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Informing National Climate Action with the Green Economy Model: A Technical Description of the Structures and Processes

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CONTENTS

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ABSTRACT

National climate ambitions have been hampered by a lack of understanding of the impacts of the transition to a low-carbon economy as well as the consequences of inaction. Amid legitimate concerns regarding transitional impacts, financing needs, and the institutional and political constraints to low-carbon policy implementation, knowledge and analytical skill gaps prevent countries from increasing necessary ambition on climate and environmental targets consistent with global goals. In this Technical Note, we present the green economy model (GEM), which aims to simultaneously improve people's understanding of complex climate, environmental, and socioeconomic linkages; equip decision-makers with adequate tools for policy development; and help close coordination gaps and build technical capacity for low-carbon policymaking. It is a practical guide for local policymakers, experts, and academics to understand the model structures and considerations for employing GEM for green economic policy analysis.

INTRODUCTION

In 2015, global leaders convened in Paris to pledge their commitment to curbing greenhouse gas (GHG) emissions, thereby hoping to abate the impacts of rising global temperatures and changing climates. Since this remarkable agreement, ambitions on addressing the climate crisis have included bolstering adaptation against more intense seasonal changes, transitions toward cleaner and more efficient energy use, and, more recently, plans for whole economies to become carbon neutral within the next several decades. Naturally, there has been wide demand for analytical tools to evaluate the environmental, social, and economic implications of taking such action to ensure more effective climate policy.

The green economy model (GEM) intends to fill the information gap left behind by many of the available economic models and methods used for country development planning. These tools have been found to focus too narrowly on select sectors to effectively capture the drivers of development, and they often ignore the many cobenefits of ambitious climate action (Bassi 2015; NCE 2018). GEM is an integrated and recursive system dynamics (SD) model that generates scenarios for climate-related, environmental, and socioeconomic variables at the macro level. The adoption of GEM has been pioneered by KnowlEdge SRL and embraced by World Resources Institute (WRI) through its New Climate Economy (NCE) initiative[1] to help equip policymakers with empirical evidence on the relationships between actions that can strengthen economic performance and those that reduce the damaging factors of climate change. Through NCE, GEM has been mainstreamed in several *strategic target* countries, which primarily consist of emerging market economies. They include large GHG emitters, such as China, India, and Indonesia, but also countries that are either critical carbon sinks (e.g., Brazil), biodiverse rich (e.g., Colombia), regional leaders with potential to influence or become role models to other countries (e.g., South Africa, Ethiopia), or offer opportunities to explore relevant climate dimensions, such as adaptation, climate resilience, and loss and damage (e.g., Vietnam, Kenya).[2]

At the country level, NCE offered implementing support aimed at raising and accelerating climate ambition by demonstrating the net costs and benefits of instituting low-carbon, green economy policies against those that emerge from inaction. The results from GEM analyses have directly fed into core national development programs and policy processes, including nationally determined contribution (NDC) updates, long-term decarbonization strategies, medium- and long-term green development plans, just transition analyses, and sectoral analyses (e.g., energy, forests, water, cities, biodiversity) (Pallaske et al. 2023). The aim of GEM is to provide national policymakers with empirical evidence of policy outcomes to better inform their climate and green economy strategies. However, all models—GEM included—are only simplifications of the sectors and economies they represent; therefore, they cannot and do not predict outcomes with absolute certainty. Rather, they are a representation of the perceived relationships between different components within systems, and the extent to which certain changes, such as the introduction of low-carbon interventions, permeate within those systems.

GEM is designed to inform policy formulation and evaluation in the context of climate mitigation and adaptation, which includes modeling for both green and circular economies.[3] It is applied and customized through a participatory approach in which subject matter experts define the main model elements and their interactions and stakeholders can contribute to relevant assumptions and inputs to ensure scenarios better reflect their understanding of reality. The intended audience of the GEM methodology and results are typically academic and institutional experts, who drive key development policies, as well as those who can influence the policy more directly, such as ministerial officials. GEM allows policymakers and relevant stakeholders to:

- comprehend and operationalize complex interrelationships between biophysical, social, and economic systems that are at the heart of the climate-development nexus;
- bring together relevant stakeholders and facilitate consensus between them to overcome typical coordination problems that hamper the advancement of climate and green ambition;
- develop customized tools that capture the local context and can be used to identify robust policies that have a potential to deliver on national and global development goals and support the identification and quantification of climate action benefits and the costs of inaction; and
- build capacity for institutional coordination in formulating and evaluating systemic development plans.

This note offers a technical characterization of GEM, including descriptions of typical model structures, data needs and sources, and other aspects associated with the construction of GEM for a particular country and policy. GEM is not an "off-the-shelf" model; instead, it is built almost from scratch and customized as part of a *cocreation* process with relevant stakeholders and subject matter experts, following *participatory modeling principles*.[4] The initial GEM descriptions in this note focus on elements common across all model renditions. These include the core, science-based, biophysical, and socioeconomic structures that affect climate-economic interactions and dynamics as well as other observed country model commonalities and relevant model features (e.g., on policies, assumptions, choice of target variables) that have emerged as empirical regularities from consultations with stakeholders across countries. Country-specific examples are interwoven to demonstrate the process of customization, though GEM applications in countries are more thoroughly detailed in their respective Technical Notes.

