NEW ECONOMY FOR BRAZIL: EMPIRICAL FRAMEWORK AND SCENARIO ANALYSIS

Leonardo Garrido, Andrea M. Bassi, Georg Pallaske, Iryna Payosova, and Arya Harsono

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Executive Summary

The New Economy for Brazil (NEB) is an initiative of WRI Brasil and the New Climate Economy (NCE) program. NEB identified opportunities in infrastructure, industrial innovation, and sustainable agriculture to achieve inclusive, robust, and resilient economic growth, as well as an opportunity to contribute to global goals on climate and the environment.

This technical note provides an in-depth description of tools and methods used to support NEB work and summarizes the efforts of a large group of experts and contributors, all of whom are acknowledged in NEB's 2020 report, *A New Economy for a New Age: Elements for Building a More Efficient and Resilient Economy for Brazil* (Romeiro et al. 2020). It also describes channels for implementing the policies NEB recommends for improving socioeconomic outcomes in Brazil, including metrics relevant for policymakers, such as value addition, income, and employment.

The paper explores what effects achieving net zero targets by 2050 or 2060 will have on the economy, simulates different timing of the intervention, and compares these scenarios to reference case scenario which reflects continuation of the past trends. Six economic development scenarios for Brazil have been developed and simulated with the suite of models used by NEB. These scenarios include a reference case or baseline and alternative runs that show different degrees of ambition in transforming

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the Brazilian economy, including through the transformation of energy systems and the movement to a low carbon economy. The reference scenario can be interpreted as a *Current Policy Scenario* where no new low carbon, green interventions are identified. The New Economy for Brazil scenario includes many green low-carbon interventions which start immediately and continue until 2030, with no incremental interventions taken thereafter. Four net zero scenarios have been developed and modeled. Two of these scenarios model that net zero emissions of greenhouse gases in Brazil will be achieved by 2050, and two scenarios model that net zero emissions will be achieved by 2060. Two scenarios have been modeled for each of the net zero "deadline" to simulate the effect of timing of the green policy mix introduction. Two scenarios start with NEB interventions that continue until 2030, followed by additional emissions-reducing actions taken in order to achieve net zero target by either 2050 or by 2060. The other two scenarios do not have NEB policies, with low carbon green interventions not immediately implemented. Instead, green interventions are delayed until 2030. All four net zero scenarios are calibrated to COVID-19 impacts and associated recovery paths reported by (IMF, 2021). The analysis shows that significant GDP growth and jobs creation are observed in association with "green" sustainable low-carbon policy interventions. The benefits of interventions are observed from the first year when these interventions were introduced. The highest benefits are observed under scenarios with early and continuous green low-carbon interventions. Late action or early but interrupted interventions do deliver benefits as well, but more modest or limited Such co-benefits extend to different areas, including lower use in primary energy; a more renewable electricity generation matrix (with no significant impacts in electricity prices); avoided deforestation while meeting food and energy demand; higher restoration effort; the leveraging on green investment to foster resilience and gaining access both from households and producers to markets; and enhanced agriculture productivity. Additional socio-economic co-benefits are also identified. Overall, the outcomes of the modeled scenarios show that the greatest benefits from low-carbon green development in Brazil will be achieved when early and sustained green policy interventions and implementations are made, from the present day and continuing to mid-century.

1. Overview

The New Economy for Brazil (NEB) is a joint initiative of WRI Brasil and the New Climate Economy (NCE) project.[1] NEB was established to provide analytical inputs and engagement activities to advance Brazil's policymaking toward a low-carbon economy. On the analytical side, NEB identifies several policy interventions capable of delivering short-term responses to the COVID-19 pandemic and sound medium- to long-term interventions for attaining inclusive development targets while simultaneously contributing to meeting climate and environmental goals. Along with WRI Brasil and NCE, NEB brings core contributions from research partners, including the Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering within the Center of Technology at the Federal University of Rio de Janeiro (COOPE/UFRJ), its CenergiaLab, and KnowlEdge Srl, a modeling consulting firm based in Geneva, Switzerland.

Technical work under NEB identifies and characterizes green development policy scenarios along with a summary of associated co-benefits for the Brazilian economy. This approach allows for comparisons between green development pathways and other development paradigms in terms of their environmental sustainability and contribution to socioeconomic welfare. This exercise calls for explicit identification of transmission (implementation channels and impacts) of green, low-carbon policies, including the core feedback (impact/reaction) triggered by policy interventions over a set of endogenously determined socioeconomic outcomes. NEB findings are presented in WRI Brasil's flagship report, *A New Economy for a New Era: Elements for Building a More Efficient and Resilient Economy in Brazil* (Romeiro et al. 2020).

NEB's technical work and the identification of policy interventions are designed around the idea that, in order to develop robust policies, one should understand the nature of connectedness, interrelations, and interdependencies of climate, biogeochemical, and socioeconomic systems. Such interdependencies are also referred to as *feedback demand* and, in turn, are captured in complementary models unified under a common empirical framework. Simply put, NEB takes inputs from integrated assessment models (IAMs), including biophysical representations of energy systems, land use, water resources, ecological diversity, and socioeconomic structures. IAM tools are often used by international research groups and the Intergovernmental Panel on Climate Change (IPCC) to define transition scenarios for a low-carbon world. These modeling tools capture the interactions between different economic sectors, greenhouse gas (GHG) emissions, and the consequences for the global climate (IPCC 2022). Modeling scenarios can cover different scopes of assessment (sector versus whole country economy, region, world) and time frame (short term versus medium and long term). Short- to medium- and long-term macro and sector level scenarios (2021–50) were generated during the preparation of this technical note.

The NEB 2020 report describes results from modeling work conducted between mid-2019 and early 2020 and thus, did not include impacts emerging from the COVID-19 pandemic (Romeiro et al. 2020). Further simulations performed during the second semester of 2020 and during January–February 2021 included COVID-19–related model structures/segments. These latest results are the ones described in this technical note. Even with COVID-19 segments in the model, results described herein are similar to the simulations performed in 2019–20. Projections for 2021–50 suggest economic recovery from the pandemic shock, in the absence of other unexpected shocks. Modeling results for key economic indicators are presently supported by the observed economic dynamics.

This note is organized as follows: the subsequent section presents a concise rationale for the technical work supporting NEB. Next, the IAMs used by NEB, along with the method of connection, are summarized. Policy scenarios are then presented, followed by the empirical results for core, endogenously determined variables. Finally, the note identifies the channels of transmission (implementation and outcomes) for policies that can deliver more robust, inclusive socioeconomic outcomes while also delivering on climate and environmental targets.

2. A rationale for the NEB technical approach

NEB is built on the premise that attaining Brazil's socioeconomic development goals, improved health care and literacy rates, and real gross domestic product (GDP) growth relies on public policy interventions and actions that deliver on ambitious climate and environment goals. These interventions include post pandemic recovery efforts as well as shifting toward a more resilient, inclusive medium- and long-term development pathway. Integrated modeling approaches have been used for dynamic modeling of climate scenarios since the early 1990s. The first GHG emissions scenarios were released by the United Nations Framework Convention on Climate Change (UNFCCC) in 1990 and 1992 and were used for climate simulations with global circulation models (IPCC 2000). Thanks to an improved understanding of the drivers of GHG emissions and their effect on climate change and the environment, these scenarios were gradually updated and modified. A new set of scenarios was released in 1996, with refined emissions baselines, information on trends in technological change, and socioeconomic development pathways across all countries. Scenarios were further updated by 2000 and were used as an input for the IPCC's Third Assessment Report, the *Special Report on Emissions Scenarios (SRES)* (Nakicenovic et al. 2000). The *SRES* climate scenarios are comprised of four families in which economic growth and world population growth rates were the key driving forces for emissions. In addition, *SRES* scenarios covered such elements as technology development, reliance on fossil versus renewable energy sources, and regional and social aspects of development.

However, the *SRES* scenarios did not include any mitigating policies. In 2005, the IPCC called for new emissions scenarios to be ready before the Fifth Assessment Report, and in 2007 the IPCC requested that the Steering Committee on New Scenarios prepare several benchmark concentration scenarios compatible with baseline, stabilization, and mitigation emission scenarios (van Ypersele 2010), as it was understood that stabilizing emissions at the baseline-year level may not be enough to slow climate change. From these processes in the IPCC and the scientific community, two new branches of climate change scenarios evolved: Representative Concentration Pathways

(RCPs) and Shared Socioeconomic Pathways (SSPs) (Riahi et al. 2017). RCP scenarios were meant to interact with climate and atmospheric projections, analysis of impacts, adaptation, and vulnerability, and IAMs for emissions and socioeconomic scenarios, policies, and various issues relevant for sustainable development. IAMs integrate information from diverse fields of science to analyze and explain the interaction of anthropogenic and natural systems.[2] RCP scenarios developed four pathways for different levels of radiative forcing (Hausfather 2018). Although RCP scenarios are intended to interact with IAMs, they do not directly include socioeconomic "development pathway" narratives within the scenarios. In contrast, SSP scenarios promote integrated analysis of climate impacts, vulnerabilities, adaptation, and mitigation to climate change, and they elaborate on energy, land use, and emissions. The central question in all these integrated modeling approaches is how the climate will be changing. The NEB technical approach, in a way, asks a reverse question and instead focuses on economic development, with elements of mitigation and adaptation.

Based on mounting international evidence, the global community has realized that the effects of climate change are taking a serious toll on the economy and society, and these negative impacts are intensifying. Such evidence is presented, for instance, in reports by New Climate Economy (2018) and Stern and Dietz (2008). These reports identify policy transmission channels and quantify expected benefits from green, low-carbon interventions in renewable energy, energy efficiency, land, agriculture, waste, industry, cities, and other areas. Recent evidence challenges common preconceptions about costs and trade-offs associated with low-carbon policies (Medrilzam et al. 2021). These technical papers also highlight often-ignored benefits of green policies, such as mitigating negative externalities and triggering other positive dynamics. These policy interventions are becoming increasingly relevant and important as countries deplete natural resources and competition for natural capital intensifies (IPCC 2022). At the national level, socioeconomic benefits from low-carbon development policies are becoming increasingly apparent, as demonstrated by enhanced resilience and other positive outcomes from the rapid transition to green technologies and processes.

Nonetheless, skepticism and resistance to green sustainable policies persist. Several factors cause this resistance, including political economy issues, such as institutional rigidity to evolving societal needs and emerging technologies; inherited legal frameworks, slow legislative processes, and the networks of power; the phenomenon of "lock-in" on traditional technologies, paired with research gaps and poor uptake of low-carbon technologies in emerging sectors; and a lack of understanding of the role played by negative externalities in determining the socioeconomic outcomes and fundamental interdependencies between economies, climate, and the environment. At the technical level, skepticism is fueled by the predominant reliance on traditional models and empirical exercises that ignore, underrepresent, or misrepresent core relationships among climate, the environment, and the social economy. At times, failure to act on climate and environmental targets is substantiated by the work from leading economic thinkers (Hänsel et al. 2020; Nordhaus 2006, 2017a; PIK 2020).

Considering the above, NEB poses an overarching question: Do interventions with higher climate and environmental sustainability ambition have greater socioeconomic development potential versus standard business-as-usual (BAU) policies? BAU policies explicitly or implicitly rely on the extensive utilization of natural capital as a production factor. The question in this technical note is presented from the socioeconomic development standpoint. It focuses on the objectives that matter most to policymakers, including value addition, income, and employment generation.[3] Low-carbon policies are not seen as end targets but rather as avenues to attain such desirable socioeconomic goals and contribute to achieving shared global positive outcomes. Along these lines, NEB modeling work strives to capture fundamental feedback relationships that exist in socioeconomic, environmental, and climate systems. It highlights linkages and incorporates monetary valuation of the market and nonmarket elements that affect individuals' well-being. These linkages and elements are often overlooked yet are crucial for developing optimal policies. The following section describes the framework and relevant models utilized.

3. NEB suite of models and their linkages

Several features determine the choice of models for analyzing policy options under NEB. Brazil is a prominent global player. In 2020 Brazil was ranked 12th among countries in terms of GDP, and in 2021 its GDP in terms of purchasing power parity was US$3.44 trillion (World Bank n.d.a). In 2010–12 the country was the 6th-largest and fastest-growing economy in the world, surpassing the United Kingdom (Leahy and Wagstyl 2012). It is the world's 7th most populous country, with 213.99 million people (World Bank n.d.b). In the world, Brazil places 7th in terms of GHG emissions (1.4 gigatons of carbon dioxide equivalent); 5th in country size (8.5 million square kilometers [km^2]); hosts 12 percent of the remaining global forests, an area totaling approximately 5 million km^2); and is 24th in value of trade (over $530 billion).

