused on presenting 15 case studies and the application of *New Economic Models of Energy Innovation and Transition.*[116] Two follow-up events in Brasilia, at the Escola Nacional de Administração Pública (ENAP), led by the UnB team (9 February 2023 – in person) and in Rio de Janeiro, at the headquarters of BNDES, led by UCAM (14 February 2023 – in person) provided an overview of the work done to date. This was followed by presentations of four case studies using three applications of agent-based models to show findings on (1) financial instability risk arising from overreliance on carbon pricing, (2) impact of the transition on the labour market and employment in Brazil, (3) sustainable farming and possible impact of policies on land use and food security in Brazil; and one application of the Future Technology Transformation (FTT) model on (4) the economic implications of solar and wind diffusion in Brazil. The second event concluded with BNDES presenting the current plans for future development in the next years to drive future research, and a proposal for further collaboration. Table 11 below shows some of the people who engaged with EEIST in Brazil.

Role	Organisation	Stakeholder Type
Senator, Chair of Commission	Senate Commission on the Environment	Congress
Leader of the Opposition	Chamber of Representatives	Congress
Minister	Ministry of Public Management and Innovation	Federal administration
Deputy Ex. Secretary	Ministry of Agriculture and Livestock	Federal administration
Director of Planning and Strategic Management	Ministry of the Environment	Federal administration
Subsecretary for Sustainable Economic Development	Ministry of Finance	Federal administration
Secretary, Electric Energy	Ministry of Mining and Energy (MME)	Federal administration
Director, Energy Planning & Development	Ministry of Mining and Energy (MME)	Federal administration
Director of Infrastructure Credit	BNDES	Federal public agency
Head of Planning	BNDES	Federal public agency
Deputy Head, Electric Power Generation	Energy Planning Company (EPE-MME)	Federal public agency
Head, Distribution Services Regulation	National Agency for Electric Energy (ANEEL)	Federal regulatory agencies
Economic Affairs Officer	UN ECLAC	International agency
President	Brazilian Solar Energy Association (ABSOLAR)	National associations
President	Brazilian Wind Energy Association (ABEOLICA)	National associations

Table 11. List of some of the policy workers engaged with EEIST in Brazil.

[116] Barbrook-Johnson, P. et al. (2023) New Economic Models of Energy Innovation and Transition: Addressing New Questions and Providing Better Answers. Exeter, UK: Exeter University. Available at: eeist.co.uk/eeist-reports.

A community of practice-centred framework for cross-country learning

As envisioned by the central engagement team in EEIST, the bottom-up engagement strategy was also used to inform the cross-country learning and impact effort at the international level (mirrored in the work with China, India and the EU). Despite the limitation of communication tools because of the COVID-19 pandemic, key stakeholders were identified and interviewed starting from the first CPr events, building one-to-one relationships, and forming stronger links across the international consortium. These allowed the consortium to ask specific questions on how ROA could support engagement and implementation of the proposed policies in the country and gather specific contextual information on the legal and policy systems. All of these contributed to the ultimate aim of highlighting opportunities for ROA to be used and applied in key economies. This line of work helped build a common ground across countries, demonstrating similarities and differences across systems of governance, and ultimately helping the international partners learn from each other and to support international impact.

Summary from engagement

The engagement strategy in Brazil illustrates the importance of a clearly conceived structure centred around CPrs, and proceeding from more general to more targeted engagement. The Brazil case demonstrates both the robustness and the effectiveness of a strong strategy that can be applied to every other country in international research projects that focus on policy impact. A clear overall design guiding the selection of country partners and relying on their leadership was a decisive factor, with the bottom-up engagement strategy played at the local level being determinant in the success of the entire programme. This, aligned with the overarching international-impact engagement strategy, supported highlighting peculiarities and barriers in those systems of governance helping to understand regulatory bottlenecks even further.

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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