This document is organized as follows:

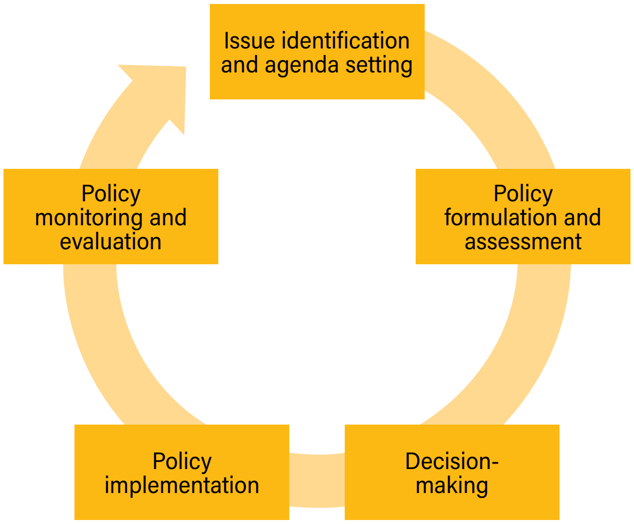
- The "Adopting GEM to drive climate ambition" section illustrates the GEM Framework (GEMF)—the process that guides the construction of each respective GEM—including the elements of multistakeholder engagement and policy support to drive climate and green economy ambition. Engagement with local partners helps identify where GEM can support the implementation of more ambitious climate policies by leveraging other methods and models and enabling the exploration of dynamics that point to the many advantages emerging from increasing policy ambition. This section also explains how model outputs have been used to inform policy.
- "The underlying modeling approach" section presents the theoretical and empirical framework behind GEM. This includes a general model explanation based on knowledge of biophysical and socioeconomic structures (and their linkages) and an understanding of key entry points for introducing GEM scenarios into development planning. This section also discusses many topics regarding the conceptual framework for building GEM and the key structures and substructures found across GEM renditions, including climate, environment, and socioeconomic domains as well as the interlinkages that determine the behavior of the model (i.e., the future trends it generates). We also define GEM's place in the modeling landscape, outlining how it differs from other macroeconomic tools used in climate-relevant policymaking and development planning.
- "Building GEM" explains the software and data needs for model construction and summarizes the model structures, calibration and robustness checks, principles for creating reference cases and scenarios, model result interpretation, and model boundaries and connections to other tools for a comprehensive climate economic analysis. (Technical details about GEM's specific modules are outlined in Appendix A.) Each country GEM is accompanied by its own technical documentation[5] that provides more comprehensive explanations on the methodology, model structures, data, assumptions, and policies.
- The final section summarizes the strengths and acknowledges the limitations of the GEM approach. We look at ways to improve GEM and what is in the pipeline that can enhance its capacity to assess the green economy.

ADOPTING GEM TO DRIVE CLIMATE AMBITION

GEM is the key tool in the larger GEMF, which is, first and foremost, driven by the needs of the country or region, as elaborated by its stakeholders. The GEMF integrates quantitative methodologies into three stages of the policymaking cycle (bolded below), as described by the United Nations Environment Programme's *Using Models for Green Economy Policymaking* report (2014) (Figure 1). In particular, the GEMF helps policymakers with these steps:

- **Identifying the focus issues** by assessing historical trends. This also **defines the development agenda** at the national and subnational levels and also allows local stakeholders to explore the complex interrelations across indicators at a sectoral or macro level.
- **Formulating the policy options** for attaining their goals by comparing a portfolio of provisions or a policy package across specific metrics; evaluating the potential impact of the policy across sectors and its effectiveness in solving identified problems or exploiting opportunities of selected interventions; and by identifying the entry points for interventions and setting targets. This informs the decision-making stage and accounts for the impacts of policy implementation, especially on socioeconomic and environmental indicators.
- **Monitoring and evaluating** the impact of the implemented interventions by assessing the actual outcomes against those projected by the model. Additionally, the models themselves are also evaluated and improved with each assessment.

Figure 1 | **Visualization of the policymaking process and where modeling can play a significant role**



Source: Authors, based on UNEP (2014).

In deploying the GEMF, NCE would seek both global and local opportunities to contribute to and champion core policy processes for enhanced and accelerated climate ambition at the national (and occasionally regional) level. Every application of GEM includes an appraisal of country needs, stakeholder mapping, targeted engagement, and the identification of policy processes that can lead to scaled-up climate action. At the country level, NCE's implementing support aimed to raise and accelerate climate ambition by demonstrating the net costs and benefits of instituting low-carbon development policies against those that emerge from inaction.

This approach intends to help countries address the gaps[6] between actual national climate commitments and commitments compatible with GHG emission paths (IPCC 2018)[7] to stay under the 1.5°C temperature increase limit and facilitate the scale-up of climate change mitigation ambition (IPCC 2022). The proposed approach also considers the need to prioritize climate action alternatives because of the limited resources available. During consultation, policymakers and stakeholders clarify their goals, and the model allows them to consider alternatives and priorities based on the simulated effects of those goals. Policy action has a better chance of taking hold when stakeholders understand and appreciate the differential impacts of development paths and have the authority and technical capacity to design, formulate, and implement effective policies (Kelly et al. 2013; Rodrik 2004).

The capacity and power to advance climate policymaking at the country level are generally distributed across different institutions. For instance, the responsibility for defining or revising NDCs and low-emission development strategies may befall an institution (e.g., a ministry of environment) that is separate from the one leading the design of associated green economy investment plans (e.g., a ministry of planning or development) or from the one in charge of the resource allocation and budgetary processes (e.g., a ministry of finance). As a result, interinstitutional policy coordination challenges tend to be significant. A critical component of the GEMF is therefore advancing implementation support while fostering coordination among relevant entities with the participation of global and local champions.[8]

NCE has previously engaged with key institutions and individuals to identify entry points for overcoming these coordination challenges to close knowledge gaps and enable practical inputs into relevant policy processes. As the National Climate Action, these relationships have been maintained in close coordination with local partners. Sustaining the connections and building the capacity of our technical and government partners facilitates monitoring and evaluation of implemented policies that were initially run through GEM exercises. Processing the actual impacts of the policy or action in question restarts the process to determine what was and was not working with the initial intervention or, in some cases, how to keep the low-carbon development on track amid significant economic shocks. For example, NCE developed GEM-Indonesia with the Indonesian Ministry of National Planning and Development (BAPPENAS), which became the basis for the low-carbon priorities in its 2019 Medium-Term National Development Plan 2020–2024 (Garrido et al. 2019). GEM-Indonesia was updated in 2021 to factor in the impacts to the country of the economic slowdown induced by the COVID-19 pandemic, including the budgetary shifts toward recovery, which informed the Indonesian government's net zero emissions ambitions (Medrilzam et al. 2021). GEM's flexibility in shifting parameters helps policymakers understand what to prioritize to achieve climate targets.