Five factors guide the choice of the model for Brazil. First, an economy as large and complex as Brazil's cannot be represented by the small, price-taking economy modeling framework that is commonly used for developing countries. Such simple models cannot accurately capture a multitude of factors, causal links, and dynamic interrelations between these factors. As a result, simple models do not give reliable results and often cannot explain more complex types of interactions. Second, Brazil's size, together with the openness of its economy, demands examination of trade channels that affect and are affected by a range of policies. As policymakers strive to preserve macroeconomic stability, a condition for sustained economic growth, careful analysis is needed in other areas as well, including the external, real, monetary, and fiscal sectors. Third, Brazil's economy is rich in natural resources, with a heavy reliance on commodities for value addition, foreign revenue, and employment. Fourth, Brazil has a great potential to embark on an energy transition that is likely to affect both the structure and dynamics of economic activity and wealth generation in decades to come. Fifth, despite episodes of macroeconomic, political and social instability, the country had, until around 2015 (with significant setbacks being registered ever since) improved its citizens' overall average per capita income. However, Brazil is experiencing persistent inequalities, and suffers from haphazard urbanization, inefficient use of inputs, and waste. In terms of the Human Development Index (HDI), in 2019 Brazil dropped five positions, moving from 79th to 84th among 189 countries (Cristaldo 2020; UNDP 2020). However, when using the novel version of the HDI, the Planetary pressures–adjusted HDI, which incorporates environmental and climate change factors (including carbon dioxide [CO_2] emissions and the number of natural resources), Brazil's ranking improves (UNDP 2000). Part of Brazil's economic development has been attained at the expense of degrading and depleting its natural resources base, including water resources, forests, and biodiversity. The pattern of extensive exploitation of natural resources demands understanding the role of negative externalities on well-being associated with the misuse and overuse of such resources.

In this way, NEB combines the following structural approaches under an integrated framework:

- A **global** model of computable general balance referred to as the **Total Economy Assessment (TEA)** model. TEA is a recursive dynamic computable general equilibrium (CGE) model that simulates the world economy's functioning through the simultaneous analysis of the existing interactions between regions, sectors, and economic agents (Cunha et al. 2020). It divides the world into 18 regions, Brazil being one of them, and includes a well-detailed representation of the agricultural and energy sectors and international trade.

- A **global**, bottom-up, dynamic perfect-foresight optimization model with extensive technological details of the energy and land-use systems, referred to as the **Computable Framework for Energy and the Environment (COFFEE)**. It is used to evaluate global and regional mitigation and technological development strategies under different climate stabilization targets (Rochedo 2016). It divides the world into the same 18 regions as TEA. COFFEE was one of many IAMs that was used to develop one of the IPCC's five illustrative mitigation pathways (IMPs).[4]

- A **national,** bottom-up, dynamic perfect-foresight optimization model referred to as the **Brazilian Land Use and Energy Systems (BLUES)** model. It describes in greater detail conventional and mitigation technologies, investments, and operation and maintenance costs for the energy, land-use, and water-use sectors in six native regions: one main, overarching whole-country region and five geopolitical subregions nested within (de Carvalho Köberle 2018). The BLUES model is used by COPPE/UFRJ (CenergiaLab).[5,6]

- A **national**, customized **Green Economy Model (GEM Brazil)**, which offers a macroeconomic assessment of the socio-economy, the natural capital that supports it, and externalities (positive or negative effects on the parties who are neither producers nor consumers) (Bassi 2015). Based on Systems Thinking principles and System Dynamics methodology, it is designed to help policymakers identify environmentally sustainable paths consistent with attaining medium- and long-term development targets, thereby enabling the transition to a more inclusive, robust, green economy. GEM Brazil allows for a better understanding of the co-benefits associated with sustainable policies, including on value of externalities related to different policy scenarios.

Altogether, these models capture core characteristics and policy-relevant elements: country size, openness, macro-stability issues, the role of primary resources, natural capital interdependencies, and the effect of externalities associated with policy scenarios. They help analyze both short- to medium-term impacts and responses to the COVID-19 pandemic and medium- to long-term development pathways. Both macro and sectoral models are being used and integrated so they can partially investigate distributional issues such as income distribution and poverty, a subject that will be more comprehensively tackled during a subsequent phase of NEB.

The key elements of the models and modeling process are described next. They refer to the integration mechanism across NEB models and the feedback that connects climate, environmental, and socioeconomic outcomes. They also encompass the unique COVID-19–related structures to describe the impacts of the pandemic and associated policy responses and the central role of externalities in assessing effects from policy interventions.

3.1. Integration across models

The flow of information that feeds into models begins with the definition of macroeconomic scenarios and the process of calibration to crucial variables, such as population and GDP growth rates, both at global and national levels. From the macroeconomic drivers, exchanging information and interactions between the global economic (TEA) and technological (COFFEE) models begins. A soft-link integration[7] between models allows the TEA model to provide endogenously generated values for the evolution of the final demand for goods and services for each sector and region in the world. The TEA inputs directly interact with the endogenously generated variables on land, energy, and others in the world, across regions from the COFFEE model.[8] The integration across models is illustrated in Figure 1.

Once the TEA-COFFEE interaction identifies Brazil's top-down boundary conditions, the bottom-up BLUES model provides more detailed results for the country, ensuring consistency with the global trajectories. These results include the penetration rate of different technologies in economic activities, possible changes in land use and GHG emissions, and the evolution of the sectorial energy intensity, represented by the relationship between energy use and the activity level of the sectors over the analyzed horizon, all of which are important indicators to support decision-makers.

Outcomes from the BLUES model are used as inputs for calibrating the GEM Brazil model (Figure 1). GEM Brazil was designed to include all key parameters and sectors relevant to the future development of Brazil: population, food demand and supply, land use and land cover, economic activity, employment, access to health care, education, energy demand and supply, air emissions, water pollution, and climate trends, among others. The model also provides an economic valuation of many externalities, including GHG emissions. The valuation is done using approved standard methodologies and based on the social cost of carbon (Nordhaus 2017b), air pollution, wastewater, waste, traffic-related impacts (e.g., accidents, noise), the opportunity cost of water (from savings in the agriculture sector), and biodiversity. GEM Brazil takes data on energy supply and demand, disaggregated by technologies, forest, land, agriculture, and socioeconomic indicators (including GDP) and is calibrated via an iterative process with the inputs from the BLUES model to ensure consistency of results (Figure 1). This calibration process is done in two steps: at first, the calibration process ignores—which is important and will be discussed below—internal feedbacks with the real GDP growth rate (so GDP results given by TEA-COFFEE-BLUES models are unchanged, in this first round, in GEM Brazil). A second step allows for complete feedback across core climate, environmental, and socioeconomic variables (including endogenous changes in GDP and the variables directly and indirectly affected by it), as explained in the following subsection. Figure 1 summarizes the process of integration across models. As shown in the figure, the integration channels from TEA-COFFEE-BLUES models into GEM Brazil included the following areas:

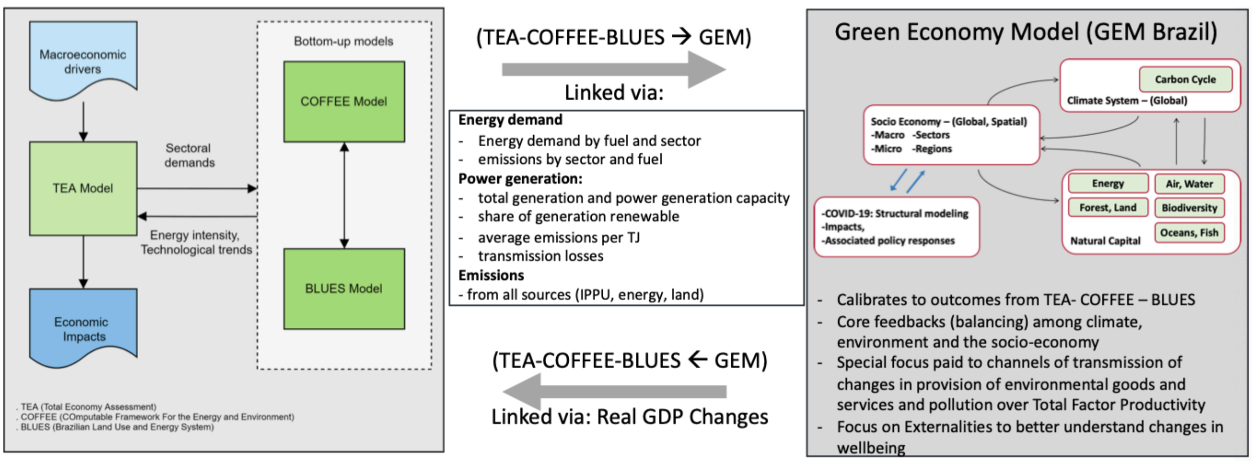
- Energy demand and emissions by the type of fuel, technology, and sector
- Power generation, including total generation and power generation capacity, through the share of renewable generation, on average emissions per terajoule generated, and through transmission/distribution losses
- GHG emissions from all sources (industrial processes and product use, energy, land)

An optional third step in the process is feeding back the endogenously generated outcomes from GEM Brazil into the suite of TEA-COFFEE-BLUES models. These new runs are once again inputted into GEM Brazil, seeking convergence in results. Usually, this is achieved after one or two iterations.

3.2. Feedback structures under GEM Brazil

GEM Brazil is built using the system dynamics (SD) methodology, serving primarily as a "knowledge integrator." SD is a form of computer simulation modeling designed to facilitate a comprehensive approach to development planning in the medium- to long-term time horizon (Forrester 2002; Meadows 1980; Randers 1980; Richardson and Pugh 1981). SD operates by simulating differential equations with "what if" scenarios, explicitly represents stocks and flows, and can integrate optimization and econometrics. The purpose of SD is *not* to make precise predictions of the future[9] or to optimize performance; instead, these models are used to inform policy formulation, compute policy outcomes (both desirable and undesirable), and assist in creating a resilient and well-balanced strategy (Probst and Bassi 2014; Roberts et al. 1983). Such an approach is consistent with policymakers' thinking framework, which weighs sets of outcomes based on political, technical, and institutional preferences in choosing from among policy packages (Garrido and Bassi 2022).

Figure 1
Integration across models under NEB



Notes: BLUES = Brazilian Land Use and Energy Systems; COFFEE = Computable Framework for Energy and the Environment; IPPU = industrial processes and product use; TEA = Total Economy Assessment.
Source: Authors

GEM Brazil includes four key capitals (physical, human, social, and natural) interconnected via the explicit representation of feedback loops (reinforcing or balancing).[10] Policies can be implemented to strengthen growth by supporting loops. For instance, they could include investments in physical capital, which, other things being equal, increases aggregate demand and potential growth. Others could curb change (e.g., by strengthening balancing loops). Under NEB, GEM Brazil was used to test the effectiveness of individual policies and investments (by assessing their impact within and across sectors and for social, economic, and environmental indicators) and inform development planning (by determining the outcomes of the simultaneous implementation of various intervention options).

Sectors are integrated within GEM Brazil and across models (TEA-COFFEE-BLUES) using stocks and flows (another central feature in SD modeling), which brings consistency to the mathematical formulations used to create the model.[11] This integration was possible through collaborative work among modeling partners, as described in the previous section. The resulting consistency within and across models provide a comprehensive, integrated view of many variables of interest for policymakers.[12]

GEM Brazil represents many feedback relationships. Two of them are noticeably absent from mainstream structural models and are highlighted in this technical note. These two feedback relationships are central for explaining the connectedness of climate, environmental, and socioeconomic outcomes and are paramount for the design of robust development policies. The first feedback relationship captures the impacts known as total factor productivity (TFP) in mainstream models. The second feedback captures the relationship structure in the main loop that governs linkages between climate, the environment (including policies), and the social economy.[13]

Channels affecting total factor productivity (TFP)

Traditional approaches, including neoclassical models, incorporate TFP as a proximate source of GDP growth. Generally, TFP is introduced in models either as an exogenous input or as a composite factor that combines an exogenous parameter or trend and an endogenous element that responds to changes in other variables, such as the rate of accumulation of human capital or physical infrastructure. GEM Brazil broadens the spectrum of factors affecting GDP and includes changes in the availability of environmental goods and services. Depletion or degradation of natural capital reduces its availability, whereas intentional or natural renewal and accumulation of natural capital increases its availability. A TFP-comparable variable is included in GEM Brazil and affects GDP. This TFP variable is a function of other groups of variables: human capital, health, education, and infrastructure of public services; air and water quality (measured through emissions); elements associated with haphazard industrialization and urbanization (waste, traffic congestion); and the quantity and quality of the natural capital (e.g., forest resources, water, biodiversity). The social cost of carbon is also included/reflected in the TFP function:

$$TFP_t^i = f\left(TECH_t^i, HEAL_t^i, EDUC_t^i, EMIS_t^i, ENER_t^i, WAST_t^i,\ INFR_t^i\right)$$

(EQUATION 1)

where *TFP, TECH, HEAL, EDUC, EMIS, ENER, WAST* and *INFR* are indexes that proxy for factor productivity, technological progress, health status, education, GHG emissions, level of energy consumption, and wastewater production.[14] The *i* subscript refers to sectors of economic activity (primary, industry, and services), and *t* refers to time. Such characterization provides the basis for understanding the differential impacts of green versus nongreen policies over socioeconomic outcomes.