A science-based, policy-informed approach

Meeting urgent climate goals requires vast, transformational changes in individuals, societal behavior, and economic structures (IPCC 2022). It becomes increasingly important for policy to be driven by the best scientific knowledge and an understanding of the system implications of climate-related factors for advancing (or abstaining from) specific interventions. Countries that explore ambitious decarbonization paths soon realize that achieving targets compatible with net zero emissions is not automatic and requires immediate effort to go above and beyond their current policies (e.g., power generation from renewable energy [RE], forest protection and restoration efforts, energy efficiency, sustainable agriculture, domestic and industrial waste, etc.).

The magnitude of change becomes overwhelming for policymakers, especially in the presence of technical, institutional, and financing gaps. GEM embraces a science-based approach that can rationalize and quantify impacts and trade-offs as well as compare the benefits of action to the costs of inaction. GEM includes many indicators commonly omitted by traditional economic assessments—such as those related to well-being, ecosystem valuation, and so forth—often due to lack of reliable information and gaps in research.

However, GEM is *not* a tool for optimization. Instead, the model is attuned to the policymaker mindset. Therefore, it focuses on a set of outcomes altogether (e.g., income *and* poverty *and* employment *and* fiscal balances, etc.) rather than one particular decision variable (e.g., minimizing energy mix costs or maximizing employment). Each element of the set is imputed (explicitly or implicitly) as a given weight or ranking based on policymakers' beliefs and preferences at a given time. Policymakers also face constraints (temporal, sectoral, spatial) that are not adequately incorporated under an optimization framework.

The outcomes of GEM are the "what if" scenarios that reflect the trajectory of current policies and low-carbon development pathways as well as their cross-economy impacts. There are several ways that government partners may utilize such information, but the most salient use has been to demonstrate that low-carbon and net zero economies are not only possible with existing provisions but also do not have to come at significant costs to economic growth or human capital. In cases where the scenarios built differ by the timing of implementation—such as the early, medium, and late action scenarios of GEM-Indonesia (BAPPENAS 2019)—cost-benefit analyses (CBAs) between scenarios demonstrate to policymakers the additional costs of delayed action to make the case for earlier implementation.[9]

Given a fixed amount of government expenditure, a more practical use of GEM may be to map how different sets of investment allocations to the various sectors spread across the economy and their impacts on macroeconomic indicators as well as emissions reductions. However, because GEM is not designed to optimize, such an approach may not show the "best" way forward. Rather, GEM would highlight which sectors to focus on for investment and policy design to achieve a given national target.

Need for a toolbox, not a stand-alone model

In advancing climate policy support to countries, *no single model* offers the empirical inputs required to address all policy questions and all policymaker and other stakeholder concerns. Policy questions at varying scales—whether macro-, meso- (sectoral), or microscale—require different tools. Some tools can add sufficient detail about the factors that determine the analyzed system's dynamics and the effects of policies and shocks; others can abstract elements that are not relevant to the problem at hand.

One of the primary activities of the GEMF is to identify, in consultation with stakeholders, the main policy questions and to determine what *set of analytical tools and methods* (or "toolbox") is needed and best equipped to answer these questions. As such, the GEMF *typically* involves the construction of a GEM, but it does not necessarily need to do so. Under an NCE country support program, the GEMF, as a term, captures GEM as a single model regardless of whether it is coupled with other models and tools[10] to provide adequate climate policy support. Each country-specific GEM has its own accompanying toolbox and documentation. This note focuses exclusively on the GEM itself rather than the additional modules under the GEMF, though those modules will be referenced and their connections to GEM highlighted.

Though GEM is useful as a stand-alone model, it is more effective as a knowledge-integration tool (i.e., integrating variables, equations, data, and results from other integrated economic models) because it is limited by what research questions it can address. This is possible because SD, the underlying methodology used to create and customize GEM, allows explicit representations of the biophysical processes that affect natural capital and other processes that contribute to GHG emissions—such as forestry and other land uses, water resources, energy supply and demand, food and waste generation and disposal, fisheries and coastal resources, and industrial processes—and also interact with economic activity in determining environmental sustainability and individual well-being. Economic activity, in this context, is one of the drivers of change for natural capital. For instance, biodiversity and habitat quality (and the resulting ecosystem services) depend on intact landscapes. The conversion of land for productive purposes (e.g., agriculture, industrial areas, plantations, etc.) reduces the integrity of landscapes, which affects the integrity of natural capital and resulting ecosystem service provisioning. These induced changes in turn may affect economic activity, for instance, if the provisioning of key ecosystem services (e.g., freshwater provisioning, pollination, nutrient cycling) are undermined. Essentially, whereas GEM can measure nature (and other indicators) in physical terms, many macroeconomic models can express variables only in monetary units, such as the economic value of trees logged rather than the hectares of deforestation or volume of trees. Such processes are modeled using peer-reviewed scientific inputs, including those in the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC 2006a). These features are further explained in the following section.

THE UNDERLYING MODELING APPROACH

This section briefly introduces the systems thinking principles and the SD methodology under which the model is developed, and it explains why a systems lens is particularly useful for a green economy assessment. It discusses the use of causal loop diagrams (CLDs), stocks and flows, the nonlinearities and disequilibrium features that are characteristic of the framework and model and their relevance in climate-development policy analysis. This is followed by a discussion of the theoretical economic elements at the heart of GEM as well as the transmission mechanisms for climate and green policy on socioeconomic outcomes, with the objective of justifying claims and supporting dynamic hypotheses regarding differential positive impacts of low-carbon, green economy interventions under GEM.

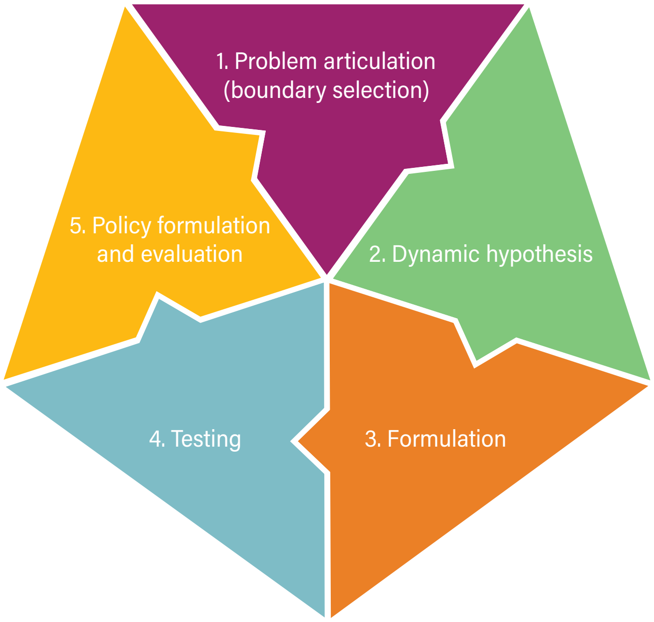
Next, a characterization of GEM is presented (elements that are common across all country or regional model renditions), including comparisons with alternative integrated approaches. This section ends by distinguishing GEM from other integrated modeling approaches that are relevant to climate policy analysis.

Systems thinking

GEM follows systems thinking principles and uses associated SD modeling techniques. Systems thinking is a holistic approach to analysis that focuses on the way that system-constituent parts interrelate over time and within the context of larger systems to which they belong (Probst and Bassi 2014; Sterman 2000). It is a way of making sense of the complexity of the world by looking at it in terms of wholes and relationships. Systems thinking is generally applied to address the "counterintuitive behavior of social systems, whereby unanticipated side effects result from people's attempt to drive a system in one direction or to stabilize it, leading it, instead, into another direction or to further destabilizing" (Forrester 1971).[11] Such dynamics result in policy resistance, which is the tendency for interventions to be delayed, diluted, or defeated by the response of the system to the intervention itself (Meadows 1982). Policy resistance emerges because of an insufficient understanding of the dynamics of the system; thus, the envisaged effects of policies aimed to improve the system do not sufficiently materialize due to the system's self-correcting properties. For example, an increase in roads to combat traffic congestion can improve traffic flow, but as traffic frees up, more people are incentivized to drive, and thus the rate of traffic reaches the previous level of congestion.

In the context of climate policy, a systems thinking perspective allows for a holistic consideration of climate, environmental, and socioeconomic domains; their linkages; and an explicit representation of policies (e.g., on land, energy, waste, agriculture), including their channels of transmission, feedback effects, nonlinearities, and delays. Systems thinking explores how social and economic activities affect and are affected by shocks in climate-related and environmental indicators. As such, the framework allows for estimating the impacts and net benefits of climate action as well as the costs of delayed or avoided action. Systems thinking stresses the need for iterating across all steps of the modeling process, from problem articulation, formulation of a (dynamic) hypothesis, model formulation, model testing, policy design, and evaluation (Figure 2). What is learned from the process of modeling may alter our basic understanding of the problem or opportunity and how it relates to the system.

Figure 2 | **Systems thinking is embedded in the modeling process**



Notes: The modeling process is iterative, whereby there are iterations between different stages of the model development. Results of any step can yield insights that lead to revisions in any earlier step (indicated by the links in the center of the diagram). Additional iteration is required when new information becomes available or if the model is not working as intended (e.g., if the value of variables exceeds realistic boundaries; see "Reality checks" in the "Building GEM" section).

Source: Sterman 2000.

System dynamics

SD is grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics, and engineering. Thus, it is applicable to physical systems (e.g., land, water, biodiversity) and technical domains (e.g., power generation, the process of value addition, capital accumulation) as well as human behavior (Sterman 2000). A core insight from SD is that the structure of a system determines its behavior. In turn, system structures can be comprehensively built based on knowledge of their stock-flow characteristics, component feedback effects, identified nonlinearities, and delays. The idea of modeling based on the construction of explicit "long-hand" structures contrasts with reduced form models, including a number of those built using statistical methods (although the latter certainly can be applied in the former). SD modeling is based on the notion that the most fundamental models of behavior (exponential growth, goal seeking, and oscillations) are generated out of simple feedback structures (positive feedback loops, negative feedback loops, and negative feedback loops with delays, respectively) that can be represented using SD tools. More complex patterns of behavior arise from the nonlinear interaction of those fundamental structures with one another, leading to S-shaped growth (with possible overshoot, or overshoot followed by collapse), stasis (equilibrium), randomness, or chaos (Sterman 2000).

Elements that are relevant to the system (what belongs to it and what should remain safely ignored) are pinpointed based on the nature of the policy questions being asked and the associated responses. This follows the fundamental principle that one should aim to model problems and not just model a system for the sake of it. For instance, policy questions on exchange rate and monetary policy are not priorities of climate policy, though they are certainly informative of and are informed by climate policy. Therefore, they are not connected to the policy analysis that must be carried out, so they *initially* can be left outside of or minimized within GEM substructures. In SD, the limits for what is included or excluded in the model structure are called *model boundaries*. Deeper dives into specific policy questions can warrant reintroduction of initially excluded elements; for example, exchange rates and monetary policy would be relevant and reintegrated if the implications of a carbon market are being assessed.

Moreover, a number of integrated approaches used in climate policy assessment tend to lack important structural components to adequately represent the processes and feedback effects between relevant climate and environmental variables (see "Comparisons with other modeling approaches" below). Different tools should be used for different purposes (e.g., macrofinancial monitoring, climate policy, trade and competitiveness analysis, poverty, distributional assessment, etc.), and best practices indicate the need for policymakers to reconcile all inputs and insights emerging from their toolbox (i.e., a need to make sure all assumptions used in each tool in the toolbox are aligned and consistent) (UNEP 2014).

Causal loop diagrams

To identify the problems to be modeled, the SD method relies on stakeholder engagement exercises to create CLDs. CLDs are useful for representing the feedback structure of the system, identifying the potential policy interventions, and deciding what elements are central to the analysis and what elements can be ignored (i.e., defining model boundaries) (Probst and Bassi 2014). CLDs are also suitable for quickly capturing hypotheses regarding causes of dynamics (associated to the problem at hand), eliciting and capturing the mental models of individuals or teams, and communicating the important feedback loops believed to be responsible for a problem (Sterman 2000).