The balancing feedback for climate, the environment, and the social economy

GEM Brazil models a fundamental feedback relationship: any policy that aims to boost aggregate final demand and output (such as the one from a fiscal stimulus for consumption or capital formation) creates a *balancing effect (or "balancing loop") that counters the growth* in the demand and output. This happens because such "stimulating" policy induces higher demand for inputs (e.g., for energy, environmental goods, and services) and, all else equal, contributes to higher GHG emissions, depletes or degrades natural capital, and negatively affects TFP. The strength of this balancing effect depends on the initial state, strength of the impacts (including the type of policy: green versus nongreen), and how binding these inputs are in the production process. By extension, the balancing effect's power is *attenuated* whenever the initial boost in demand is composed of low-carbon, environmentally sustainable policies or is supported by them. Appendix A provides a high-level representation for a CLD representing this core feedback, balancing loop.

3.3. COVID-19–related structures

Recent literature on the economic impacts of the COVID-19 pandemic highlights three main channels of shock delivery (Fiddamann, T. 2020). The first channel delivers shocks to the economy through medical and health emergencies (Kaye et al. 2021). The second channel delivers policy-induced supply shocks and impacts of public and private containment measures, which, in turn, have triggered a demand effect (Guan et al. 2020; Helper and Soltas 2021). The third channel of shock is through policy responses aiming to refloat economies and bring them back onto the path of sustained economic growth (Kirti et al. 2022; OECD 2020, 2022).

GEM Brazil does not incorporate specific structures to model COVID-19's dynamics,[15] and it does not include estimates of the number of infected, deaths, or the pattern of the epidemic (number of waves, their amplitude, and height) in response to virus-intrinsic factors (e.g., the R0 factor) or social and policy responses. However, GEM Brazil incorporates four different substructures to capture the policy-induced shocks and the alternative types of responses. A key difference of COVID-19 from previous economic crises (e.g., the 2008–9 global financial and economic crisis) is that in the case of COVID-19, both consumption and production have been impacted. These impacts are incorporated in the GEM Brazil model through the following:

- A shock to economic activity from reduced production (a supply-induced shock that affects demand and limits labor force availability). In GEM Brazil, this is represented by including a constraint to labor availability, which directly impacts production.

- A shock to economic activity from reduced consumption and investments (e.g., due to social distancing, avoided travel). This is represented in the model by including a temporary constraint to consumption (of the same strength as the constraint to employment) and investment, resulting in a higher propensity to save that does not translate into investment.

- A shock to capital utilization from the increased cost of doing business and reduced access to markets. This is represented in the model as reduced capital stock due to business closures.

- Additional shocks to specific sectors, negatively impacting transport demand and energy consumption when business activity is constrained.

These four model substructures are included in GEM Brazil, which is then calibrated using data from TEA-COFFEE-BLUES models to retrieve key model parameters introduced in them. Appendix B provides further details on how these four substructures are constructed.

Those structures can be utilized to capture candidate policy interventions (see "Summary of assumptions and policy interventions").

3.4. Externalities

GEM Brazil includes structural representations of different natural capital components, capturing the provision of environmental goods and services to the economy. Both quantity and quality factors are included. This enables the model to estimate (generally unintended) consequences of policies and investments that are meant to fuel economic activity. These consequences refer to air and water pollution, the generation of solid wastes, transport-related costs (e.g., accidents, congestion), and biodiversity losses (and corresponding ecosystem service losses). The social cost of carbon (SCC)[16] is also estimated. Table 1 summarizes the externalities computed by GEM Brazil, their definition (how they are calculated), and the costs per unit of the different externalities (Nordhaus 2017b), as identified in the relevant literature and generally accepted as the current global standard.[17]

Table 1

Economic Valuation of Externalities

EXTERNALITY	COMPUTED AS (DEFINITION)	COSTS PER UNIT OF EXTERNALITY
Air pollution (excluding from transport)	Sum of costs from nitrous oxide (NO_X), particulate matter ($PM_{2.5}$), and sulfur dioxide (SO_2) emissions	$PM_{2.5}$ = US$120,000/tonne[a] SO_2 = US$31,000/tonne[b] NO_X = US$4,600/tonne[c]
Solid waste (open dumping and managed landfills)	The environmental cost of open dumping (cost of greenhouse gas emissions) plus the total cost of managed landfills (sanitary and others)	Open dumping, social cost of carbon = US$31/tonne[d] Cost of managed waste = US$63.1/tonne of managed waste[e]
Traffic/transport-related	Sum of cost of air pollution; plus the cost of noise; plus the cost of urban effects; plus the cost of accidents	Cost of air pollution = €0.0052/vehicle/km[f] Cost of noise = €0.0019/vehicle/km[g] Cost of accidents = €0.029/vehicle/km[h] Cost of urban effects = €0.0008/vehicle/km[i]
Water opportunity cost	Foregone value added from use in thermal generation in industry and agriculture	Value added per acre-foot used for agriculture production = US$60.49/acre-foot[j] Value added per acre-foot used for industrial processing = US$228.02/acre-foot[k] Value added per acre-foot used for thermal generation = US$27.26/acre-foot[l]
Biodiversity loss (change in the value of ecosystem services provided)	Net change in value of biodiversity from the following: • agriculture to waste • forest to agriculture • forest to settlement • waste to forest • waste to settlement	Value of biodiversity, agricultural land = US$1,115/ha Value of biodiversity, fallow land = US$45,058/ha Value of biodiversity, forest land = US$50,110/ha Value of biodiversity, urban land = US$352/ha

Note: Averages are calculated using open-source databases for Brazil and recognized industry methodologies. Health costs per unit valued at $US\$_{2010}$ and $€_{2008}$ prices.

Sources: compiled by Bassi A. and Garrido L.

a–c. EPA 2013

d. Nordhaus 2017b

e. EconStor 2004 (Dijkgraaf and Vollebergh 2003)

f–i. (CE Delft 2011)

j–l. Frederick et al. 1996

What is critical regarding these negative externalities is that although they do not have a market-defined value, they impose a cost to society that may not be immediately manifested in monetary terms. Instead, the externalities take the form of direct loss of individuals' well-being, including increases in the rates of mortality, morbidity, and other parameters that measure changes in quality of life or amount of life. From there, externalities manifest in economic activity, such as through reduced quantity and quality of human capital and through inefficiencies in the production process. These parameters, in turn, increase intermediate costs and reduce potential and effective output. Furthermore, the monetary costs of mitigating the impacts of negative externalities often affect GDP (e.g., costs of hospitalization, waste management, public services to ease or solve traffic problems). Under these circumstances, what happens is that this "value addition" is not incurred to enhance individuals' welfare but to offset (to a certain degree) the loss of welfare that occurs as a result of the externality. Therefore, such value addition reduces available resources (consumption and investment), and, instead of leading to a net increase in individuals' well-being, the resources often are used to support the status quo.[18]

3.5. Some caveats regarding the modeling framework

Three caveats are worth considering for better understanding outcomes from the modeling work and their ability to answer questions regarding the time benefits of NEB policies and their distribution across actors.

First, the empirical exercise combines optimization, equilibrium frameworks (CGE, land and energy models: TEA, COFFEE, and BLUES) with a "what if" approach that allows for disequilibrium conditions (GEM Brazil). Results from optimization correspond to optimal endogenous outcomes as related to a given "objective function" (such as the lowest cost of the energy technology mix or the maximum utility for a representative agent). Results from the equilibrium frameworks, in turn, are a realization set for a larger number of variables (including variables for natural capital, externalities) that is consistent with results from optimization. This framework may or may not be aligned to a given policymaker's preferences. In other words, it is open for discussion whether the choice of policies is consistent with (subjective) weights stakeholders and policymakers assign to associated development outcomes.

Second, TEA-COFFEE models run with 10-year time steps, and the BLUES model runs on 5-year time steps, which makes it difficult to appraise short-term dynamics and transitions to low-carbon systems, especially during the critical 2020–30 period. GEM Brazil, in turn, is run with monthly time steps (to capture several climate-related seasonal patterns) and yields results on an annual basis. However, because it uses inputs from TEA-COFFEE-BLUES, there are some limitations to appraise short-term dynamics, including impacts and responses to COVID-19.

Third, it is worth noting that the empirical exercise does not include a comprehensive, economy-wide cost-benefit analysis. Such analyses could provide a foundation to assess how the costs of NEB interventions compare to the variables policymakers care about, such as value addition and income and employment generation. The exercise is limited to identifying the lowest cost for a given energy mix but falls short of providing a fuller appraisal of fiscal implications and of financing needs.

4. Summary of assumptions and policy interventions

Six scenarios have been created with the suite of models used by NEB, including a reference case, or baseline, and alternative runs that show different degrees of ambition in transforming the Brazilian economy, including through the transformation of energy systems and the transition to a low-carbon economy. They are summarized in Table 2.

Table 2

Definition of modeled scenarios: NEB and net zero

CLIMATE AMBITION	SCENARIO
Reference	Ref
New Economy for Brazil	NEB
Net zero in 2050	NetZero
New economy for Brazil and net zero in 2050	NEB_NZ
Net zero in 2060	NetZero_60
New economy for Brazil and net zero in 2060	NEB_NZ_60

NEB SCENARIOS	NET ZERO SCENARIOS
• Increased share of sales for the following: • Hybrid flex-fuel vehicles • Electric buses • Fuel cell (light, medium, and heavy trucks) • Increased share of biojet kerosene • Energy efficiency for building sector • Concentrated solar power and photovolatic reservoir • Charcoal use in iron and steel sector • High productivity agriculture and pasture	• Linear decreasing trajectory to net zero emissions in 2050 or 2060

Source: Authors.

Reference case. It reflects a continuation of past trends. It can be interpreted as a *Current Policy Scenario* (2020) where no new low-carbon, green interventions are identified. Historical trends are maintained over the horizon.

NEB scenario. This includes many interventions spanning areas of technology adoption of low-carbon solutions, including in the transportation sector, commercial and residential buildings, the power generation sector, the introduction of new material on the productive process, and actions that enhance productivity in the agricultural sector. The NEB scenario also includes other selected interventions that affect energy consumption, electricity generation, industrial processes, and product use that affect land dynamics. Table 2 summarizes all such interventions, and Appendix C identifies quantitative targets by five-year periods. Critically, the NEB scenario stops the increase in policy ambition by the year 2030. Thus, policy targets post-2030 for NEB remain at the 2030 level, as detailed in Appendix C. The NEB scenario is comparable to the "NEB+" discussed in the NEB 2020 report (Romeiro V. et al., 2020), but it has been revised to account for the impacts of COVID-19 and the effect of associated responses. For this purpose, World Economic Outlook data from the International Monetary Fund (IMF) was utilized (IMF 2021).

Net zero scenarios. Four net zero scenarios are produced, all of which are also calibrated to COVID-19 impacts and associated recovery paths reported by IMF (2021). The COVID impact is the same across all scenarios, including the short-term negative impact and the recovery path. Two of them include policy ambitions that are consistent with Brazil moving to net zero CO_2 emissions by 2050, and the other two are compatible with reaching such targets by 2060:

- **NEB_NZ** adopts the same policy mix as NEB by 2030 and continues increasing mitigation ambition, so the net zero CO_2 emissions target is reached by 2050. This is the most ambitious low-carbon scenario produced under NEB.