In applying GEM for national support, one of the first steps in implementing project support and creation of a customized GEM is engaging relevant stakeholders to cocreate CLDs. Which stakeholders are involved depends on the policy question (e.g., which ministry oversees crafting the policy document) and on all important (expected) outcomes of action or inaction. The goal is to involve all parties that can affect the system as well as those that are impacted by the system. For example, if the policy process is at the planning level, the stakeholders are normally representatives of ministries, academia, and civil society.

A CLD consists of variables identified as relevant for the analysis; these variables are connected by arrows denoting the causal influences among them, along with the resulting important feedback loops. Arrows (links) denote direction of effect; positive links mean that if the cause increases (decreases), the effect also increases (decreases) above what it would otherwise have been. A negative link means that if the cause increases (decreases), the effect decreases (increases) above what it would otherwise have been. The "all else equal" notion applies in these circumstances. CLDs provide an excellent opportunity to bring together experts from different disciplines for a unanimous representation of climate impacts and to discuss potential alternative policy interventions (Probst and Bassi 2014). A comprehensive discussion on CLD notation, guidelines, and principles for engagement is presented in Sterman (2000). The co-development of the CLD with experts constitutes a knowledge-integration exercise during which the structural components relevant to the local context are validated. This process is the foundation for customizing the assessment framework to the context in which it shall be applied. Although important major feedback loops may be similar, independent of the context, the strength of the drivers underlying these key dynamics is likely different; this is something that can only be understood and captured by means of both empirical analysis *and* expert involvement.[12]

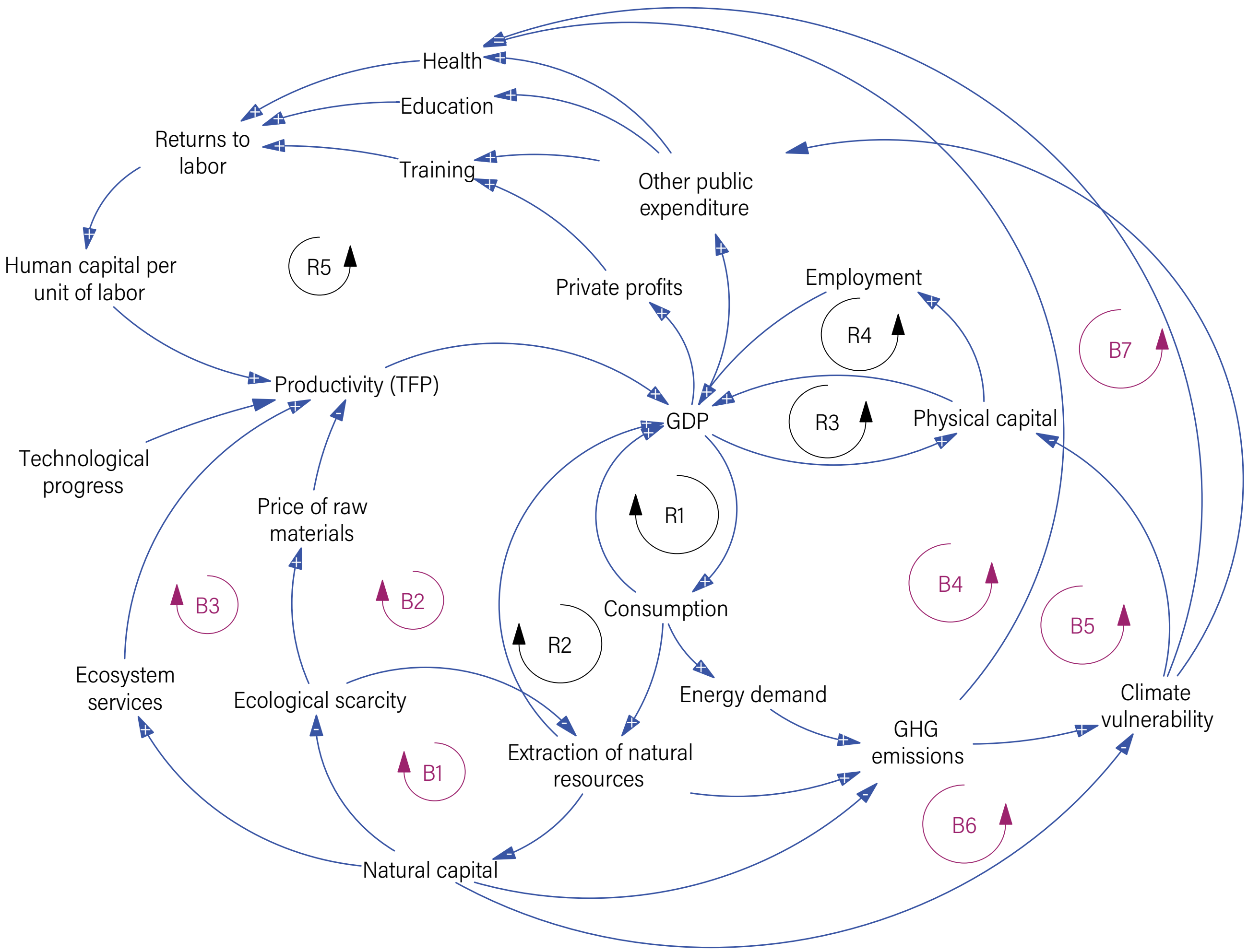
Figure 3 shows a simple CLD that includes variables representing *some* of the core modules included in GEM along with some of the model's main feedback loops.[13] Variables included in the figure are generally interpreted as *module proxies*—that is, they are *indicative* of existing, fleshed out structures in GEM (e.g., "employment" for a demographics and labor module; "gross domestic product (GDP)" for an income and value-added module, including sectors of economic activity; "GHG" for a module of GHG emissions from energy, land, waste, and industry; etc.).

Figure 3 incorporates socioeconomic feedback loops typically represented in mainstream integrated assessment models (IAMs; including those depicting the role of factors of production in value-added generation) but also other components, including on the relationships between climate impacts, natural capital, and associated environmental goods and services. Despite the country-specific nature of GEM, several feedback loops are common across countries and play an important role in model dynamics, including the following:

- *Reinforcing loops*, where value addition and income increase over time as a result of productivity gains (from, among other things, technological progress) and the accumulation of human, physical, and, in the case of GEM, natural capital. In Figure 3, these are represented by the loops R1–R5. A reinforcing loop occurs when a given shock or policy that affects a variable in one direction transmits through the system in a way that leads to further changes in the variable in the same initial direction. In Figure 3, all else equal, a shock that increases value-added GDP leads to increased total consumption, which positively reinforces GDP growth (a multiplier effect, reinforcing feedback R1). In general, and in absence of constraints, increases in aggregate demand along with productivity gains trigger multiplicative effects that allow those factors of production, GDP, and income to grow over time. In mainstream integrated models, such as computable general equilibrium (CGE) models, constraints to the expansion of economic activity emerge from sources such as the availability of savings, labor market restrictions, and other market-related elements. The loop is representative of continued exponential growth that occurs in the absence of market frictions and with no constraints on the supply of factors of production (e.g., labor, physical capital, human capital, natural capital). In real-world systems, there are typically balancing processes (see below) that will cause friction or constraints over time, hence limiting the period over which exponential growth can occur (i.e., limits to growth).

- *Carrying capacity loops* are balancing loops B1–B3, which show that increases in output and income associated with, say, increases in aggregate demand, are bound by the availability of natural capital and the associated environmental goods and services, which support the former. For an initially given and limited amount of natural capital, the depletion and degradation of such resources—which are increasingly demanded to support the GDP growth—reduce the rate of economic growth (and may lead to lowered outcomes) *relative to a counterfactual* where such depletion and degradation do not take place.
- *GHG emissions and climate vulnerability loops* are additional balancing loops B4–B7, which capture the damage to physical and human capital, and, consequently, to economic activity, from climate-related hazards and local emissions. These impacts and damages vary from country to country, and the parameterization of the relationships is usually based on existing studies or the best available information. In the case of large countries (e.g., China, India), GHG emissions have larger impacts on global GHG concentrations and changes in temperature, increasing the strength of these balancing loops. GHG emissions arise from different sources, including from energy demand, consumption (and waste), and the demand for natural resources, which also negatively affects carbon sinks.

Figure 3 | **A typical CLD representing the underlying structure of GEM**



Notes: GDP = gross domestic product; GHG = greenhouse gas; TFP = total factor productivity.

Source: Authors, based on Bassi (2015).

In Figure 3, the feedback loops R1 and R2 capture the impacts of investment, capital accumulation, and employment generation on GDP. An increase in GDP will cause an increase in government revenues and expenditure, along with disposable income and savings. This in turn increases overall investments, affecting capital and GDP, thereby completing a feedback loop linking GDP and investments. Capital accumulates over time and contributes to economic growth. At the same time, it generates additional employment, which further increases the beneficial impact of capital accumulation on productivity and growth. This dynamic is reinforced by the beneficial impacts of economic growth on household income and consumption (R3). An increase in GDP causes total disposable income to grow, increasing both consumption and tax revenues and generating additional (full-time-equivalent) jobs in the economy. Those jobs contribute to economic growth. The impact of increased taxation on disposable income is captured by the balancing loop B1. As taxation increases, disposable income declines, causing consumption and related employment generation to decline as well. Increased taxation thus has a negative impact on employment generation and economic growth. On the other hand, as indicated above, higher taxation results in a higher public budget, which, through different channels, can also create jobs and stimulate the economy (R4). More specifically, the R4 loop captures multiple reinforcing loops that support beneficial impacts of government spending on productivity and stimulate economic growth and development. These beneficial impacts include the following:

- Increased investments in education and health care as a result of increased government revenues
- Improvements in access to public services due to higher disposable incomes
- Expansion of infrastructure (power generation, roads, etc.) following an increase in investment in public services
- Increased technology adoption by supporting research and development and reducing technology costs

The balancing loop B2 captures the impact of energy demand on total factor productivity (TFP) through GHG emissions and health, thereby reducing overall productivity and negatively affecting GDP. The impacts of emissions on TFP are illustrated by the balancing loop B3. Higher economic growth increases energy demand and emissions related to energy consumption. In addition to the GHG emissions, energy use causes air pollution through particle and other emissions, with adverse impacts on human health. As the concentration of pollutants increases, people are prone to contract respiratory diseases, which reduces productivity and increases health care expenditures.

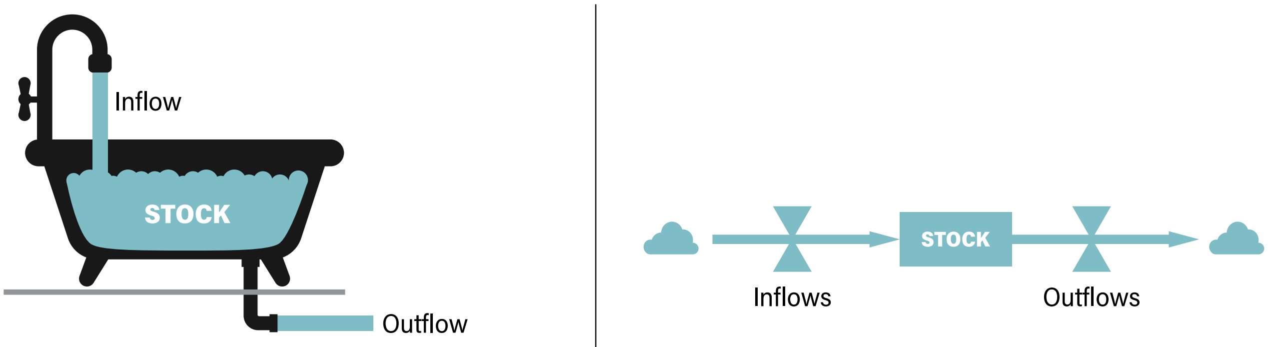
Stocks and flows

Identifying and representing stocks and flows constitutes an essential element for understanding the dynamics of systems and modeling their behavior. Figure 4 presents various illustrations of stock-flow relationships. Stocks are affected by flows (e.g., the annual flow of deforestation affects [reduces] the stock of forest; the annual flow of tree planting affects [increases] the stock of forest). Stocks, therefore, represent accumulations that characterize the state of the system and generate information upon which decisions and actions are based and take time to realize (Sterman 2000). As a result, stocks introduce delays in a system (e.g., 20 years for a tree to grow to its full size; 4 years for a power plant to become operational). The presence of delays, introduced by stock and flow accumulations, often results in system disequilibrium (e.g., when our expectations of immediate action are countered by delays in natural and physical processes).