- **NetZero** also attains the net zero CO_2 emissions target by 2050 but delays the launch of low-carbon policies until 2030.

- **NEB_NZ_60** adopts the same policy mix as NEB (and NEB_NZ) by 2030 and continues increasing mitigation ambition so that the net zero CO_2 emissions target is reached by 2060. NEB_NZ_60 has higher ambition than NetZero by 2030, but after that, the pace of progress slows compared to NetZero.

- **NetZero_60** attains the net zero target by 2060 but delays the launch of low-carbon policies until 2030. It is less ambitious than NEB_NZ_60.

4.1. Summary of Results from NEB Modeling work

Net zero CO_2 emissions in 2050 and 2060 are not the same level as 2005. To reach net zero, all CO_2 emitted must be compensated by CO_2 removals, so the sum is zero.

The NEB 2020 report (Romeiro V. et al. 2020) summarized the positive outcomes associated with NEB scenarios. Net zero scenarios with higher climate and green ambition were shown to also have more considerable co-benefits. From the use of TEA-COFFEE-BLUES models, such co-benefits extend to different areas:

- Lower use in primary energy

- A more renewable electricity generation matrix (with no significant impacts in electricity prices)

- Avoided deforestation while meeting food and energy demands

- Higher restoration effort

- Leveraging green investment to foster resilience and gaining access both from households and producers to markets

- Enhanced agriculture productivity

The use of GEM Brazil also identified additional socioeconomic co-benefits. They manifest through lower primary energy use (further explained in "Channels of enhanced well-being associated with NEB policies") to determine enhanced outcomes relative to those indicated in Romeiro et al. (2020).

To start, NEB scenarios expand diverse renewable energy sources capable of meeting the country's growing energy demand while shifting toward the decarbonizing path. These scenarios expand solar, both photovoltaic and concentrated solar power; increase energy generation from biomass and sugarcane; replace fossil fuels with biomass-based fuels, such as diesel and kerosene biomass-to-liquid (BTL) fuels for transportation and bioenergy with carbon capture and storage (BECCS), associated with ethanol and biomass-based fuels production. Figure 2 summarizes outcomes from the BLUES model on the distribution of primary energy, shares in electricity generation, biofuels, and transport energy consumption.

As Figure 2 illustrates, primary energy demand will increase over the next 30 years, in all modeled scenarios. Reliance on oil as a primary energy source will reduce in all scenarios by 2030, and even more so by 2050. The share of sugarcane as a primary energy source will also decline in all scenarios, most prominently in the NEB_NZ scenario. Instead, the share of natural gas as a primary energy source will increase and will largely compensate for the reduction in oil use in four scenarios out of six that were modeled: in the reference scenario, NEB, NetZero, and NetZero_60. All models show that the biomass will become the most important primary energy source in Brazil during the following decades. The strongest (approximately quadruple) increase of biomass as a primary energy source over the 30-year period is observed in the NEB_NZ scenario, followed by slightly more modest growth of biomass in the NEB_NZ_60 scenario. Hydropower capacity as a primary energy source is not anticipated to increase. It remains largely unchanged in all scenarios, both in the next 10 years and by 2050. Nuclear energy as a primary energy source will marginally increase, and coal will marginally lose its role. Three scenarios out of six project that solar will strengthen its position as a primary energy source, yet its share in the total primary energy demand remains very low, only slightly higher than that of wind.

The main share of electricity is generated by hydropower plants, and all scenarios show an increase in electricity generation, both in absolute terms and in the volumes of hydrogeneration. The generation volume is increasing more than hydropower generation. An additional amount of electricity generation, according to the model and scenarios, will come from bagasse (sugarcane) and solar, and the share of electricity generated from natural gas will steeply decline between 2030 and 2050. The NEB, NEB_NZ, and NEB_NZ_60 scenarios all forecast a substantial increase in electricity generation from concentrated solar power.

For biofuels, three scenarios out of six (NetZero, NEB_NZ, and NEB_NZ_60) predict that first-generation ethanol will be phased out by 2050 and will be partially replaced by the ethanol from BECCS. These three scenarios also predict that a substantial share of biofuels in Brazil will be composed of advanced biodiesel BTL carbon capture and storage by 2050. The volumes of advanced biokerosene BTL will nearly double in all scenarios between 2030 and 2050.

Overall, the NetZero and NetZero_60 scenarios show the same level of transport energy consumption in 2050 as the reference scenario. The greatest reduction is predicted by the NEB_NZ and NEB_NZ_60 scenarios. These scenarios also show the lowest use of anhydrous ethanol among the six scenarios. Transport energy consumption will be mainly met by diesel. NetZero and NetZero_60 scenarios show greater reliance on diesel in 2050 than other scenarios evaluated in the model. Gasoline and kerosene, with about equal shares in transport energy consumption, are the second most important after diesel.

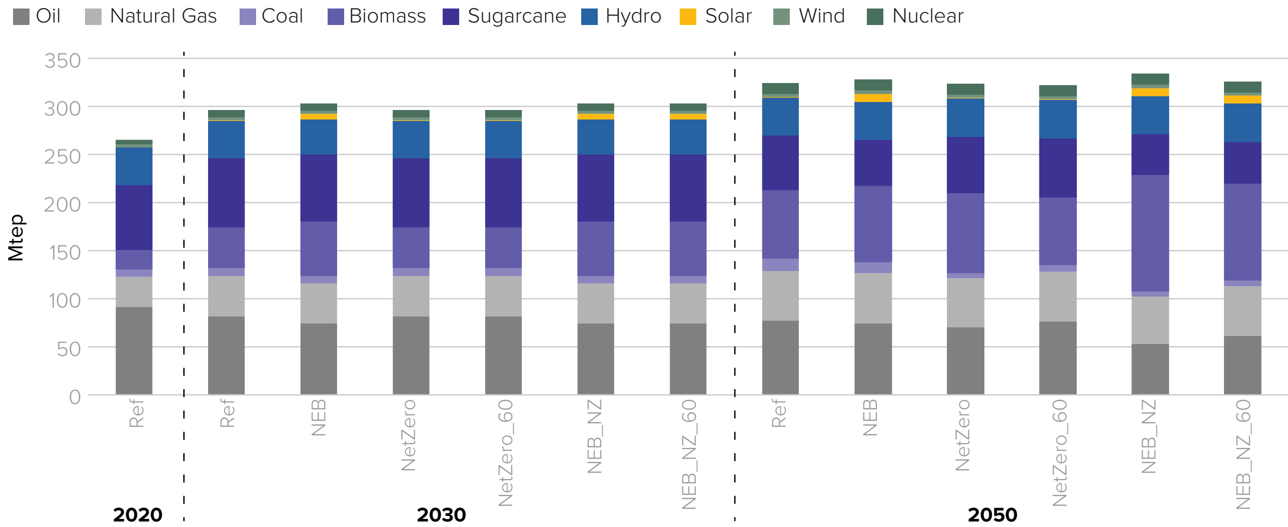
Figure 3, in turn, summarizes the results of NEB scenarios on the land and agriculture sectors. NEB policies include extensive land-use changes due to higher productivity of pasture and agricultural areas. Under the NEB_NZ scenario, about 40 million hectares (ha) of pasture are recovered, compared to about 15 million ha proposed on Brazil's nationally determined contribution (NDC). NEB also includes a 2 million ha reduction in deforestation as one of the cheapest ways to decarbonize the economy.

NEB policies help rapidly decrease CO_2 emissions: in 2030, projected emissions under this scenario are about 40 percent lower than in the reference scenario. Although all NEB scenarios comply with the revised NDC's intermediate target (a 43 percent GHG reduction in 2030, relative to 2005 levels), only the most ambitious ones (NEB_NZ and NEB_NZ_60) would align with the Paris Agreement. To ensure that temperature increase

Figure 2

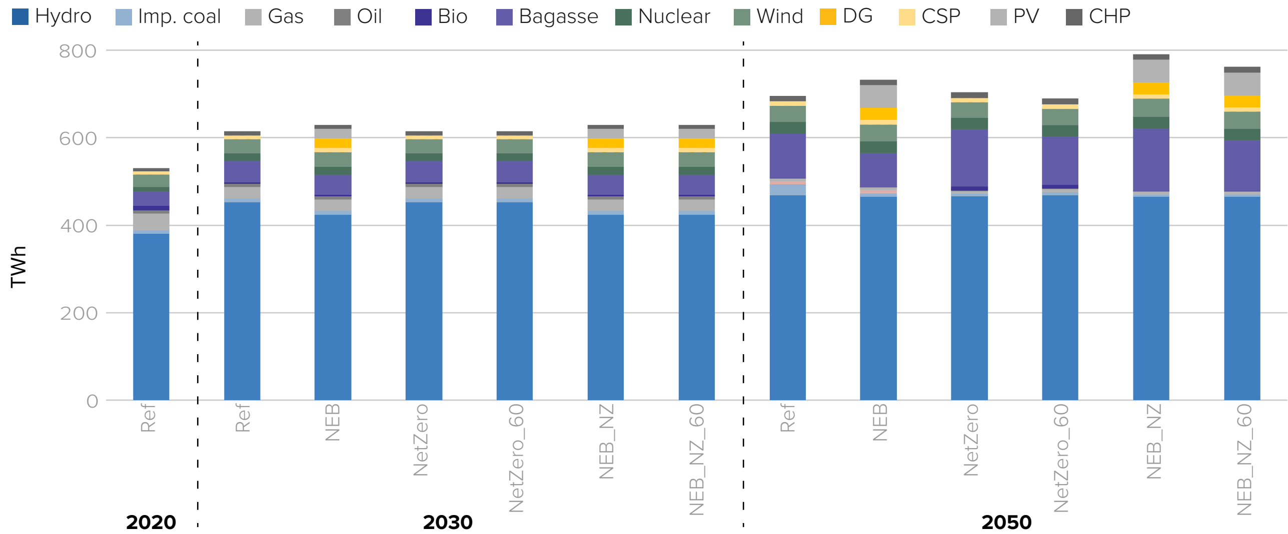
BLUES model results for the energy and transport sectors

a. Primary energy



Notes: Mtep = Million-Ton Equivalent of Petroleum; TWh = Terawatt-hour; CCS = carbon capture and storage; CHP = combined heat and power generation; CSP = concentrated solar power; DG = distributed generation; IC = imported coal; NC = nationally-sourced coal; PV = photovoltaic.