Stocks are easily identified because they can be measured *at a point in time*. Examples include the value of physical capital, the size of the labor force, the level of technology, and the concentration of GHG in the atmosphere. Flows are rates of change that increase (inflow) or decrease (outflow) the size of the stock. Flows are also easily identified because they can be expressed only as values over a time period, as rates of change in the stock. Examples include investments, changes in the size of the labor force, changes in the level of technology, and GHG emissions.

Specialized SD software, such as Vensim, distinguish stock and flow variables from the rest using boxes and arrows to depict them, respectively (Figure 4, top right). A mathematical representation in continuous time has the stock of variable X at time t (X_t) being computed as the integral of inflows and outflows between an initial period 0 and period t, given the initial value of the stock X_0 (Figure 4, bottom left). A semicontinuous representation has X_t being obtained as the sum of differences of inflows and outflows plus the initial value of the stock X_0 (Figure 4, bottom right).

Figure 4 | **Visual and mathematical representations of stock-flow relationships**



$$X_t = \int_0^t (inflow_s - outflow_s)ds + X_0$$

$$X_t = \sum_0^t (inflows - outflows) + X_0$$

Notes: The bathtub example (top left) is a simple but powerful analogy for the dynamic behavior of a variable that results from changes over time in its related inflows and outflows. The level of water in a bathtub remains unchanged when there are no inputs (faucet is switched off) and no outputs (drains are closed, so there is equilibrium). Said level is also unchanged when the faucet and drains are open, and the value of inflows (incoming water) equals that of outflows (draining water) so there is stasis—a stable state. When water inflows exceed outflows, the bathtub level increases. The bathtub analogy helps explain, for instance, why a reduction in greenhouse gas (GHG) emissions insufficiently reduces total GHG concentrations in the atmosphere and their associated impact on global temperatures. Only when GHG emissions (inflows, from faucet) fall below carbon removals (outflows, from drain) the GHG concentration (stock, water level) would drop and lead (eventually, with delays) to a stabilization of global temperatures.

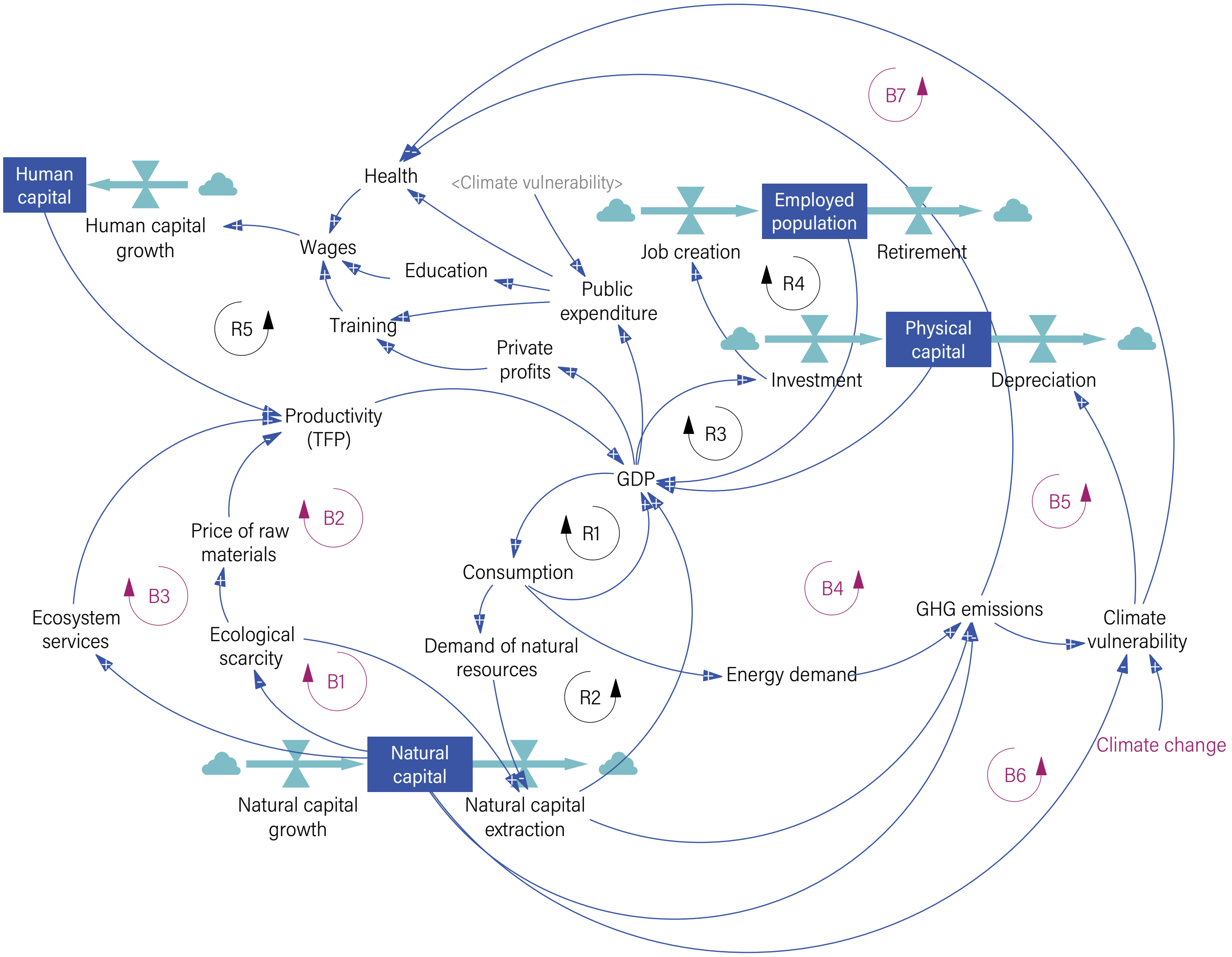
Source: Authors' sketch based on Sterman (2000).