b. Electricity generation



c. Biofuels

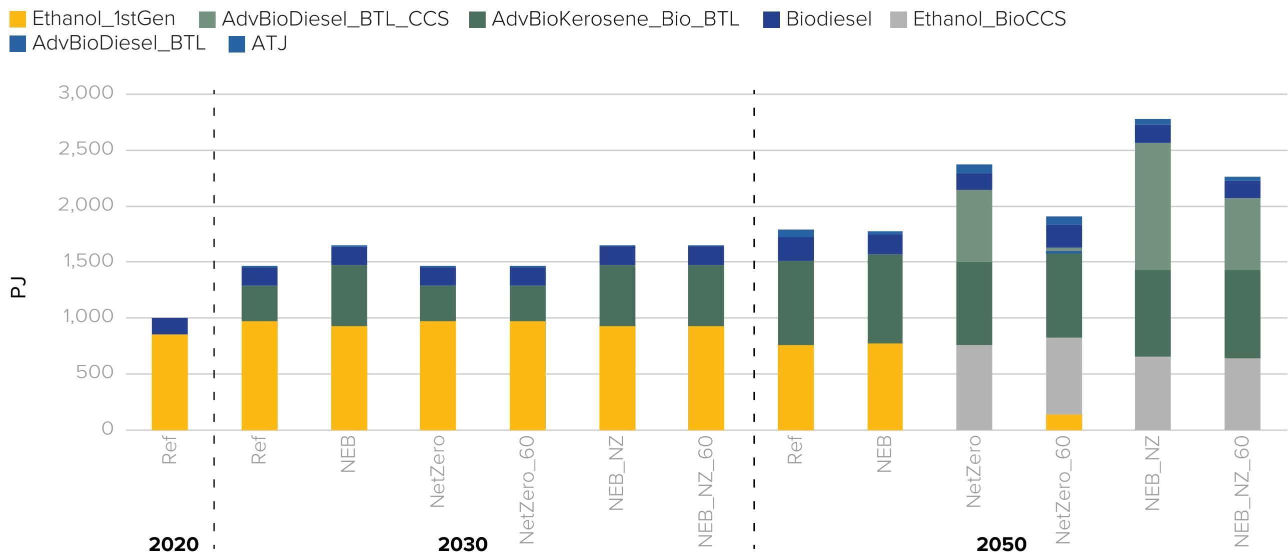
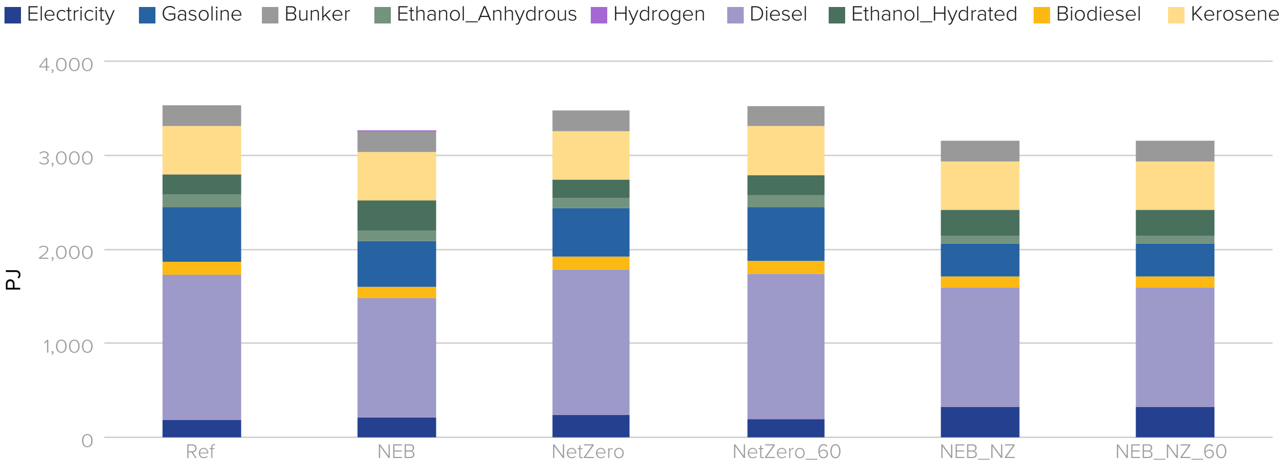


Figure 2
BLUES model results for the energy and transport sectors (Cont'd)

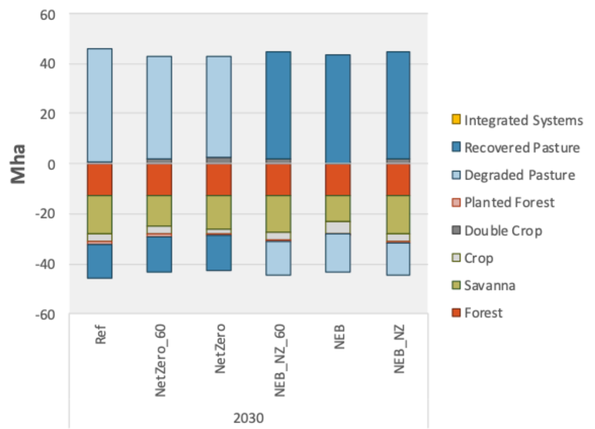
d. Transport energy consumption in 2050



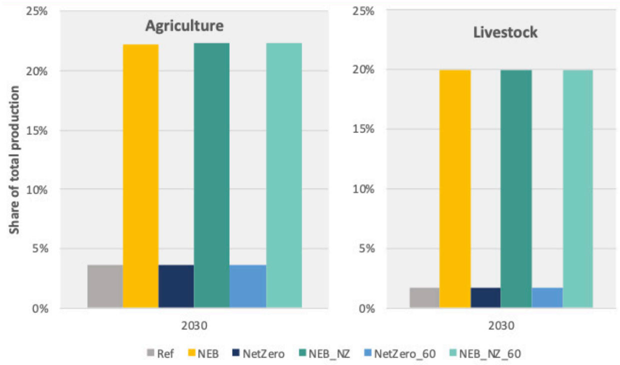
Source: Authors, via TEA-COFFEE-BLUES models.

Figure 3
BLUES model results for the land and agriculture sectors

a. Cumulative land-use change between 2011 and 2030



b. High productivity technologies



Source: Authors, via TEA-COFFEE-BLUES models.

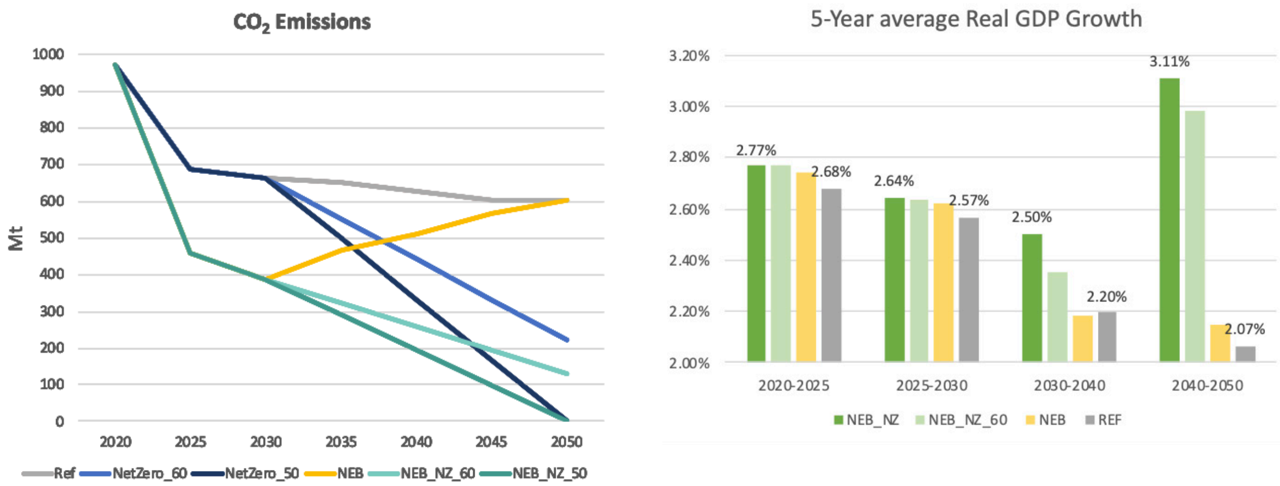
does not exceed the 1.5°C–2°C limit, both carbon reduction and carbon removal technologies are extremely important, as are the recovery of significantly degraded pastures and BECCS. This is reflected in Figure 4 (panel a). When complying only with the intermediate targets and not taking further action, as in the NEB scenario, emissions can increase after 2030, returning to reference case levels. However, with more ambitious actions, Brazil could comply with net zero targets.

Real GDP growth accelerates with increased ambition in the net zero scenarios, especially in the last analyzed decade (2040–50), following a long-term recovery from the COVID-19 pandemic and a full push from NEB policies to meet the climate targets.

Figure 5 shows how different scenarios will be realized in real per capita income (GDP). The NEB_NZ scenario has the highest growth rate in total GDP, and in 2050 it yields per capita income that is over 15 percent higher than that computed for the reference case: R$24,981 versus R$21,627, in constant prices. In the GEM model, the base year is 2000, but the results for income are smaller. Additionally, calculations were made with 2005 and 2010 as a base year. All other scenarios show less ambitious results, yet all intervention scenarios (NEB, NetZero_60, NEB_NZ, NEB_NZ_60) show higher real per capita GDP than the reference case scenario. General improvements in the economy are accompanied by reduced impacts from negative externalities (summarized in Table 1). GEM Brazil estimates an average reduction in the

Figure 4

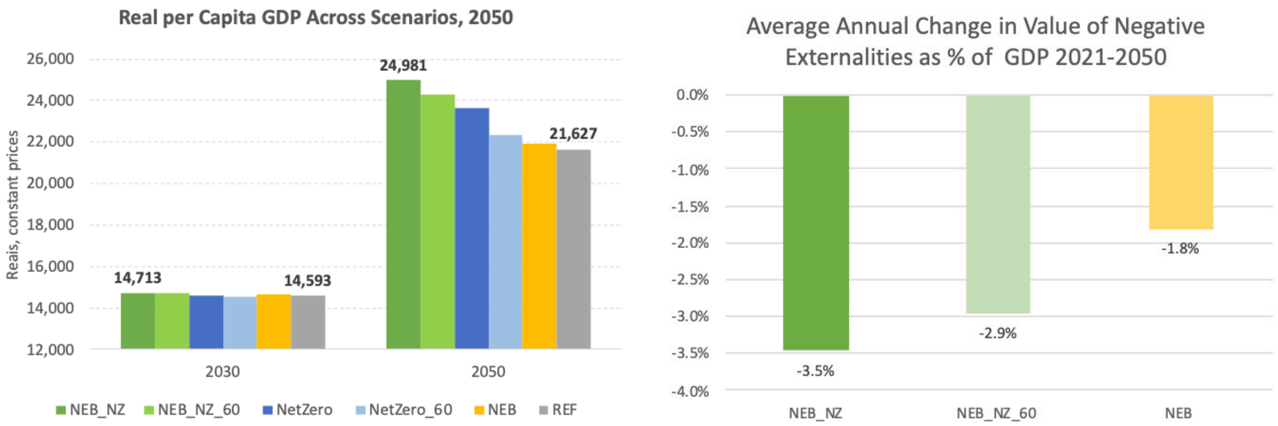
CO_2 emissions and real GDP growth



Source: Authors, via TEA-COFFEE-BLUES models.

Figure 5

Real per capita income and average value of externalities



Source: Authors, via TEA-COFFEE-BLUES models.

costs associated with negative externalities. Here, the reduction in the cost of negative externalities could be viewed as avoided costs or avoided losses to national economy and are expressed as a share of GDP. The NEB_NZ scenario shows the highest reduction: in 2021–50, the cost of negative externalities to Brazil's economy is reduced to the equivalent of 3.5 percent of GDP. Under the NEB_NZ_60 scenario, the cost of negative externalities is reduced by 2.9 percent of GDP. Under the NEB scenario, the cost of negative externalities is reduced in the amount of 1.8 percent of GDP (Figure 5).

5. Channels of enhanced well-being associated with NEB policies

Results from the "Summary of assumptions and policy interventions" section indicate general improvements in socioeconomic outcomes from low-carbon policies relative to the reference case. No intertemporal trade-offs are seen on aggregate, meaning that Brazil does not need to wait to benefit from those policies. Although losers are naturally expected in the transition—mainly those dependent on or linked to high carbon sectors—the overall NEB picture shows cumulative immediate and sustained gains for most of the population and for the economy. This underlined statement will be explained below.

Traditionally, potential gains from low-carbon policies have been ignored or underestimated. As explained above, many economic models fail to incorporate core linkages among climate, the environment, and the social economy. In other circumstances, such a connection is not sufficiently captured and established. There were attempts to quantify the contribution of some natural capital inputs (e.g., land, water), yet issues such as the quality of those resources (pollution) were commonly ignored. The role of externalities is rarely considered. Therefore, under many circumstances, low-carbon policies show minimal differential impacts on well-being (as proxied, for instance, by income, value addition, employment, and poverty changes) relative to standard policy packages.[19]

First, this section addresses some caveats regarding the benefits of development policies characterized by their low-carbon, environmental sustainability profile. Next, it summarizes the sources of improved well-being in low-carbon scenarios relative to a reference case and aligns with findings of alternative models and empirical exercises. The sources of improved well-being can be divided into three main channels: through TFP, through the availability of natural capital and associated primary resources, and via externalities.

5.1. Qualifying co-benefits associated with low-carbon policymaking identified under NEB

The real gains from low-carbon development policies have been empirically observed around the world and are within reach for Brazil, should the country embark on a transition to low-carbon systems like the one described by NEB. However, potential benefits from the NEB policies need to be adequately qualified, as indicated next.

The NEB scenarios: Not a forecasting exercise

The policy scenarios generated from TEA-COFFEE-BLUES-GEM models should not be interpreted as a "forecasting" exercise. For instance, when a 3.1 percent average real GDP growth rate is reported for 2021–50 under a NEB_NZ scenario, this does not mean that NEB is predicting such a result over the period. It means that under the NEB integrated framework (both from the optimization TEA-COFFEE-BLUES side and the "what if" GEM Brazil framework), the associated policies are consistent, and result is the attainment of output growth and other endogenous outcomes.

Focus on strengthening the loops between socioeconomic and climate-environmental structures in the appraisal of co-benefits

TEA-COFFEE-BLUES models provide a complete picture of the demand and supply elements to determine the optimal level and changes in the allocation of resources in response to policy. It is understood that demand-side factors play a fundamental role in the resulting socioeconomic outcomes. In the case of Brazil, changes in the allocation of resources are affected by labor market rigidity, by financial sector constraints (including savings availability and financial intermediation problems), by the lack of fiscal space, and so forth. However, the analysis of potential socioeconomic benefits under GEM Brazil is restricted to elements that affect potential output and the derived implications over variables such as income, employment, fiscal outcomes, and so on. Therefore, NEB focuses on strengthening the loops between socioeconomic structures and climate-environmental structures. From this perspective, increases in GDP in the NEB scenarios relative to the reference case, should be interpreted as the potential realization of such gains in value addition on the condition that no binding constraints (for instance, from the demand side) are in place. In this research, proxy indicators are used for measuring externalities linked to the availability and quality of environmental goods and services that contribute to and are affected by anthropogenic activity.

About inclusiveness and robustness of growth under NEB scenarios

NEB brings together several global and national-, macro-, and sector-level tools and associated policies through TEA-COFFEE-BLUES-GEM Brazil models (Bassi, A., and G. Pallaske, 2020). Describing outcomes from the NEB 2020 report highlights the role of the NEB policies to help build resilience in Brazil's socioeconomic systems, helping chart a more inclusive, welfare-improving growth path (Romeiro et al. 2020). Some of the channels include advancing quality infrastructure, adopting sustainable technologies, and transitioning to more sustainable and resilient agriculture. With all these in mind, it is also acknowledged that a more comprehensive, empirically grounded analysis would require incorporating additional tools into NEB. For instance, the tools from micro-level analyses, spatial assessments, and several case studies could shed more light on distributional, sectoral, and regional impacts of policies for a just transition toward low-carbon systems.

5.2. Channels of transmission

This last discussion builds on the identification of distinct NEB model structures (see "NEB suite of models and their linkages"), which enables a better understanding of the climate-environment-socioeconomic development nexus and describes channels of transmission for NEB policies that determine enhanced socioeconomic outcomes.

Total factor productivity (TFP)

Equation 1 in the "Feedback structures under GEM Brazil" section describes the set of variables that directly affect the productivity of economic activity sectors—and, consequently, the GDP—and associated socioeconomic variables. Changes in TFP are driven by GHG emissions, proxies for human capital (health, education), technology, energy costs, and wastewater. As explained above, ecological scarcity and the associated value of biodiversity losses are also conceptually and empirically identified as drivers of TFP. However, under the current GEM Brazil version, this link is not incorporated. The connection of biodiversity to land sector variables is high level. It is not sufficiently disaggregated to account for heterogeneity elements and other factors that properly capture ecological scarcity and the value of biodiversity in Brazil. Appendix D further identifies variables and other model parameters that affect the explanatory elements (proxies) included in Equation 1.

Such specification for TFP highlights the role of NEB policies relative to alternative interventions (Romeiro et al. 2020). Specific TFP-enhancing effects occur from the following:

- Technological progress in sectors (industry, services) associated with innovative low-carbon solutions
- Reduction of intermediate energy consumption relative to gross output under energy efficiency measures
- Improvements in human capital associated with enhanced air quality and, in general, lower SCC
- Improved wastewater treatment, which also contributes to human capital and increases water availability for the agricultural sector
- Enhanced availability and resilience of infrastructure services, providing more extensive and reliable access to a more significant fraction of producers and households

NEB policies are associated with differential improvements in all topics above, thus helping to attain enhanced socioeconomic outcomes.

Availability of natural capital and associated primary resources

In Appendix A, Figure A-1 highlights the role of natural capital for value addition, especially in primary resource-dependent economies. NEB policies to enhance agricultural productivity, improve water quality and availability, expand infrastructure service and energy access, and reforest or restore degraded land enable greater availability of environmental goods and services, all of which directly (and indirectly) contribute to the output. Appendix E summarizes the transmission mechanism of those NEB policies to agriculture production (both in conventional and sustainable activities) and value added per unit of production.

NEB policies tackle a primary concern in Brazil. They reconcile the need to increase output in primary activities to meet the growing national (and global) demand while preserving national forests and the biodiversity base. Sustainable agricultural practices that can be applied to existing crops include fertilizers, sustainable roads and transportation, tackling preharvest losses, wastewater treatment, other interventions of research and development, and human and physical capital. All of these would enable additional yield. Innovative business approaches can directly benefit from the vast, rich biodiversity base. These practices have the potential to boost primary sector-related inputs while maintaining the primary forest and continuously recovering degraded land.

Externalities

The "NEB suite of models and their linkages" section summarized externalities and their valuation method under GEM Brazil. Mitigating such externalities through the NEB scenarios contributes to enhanced socioeconomic outcomes, as described above. Wastewater output is reduced or treated, air quality is improved, and both outcomes positively affect human capital. In several cases, mitigation of externalities is not directly connected to GDP outcomes. Among those externalities are pressure on biodiversity and traffic-related externalities other than emissions. However, addressing these externalities still has an unambiguously positive effect on well-being. Table 1 gathered, from the empirical literature, the per-unit costs of negative externalities. Total estimated values of mitigating such negative externalities can be combined with standard metrics of well-being to discern the economy-wide benefits of NEB. An ongoing challenge under standard national accounting is precisely understanding how to bring together typical proxies for well-being, such as income and GDP per capita, with other nonmarket elements that are equally relevant for welfare analysis.

6. Concluding Remarks

The NEB 2020 report (WRI Brasil 2020) summarized the positive outcomes associated with NEB scenarios. Under NetZero scenario GDP per capita is more than 15 percent higher than in the reference scenario. Economic performance in low-carbon scenarios with green investments is improved through higher total factor productivity. The economic modeling carried out to evaluate the benefits was initiated before the COVID-19 pandemic, and the modeling results still stand when including the impact of the pandemic. These new economic pathways offer Brazil a stronger and better economic recovery trajectory and employment boost compared to a BAU recovery. The impact of COVID-19 within modeled scenarios is smoothed by the model's use of data values averaged over five-year intervals. Furthermore, although COVID-19 did cause a slowdown in Brazil's economy, the effect was short term, and the economy promptly started to recover. The negative impacts of the pandemic are expected to fully abate by 2030, with greater recovery predicted by 2050. The projected recovery numbers observed in the modeling scenarios so far have been supported by actual data. **The analysis presented herein showed that sustainable, low-carbon practices can lead to significant GDP growth, with a total accumulated gain of R$2.8 trillion by 2030 compared to BAU and reference year of 2005.** Adopting these measures could lead to a net increase of more than 2 million jobs in the Brazilian economy in 2030 when compared to BAU, yielding benefits from the very first year. These measures would also reduce GHG emissions, exceeding Brazil's current ambitious commitment under the Paris Agreement to reduce GHG emissions by 37 percent by 2025 versus 2005 level.

The higher ambition NetZero scenario runs have even higher climate and sustainability ambition and provide even more considerable co-benefits. Such co-benefits extend to different areas and include a lower use of primary energy, more renewables in the electricity generation matrix (with no significant impacts in electricity prices), reduced deforestation while meeting food and energy demands, higher rates of land restoration, the leveraging of green investment to foster resilience, expanding market access among households and producers and improving equality, and enhanced agricultural productivity. Additional socioeconomic co-benefits have also been noted. They occur through several transmission channels (see “Channels of enhanced well-being associated with NEB policies”) and determine enhanced outcomes relative to the reference case.

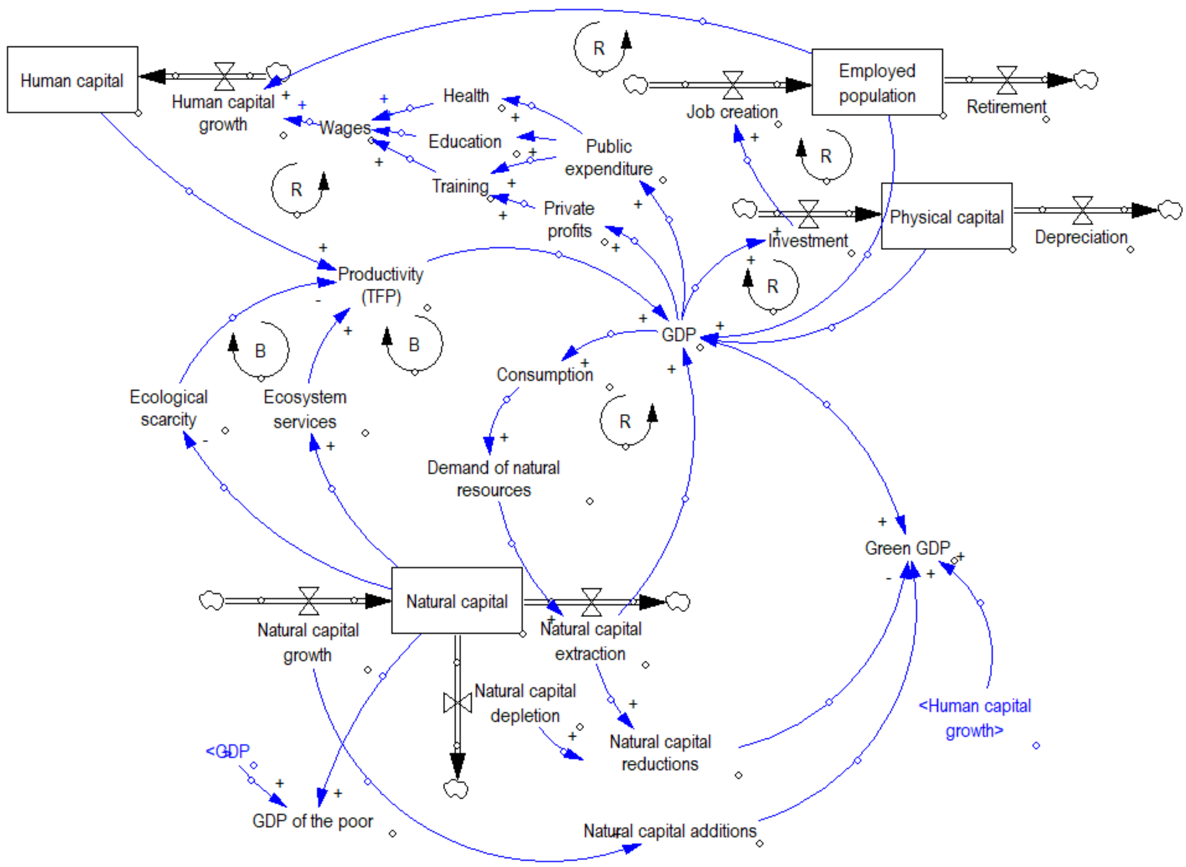
By highlighting the linkages among climate, environmental, and socioeconomic dimensions, NEB’s technical work allows us to understand the potential of low-carbon policies to attain inclusive development outcomes in Brazil. From an analytical standpoint, NEB provides a thorough examination of relevant domains (global, national, sectoral) and their interactions. Additional opportunities for new research under NEB include regional analyses (with particular focus on the Amazonia), distributional impact analyses based on micro-level data, and closer examinations of biodiversity and valuations of ecosystem services.

Appendix A: Generalized (high-level) GEM Brazil structure

Figure A-1 presents the generalized underlying structure of GEM, the model used as a starting point for creating the GEM Brazil model. This diagram shows how the key capitals are interconnected, and contribute to shaping future trends across social, economic and environmental indicators. Specifically, feedback loops can be identified that are reinforcing (R) in all areas, pertaining to economic growth and social development. These are enabled by the availability of natural capital, which, if not properly managed, can constrain economic growth (hence the balancing loops -(B)- identified in the diagram). Policies can be implemented to promote sustainable consumption and production, decoupling economic growth from resource use (also through education and behavioral change), to mitigate the exploitation of natural capital and generate a stronger and more resilient green growth.

Figure A1

Casual Loop Diagram (CLD) representing the main variables and feedback loops of GEM applications



Source: Forrester, 2002; Bassi, 2015.

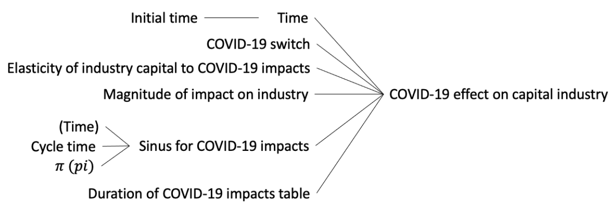
Appendix B: Summary of COVID-19 impacts

Different impacts of the COVID-19 pandemic are identified below. Effects are manifested across all economic sectors. The figures and equations below use the industry sector as an example. GEM Brazil does not model drivers of infections (and associated deaths), nor does it produce endogenous patterns and factors that could result from changes in epidemiological factors, social behavior, and policy responses. Instead, a calibration exercise is conducted—based on data from the IMF's World Economic Outlook as well as other sources—that captures emerging short-term economic dynamics associated with the pandemic. The modelers used the most recent IMF estimate of the impact of COVID-19 as well as the forecasts published in the World Economic Outlook. Instead of inputting COVID impacts as a fully exogenous variable, they have calibrated the impact via the four channels described, calibrating the model to match the observed and forecasted impacts on different variables, not only on GDP.

The elasticities capture endogenous industry sector structures for COVID-19 response, including potential different resolutions to the pandemic that could be incorporated in subsequent NEB stages. Initially, the primary economic concern of COVID-19 was its effect on labor: deaths and sick leaves due to the disease. Over the course of the pandemic, one was able to observe how different sectors had different adaptive capacity to the pandemic shock due to endogenous factors, and some sectors saw a surplus of labor while others experienced shortages.

Figure B1

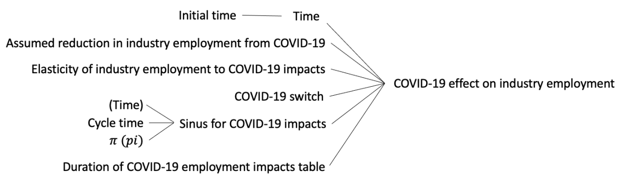
Effect on capital stock



COVID-19 effect on capital industry = IF THEN ELSE (COVID-19 switch = 1, IF THEN ELSE (Duration of COVID-19 impacts table (Time) > 0, (1 + ((Sinus for COVID-19 impacts + Magnitude of impact industry) * Duration of COVID-19 impacts table (Time))) ^ Elasticity of industry capital to COVID-19 impacts, 1),1)

Figure B2

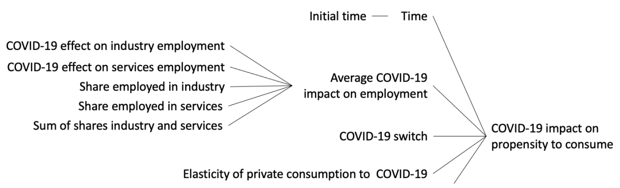
Effect on industry employment



COVID-19 effect on industry employment = IF THEN ELSE (COVID-19 switch = 1, 1 - (1 + Sinus for COVID-19 impacts) ^ Elasticity of industry employment to COVID-19 impacts * Duration of COVID-19 employment impacts table (Time) * Assumed reduction in industry employment from COVID-19, 1)

Figure B3

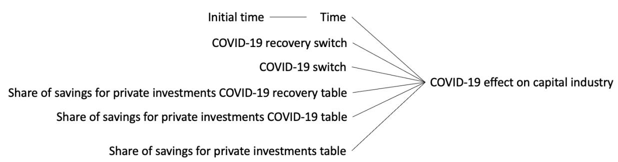
Effect on total consumption



COVID-19 impact on propensity to consume = IF THEN ELSE (COVID-19 switch = 1: AND: Duration of COVID-19 impacts table (Time) > 0, Average COVID-19 impact on employment ^ Elasticity of private consumption to COVID-19, 1)

Figure B4

Effect on savings



Share of savings for private investment = IF THEN ELSE (COVID-19 switch = 1: AND: COVID-19 recovery switch = 1, Share of savings for private investments COVID-19 recovery table (Time), IF THEN ELSE (COVID-19 switch = 1, Share of savings for private investments COVID-19 table (Time), Share of savings for private investments table (Time)))

Appendix C: Summary tables with policy interventions included in the NEB scenarios

Table C1

Scenario inputs for policies/interventions/technology adoption

	2020 (%)	2025 (%)	2030 (%)	2035 (%)	2040 (%)	2045 (%)	2050 (%)
Transportation (share of new sales)							
Hybrid flex-fuel vehicles	0	17	33	50	50	50	50
Electric buses	0	17	33	50	50	50	50
Fuel cell:							
- Light trucks	0	7	13	20	20	20	20
- Medium trucks	0	3	7	10	10	10	10
- Heavy trucks	0	7	13	20	20	20	20
Biojet (share of total kerosene)	0	5	20	50	50	50	50
Buildings (energy demand reduction)							
Energy efficiency	0	3	7	10	10	10	10
Power sector (share of total electricity)							
Concentrated solar power + photovoltaic reservoir	0	2	4	6	6	6	6
New materials (share of expansion)							
Charcoal (iron and steel sector)	0	17	33	50	50	50	50
Agriculture							
High productivity (share)	0	10	20	30	30	30	30
Pasture	extra cost for low productivity technologies						

Notes: CSP = concentrated solar power; PV = photovoltaic.

Table C2

Direct outcomes for selected interventions

	2020	2025	2030	2035	2040	2045	2050
Incremental energy consumption							
Hybrid flex-fuel vehicles and electric buses							
Electricity for passenger transport (PJ)	0	0	23.1	63.7	81.3	43.4	26.5
Biojet (PJ)	0	329.7	555.7	599.7	648.9	769.4	827.8
Buildings (change in energy demand)	Decreased by the percentage shown in the table above						
Change in electricity generation (TWh)							
Concentrated solar power	0	10.57	22.02	22.19	23.99	25.82	27.3
Photovoltaic reservoir	4.47	10.56	22.02	23.49	31.75	42.87	52.37
Additional energy use in industry (PJ)							
Charcoal	0	44.4	66	89.4	126.1	163.7	202.3
Land-use change (thousand hectares)							
Cropland	0.33	-1.36	-2.23	-2.52	-3.4	-3.21	-2.61
Degraded pasture	-9.79	-34.8	-60.58	-84.49	-98.53	-102.19	- 104.07
Recovered pasture	7.75	32.34	56.73	80.8	95.23	98.7	99.95

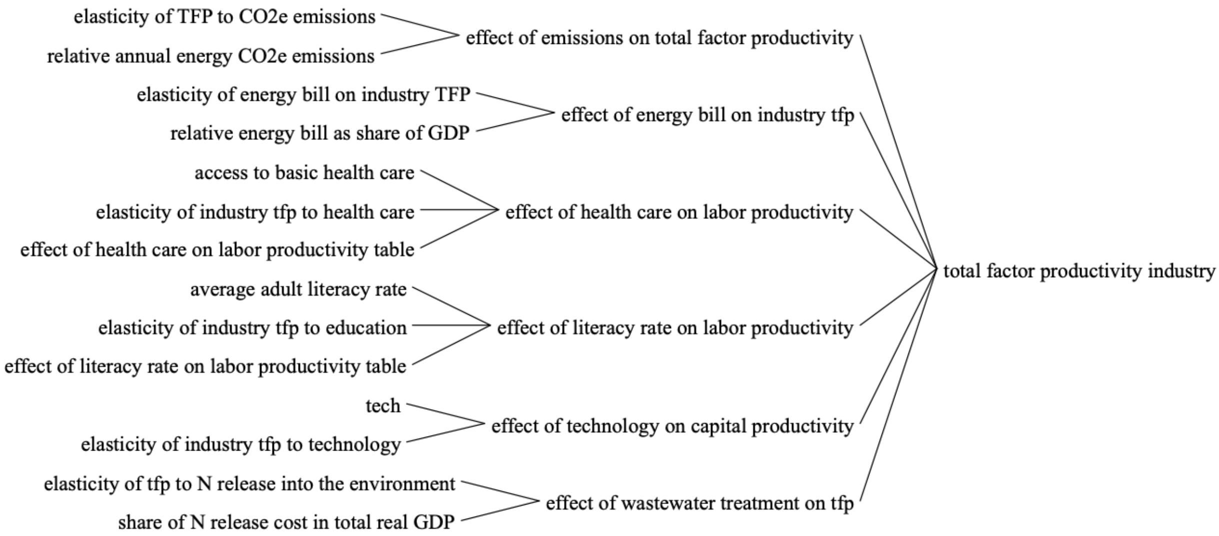
Notes: CSP = concentrated solar power; PV = photovoltaic; PJ = petajoule; TWh = terawatt-hour. Direct outcomes include megawatts of power generation capacity by source and hectares of land affected; selected interventions include power generation and/or land-based emissions reduction.

Appendix D: Channels of transmission for low-carbon policies to GDP through productivity

Figure D-1 and Table D-1 further explain the set of productivity drivers under GEM Brazil, concerning the industry sector, with similar structures being introduced for the services and primary sectors.

Figure D1

Productivity drivers



Notes: CO_2e = carbon dioxide equivalent; GDP = gross domestic product; N = nitrogen; TFP = total factor productivity.

Table D1

Equations used to calculate the effect of drivers of total factor productivity

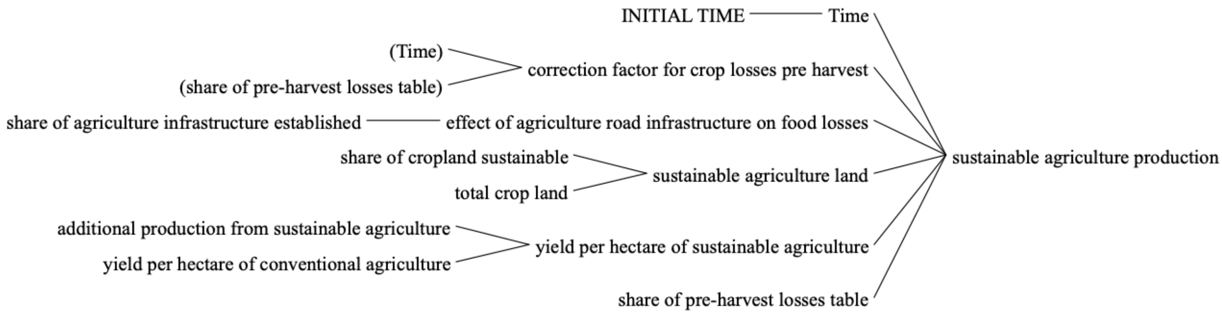
EFFECT NAME	EFFECT EQUATION
Effect of technology	Tech ^ ELASTICITY OF INDUSTRY TFP TO TECHNOLOGY
Effect of emissions	DELAY3I(relative annual energy CO_2e emissions ^ ELASTICITY OF TFP TO CO_2E EMISSIONS, 1, 1)
Effect of health care	EFFECT OF HEALTH CARE ON LABOR PRODUCTIVITY TABLE (access to basic health care) ^ ELASTICITY OF INDUSTRY TFP TO HEALTH CARE
Effect of literacy rate	EFFECT OF LITERACY RATE ON LABOR PRODUCTIVITY TABLE (average adult literacy rate) ^ ELASTICITY OF INDUSTRY TFP TO EDUCATION
Effect of energy bill	DELAY3I(relative energy bill as a share of GDP ^ ELASTICITY OF ENERGY BILL ON INDUSTRY TFP, 1, 1)
Effect of wastewater treatment	DELAY1I((1 - share of n release cost in total real GDP) ^ ELASTICITY OF TFP TO N RELEASE INTO THE ENVIRONMENT, 1, 0.95)

Appendix E: Agriculture production and agriculture GDP

The value of agriculture GDP is computed from agriculture production and value added per tonne of production and adjusted for production lost during transport to market. Agriculture production, in turn, is the sum of that from sustainable and conventional methods. Value added per tonne of production is a function, among other things, of the availability of infrastructure services. NEB policies allow for improvement on several dimensions, including yields per unit of land, reduction of preharvest losses, postharvest losses, including road infrastructure improvements, and other transport sector policies.

Figure E1

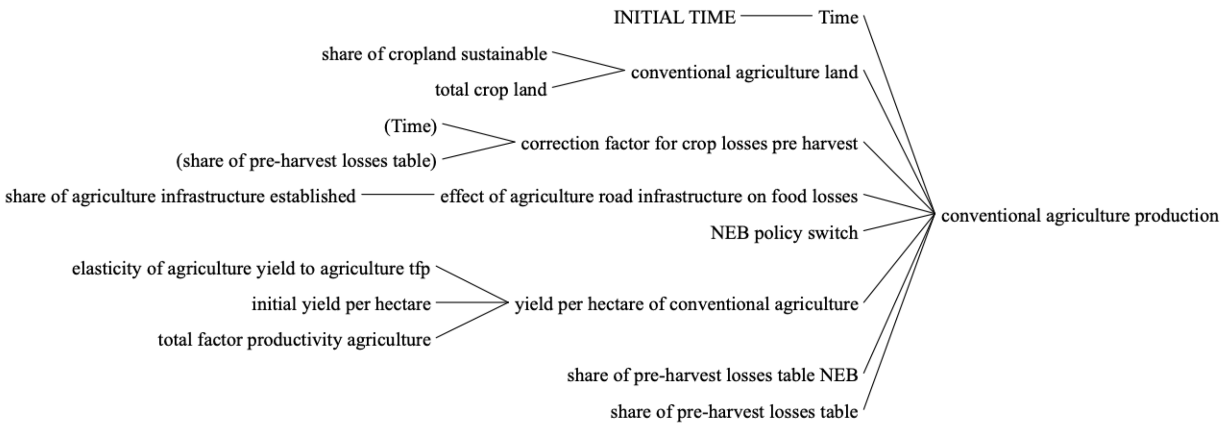
Sustainable agriculture production



*Sustainable agriculture production = Sustainable agriculture land * Yield per hectare of sustainable agriculture * (1 - ("Share of preharvest losses table" (Time) / Effect of agriculture road infrastructure on food losses - correction factor for preharvest crop losses))*

Figure E2

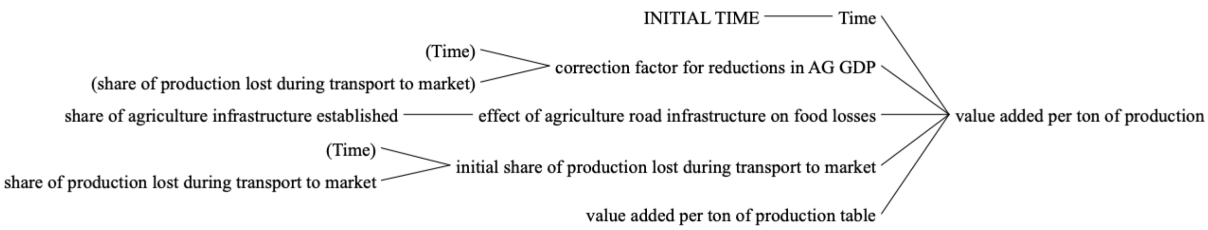
Conventional agriculture production



*Conventional agriculture production = traditional land of agriculture * yield per hectare of conventional agriculture * (1 (IF THEN ELSE (NEB policy switch =1, "Share of preharvest losess table NEB" (Time)/Effect of agriculture road infrastructure on food losses, "Share of preharvest losses table" (Time)/Effect of agriculture road infrastructure on food losses) - Correction factor for crop losses preharvest)).*
Notes: NEB =- New Economy for Brazil; TFP = total factor productivity; AG = agriculture.

Figure E3

Value added per ton of production



*Value added per tonne of production = Value added per tonne of production table (Time) * Effect of agriculture road infrastructure on food losses * (1 + Initial share of production lost during transport to market + Correction factor for reductions in AG GDP)*
Notes: AG = agriculture; GDP = gross domestic product.

Abbreviations

BAU	business as usual
BECCS	bioenergy with carbon capture and storage
BLUES	Brazilian Land Use and Energy Systems
BTL	biomass to liquid
CCS	carbon capture and storage
CGE	computable general equilibrium
CLD	causal loop diagram
COFFEE	Computable Framework for Energy and the Environment
COPPE	Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CSP	concentrated solar power
GDP	gross domestic product
GEM Brazil	Green Economy Model
GHG	greenhouse gas
HDI	Human Development Index
IAM	integrated assessment model
IMP	illustrative mitigation pathway
IPCC	Intergovernmental Panel on Climate Change
IPPU	industrial processes and product use
NCE	New Climate Economy
NDC	nationally determined contribution
NEB	New Economy for Brazil
N_2O	nitrous oxide
$PM_{2.5}$	particulate matter
PV	photovoltaic
RCP	Representative Concentration Pathway
SCC	social cost of carbon
SD	system dynamics
SO_2	sulfur dioxide
SRES	Special Report on Climate Scenarios
SSP	Shared Socioeconomic Pathway
TEA	Total Economy Assessment
TFP	total factor productivity
UFRJ	Federal University of Rio de Janeiro
UNFCCC	United Nations Framework Convention on Climate Change

Endnotes

1. To learn more about WRI Brasil, visit https://www.wribrasil.org.br/; for more information about NCE, see https://newclimateeconomy.net/.
2. According to the UNFCCC (n.d.), the Atmospheric Stabilization Framework (ASF) Model is an "integrated assessment model, which provides a framework for developing scenarios of future emissions based on consistent demographic, economic, and technological assumptions. Its strength is in its links between the use of biofuels, land use, technological development and GHG policy. It is therefore an appropriate tool for evaluating the land-use impacts of response measures."
3. Regional distributional aspects are also of primary interest for NEB but are being tackled in a new phase for the initiative, under the so-called New Economy for the Amazonia (NEA).
4. See Figure SPM.5: Illustrative Mitigation Emissions Pathways (IMPs) and net zero CO_2 and GHG emissions strategies in IPCC (2022).
5. CenergiaLab was established in 2002 as one of the research branches of the Energy Planning Program of COPPE/UFRJ. See Cenergia's publications and peer-reviewed research: https://www.cenergialab.coppe.ufrj.br/publications-1.
6. The BLUES model is a perfect-foresight, least-cost optimization model for Brazil. It chooses the energy system configuration with the least total system cost over the entire time horizon of the study, in this case 2010–50. The model minimizes the costs of the entire energy system, including electricity generation, agriculture, industry, transport, and the buildings sectors. BLUES finds optimized mixes for the energy system as a whole rather than evaluating sectorial optimal solutions. It includes CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions associated with land use, agriculture, and livestock; fugitive emissions; fuel combustion; industrial processes; and waste treatment. Link to the model: https://www.iamconsortium.org/resources/model-resources/brazilian-land-use-and-energy-system-blues/.
7. Soft-linking is a method designed to jointly/iteratively use the top-down CGE models for a country's economy and bottom-up energy system optimization models. This method allows two models to operate together, in an iterative process, until they converge on the values of price and quantity parameters in both models. Hard-linking integrates two models. Solutions are found through simultaneous optimization, not iteration (Krook-Riekkola et al. 2017).
8. It is noteworthy that the demands of the energy sector in the COFFEE and BLUES models are demands for energy services, in which the models are free to choose the portfolio of final sources of energy that can meet these demands through different energy end use technologies (different types of vehicles, thermoelectric power plants, industrial boilers, residential water heaters, etc.). In the case of the land use modules, the demands are for agricultural products, considering the domestic and foreign markets provided by the TEA model.
9. There are two ways of building future projections. One focuses on measuring/predicting the anticipated output from a given input (factor). Another approach is exploratory; it seeks to understand how a certain scenario will reflect on the performance and dynamics of the system as well as the nature and magnitude of changes in the interconnected system elements. The models described herein are in the latter family of analytical tools.
10. In a reinforcing loop, a change in one direction is compounded by more change. Policies or shocks that move a variable in one direction transmit through the system in a way that leads to further movement in the same direction in such a variable over time. For example, money in a savings account generates interest, which increases the balance in the savings account and earns more interest. Balancing loops, in contrast, counter change in one direction with change in the opposite direction.
11. The use of stocks and flows, along with feedback structures, nonlinearities, and potential delays are at the heart of SD modeling. By capturing these core features that characterize systems (e.g., land, energy, economic) SD modeling can reproduce behavior. Indeed, SD is based on the fundamental idea that the structure of a system determines its behavior over time.
12. GEM Brazil includes a total of 993 variables and data inputs, including 91 endogenously determined stocks/levels and 638 endogenously determined auxiliary variables (including flows). Whereas many of those endogenous variables are of primary interest to policymakers (e.g., the level and growth rate of per capita GDP; the level and ratio of employment; and the GHG emissions, total and by source), others are informative for policy (e.g., the amount of primary forest, the level and distribution of energy demand, and the social cost of carbon).
13. GEM Brazil, being a large model in terms of number of variables included for several dimensions (climate, the environment, and the social economy) and the coverage of sectors and technologies, includes a large number of feedback loops (over 11,000). Many are major loops directly included in models as part of the conceptualization and customization process, in what is called the causal loop diagram (CLD) building exercise. Many others emerge naturally from the process of transforming CLDs into consistent mathematical representations.
14. At this stage of NEB, GEM Brazil does not incorporate direct effects of biodiversity changes in GDP via TFP because the estimation of the latter is made at a high level and based on land cover changes only, which does not provide sufficient certainty about the change in the value of the biodiversity variable. More detailed work on biodiversity is expected under a new NEB phase, at which time the linkages to TFP and GDP will be made. NEA, also known as the New Economy for the Brazilian Amazon Project, also investigates related issues.
15. A GEM-related SD model produced for Indonesia—referred to as Indonesia Vision 2045, which is part of the country's Low Carbon Development Initiative led by the Ministry of National Planning—does include such specific structural representation for the COVID-19 epidemic (Medrilzam et al. 2021), based on the so-called susceptible-infected-recovered model (Fiddaman 2020). Under a new phase of NEB, GEM Brazil could incorporate a structural representation of COVID-19 considering the likelihood that the pandemic may not have a short-term resolution and that important tail effects could eventually persist.

16. The SCC is an estimate, in dollars, of the economic damages that would result from emitting one additional tonne of GHGs into the atmosphere. Specifically, it refers to the marginal cost of the impacts caused by emitting one extra tonne of GHG (CO2 equivalent) at any point in time, inclusive of "nonmarket" impacts on the environment and human health.
17. Note that this refers to exogenous assumption of SCC. The cost of externalities is global—not specific to Brazil—but is accepted and approved for use in SCC estimations.
18. Externalities could be viewed as a portion of the cost in the production, which is not incurred by the producer nor by the consumer but is born by the society, the state, and the "other people." Somebody must "foot the bill." Since externalities are not included in the estimation of cost, they lead to market distortions. If the producer bore the full cost, including the externalities, some of the activities/products would be economically unfeasible or the market price would be higher.
19. Moreover, macroeconomic scenario analyses fail to consider the effects of climate and natural capital depletion and degradation on baselines. Thus, differential impacts between the baseline and low-carbon, green scenarios over key socioeconomic indicators are even larger than normally thought.

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About the Authors

Leonardo Garrido, Ph.D.: NCE Lead Economist at the time of advancing this research, currently independent climate economics consultant.
Contact: oikonomo@gmail.com

Andrea M. Bassi, Ph.D.: expert in System Dynamics and green economy strategies and scenarios, KnowlEdge Srl.
Contact: andrea.bassi@ke-srl.com

Georg Pallaske: specialist in System Dynamics and sustainability assessments, KnowlEdge Srl.
Contact: georg.pallaske@ke-srl.com

Iryna Payosova, Ph.D.: is an Economist with WRI New Climate Economy.
Contact: iryna.payosova@wri.org

Arya Harsono: is a Research Analyst with WRI New Climate Economy.
Contact: arya.harsono@wri.org

About WRI Brasil

WRI Brasil is a research institute that transforms great ideas into actions to promote environmental protection, economic opportunity and human well-being. It works in the development of studies and implementation of sustainable solutions in climate, forests and cities. It combines technical excellence with political articulation and works in partnership with governments, companies, academia and civil society.

WRI Brasil is part of the World Resources Institute (WRI), a global research institution operating in more than 60 countries. WRI relies on the expertise of approximately 1,700 professionals in offices in Brazil, China, the United States, Europe, Mexico, India, Indonesia and Africa.

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About the New Climate Economy

The New Climate Economy (NCE), a flagship project of the Global Commission on the Economy and Climate, brings together government, business and economic leaders to enhance global and national understanding of how climate action can drive economic, social and development objectives.

THE NEW CLIMATE ECONOMY

WRI Brasil

Rua Cláudio Soares, 72 Cj. 1510
05422-030 | São Paulo (SP)
Tel.: +55 11 3032-1120

Av. Independência, 1299 Cj. 401
90035-077 | Porto Alegre (RS)
Tel.: +55 51 3312-6324

wribrasil.org.br

New Climate Economy

c/o World Resources Institute
10 G St NE
Suite 800
Washington, DC 20002, USA
+1 (202) 729-7600

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