Stocks and flows are particularly important in climate economic modeling and play a prominent role in GEM. Arguably, an inadequate understanding of the stock-flow relationships that determine climate dynamics constitutes an important obstacle in identifying GHG emission paths that are 1.5°C-compatible at the country level. Beyond continually debating what constitutes "fair share" contributions to 1.5°C targets, policymakers and stakeholders often ignore that a definition of a GHG emission (flow) reduction target in a particular time period should be accompanied (or, at least, primed) by information regarding the emission path itself; this would enable policymakers and stakeholders to determine how the resulting global GHG accumulation compares to the remaining global carbon budget (stock). Aside from GHG emissions and concentration, GEM includes many important stock-flow relationships relevant to the green economy, including the following:

- Natural capital (e.g., land, water, biodiversity), which defines boundaries and thresholds and interacts with socioeconomic activity
- Power generation, which keeps track of potential electricity generation and generation capacity, by technology
- Other factors of production (labor, physical and human capital, the level of technology)

Figure 5 is a modified version of Figure 3, with the addition of key stocks typically included in a GEM that affect economic activity, the provision of environmental goods and services, and climate-related outcomes.[14] From the figure, it becomes clearer, for instance, that the continued extraction of natural resources introduces a limit to growth models where the depletion and degradation of natural capital is not compensated by interventions restoring and improving a country's primary resource base. It should be noted that GEM typically forecasts these limits to growth based on a country's potential and that trade of resources is not considered in the assessment of natural resource management, unless specifically requested by decision-makers or experts.

Figure 5 | **Cross-economy CLD**



Notes: GDP = gross domestic product; GHG = greenhouse gas; TFP = total factor productivity.

Source: Authors, based on Bassi (2015).

Patterns of behavior observed in systems in the real world, even complex ones, can result from the interaction of simple stock-flow relationships, nonlinear relationships, and delays (Meadows 2008). The interaction of reinforcing and balancing feedback loops can give rise to exponential growth or decline, goal-seeking patterns,[15] and equilibrium. For instance, a simulation model that analyzes economic growth between 1950 and 2050 could exhibit exponential growth in the early years of the simulation, with reinforcing loops dominating the system. However, in the future, balancing feedback loops will gain strength and start dominating the system due to air and water pollution that reduce labor productivity—climate impacts that challenge capital productivity (Meadows et al. 1972). Overall, GDP for a developing country may show an S-shaped trend, with fast growth in early years and slower growth in later years due to the interaction of two key feedback loops and accumulations in several stock variables. Linear growth or linear decay are rare forms of system behavior. Changes in trends and feedback dominance are normally what we find in real world systems.

Theoretical foundations and the role of externalities

GEM follows post-Keynesian economics (PKE) principles, echoing stock-flow consistent computational models such as E3ME (Cambridge Econometrics 2022) or the General Monetary and Multisectoral Macrodynamics for the Ecological Shiftmodel (AFD n.d.). PKE principles rely on the idea that effective demand is a key determinant of economic performance, and economic activity in a PKE model is therefore driven primarily by expenditure decisions. In contrast to neoclassical economics, investment is not inherently constrained by the availability of savings or other elements that generally constrain aggregate demand.[16] Thus, GEM is an approach that focuses on supply-side elements, which is important to consider when interpreting outcomes from GEM, as will be further explained in the next subsection.

Though GEM often takes a supply-side approach to model the economy—which is the most common approach for developing countries where consumption is constrained—it does include variables that compute demand. The supply-side approach refers to the way in which the drivers of the economy are prioritized via capital, labor, and various factors affecting productivity. For other sectors and infrastructure (e.g., energy, water, food demand, roads), the model is demand driven, with the main drivers being population and GDP, in general terms. The main difference is the focus on what drives growth as well as what the key target of the policy and investment in question is. As a result, when it comes to economic analysis, GEM is best applied to analyze any strategy, policy, or specific impact (e.g., climate impacts) that targets production directly and then goes on to affect consumption. In this respect, GEM has been customized to both developed and developing countries for assessments that primarily aim at impacting production from the supply side (e.g., in the context of climate impacts and investments in climate resilience) and for intervention options (e.g., on energy demand, with energy efficiency, fossil fuel subsidy removal) that go on to affect economic activity directly and indirectly.

In terms of the calibration and validation of macroeconomic concepts, such as investment and consumption or GDP, GEM relies on a simplified System of National Accounts (SNA).[17] Combining such economic principles for modeling with stock-flow representations for natural capital enables a deep focus on key questions to further understand the impacts of climate scenarios and how low-carbon policies and interventions might improve socioeconomic outcomes, leaving aside other demand-side elements.[18] Under PKE, economic activity cannot be reduced to the outcome of some optimizing behavior, and economies are not systems of equilibria between real variables, which is attuned to the SD approach of the GEM.

Thus, under GEM, the behavior of relevant socioeconomic variables emerges from social interactions, biophysical characterizations, and standard (macro) definitions and identities, generating endogenous values for a set of variables beyond the typical metrics of well-being and economic performance to which policymakers pay attention (e.g., GDP, income, employment, poverty, fiscal outcomes). In this regard, GEM generates paths for groups of variables on forests, biodiversity, the energy sector, food and agriculture, domestic and industrial waste, oceans, their resulting GHG emissions (including methane), and associated externalities. Externalities become increasingly important as the magnitude and trends in depletion and degradation of natural capital impose limits on the expansion of material well-being, and directly affect other nonmonetary dimensions of people's welfare. For instance, GEM can produce endogenous values for variables associated with the damage and loss linked to GHG emissions, such as the social cost of carbon (SCC), air pollution–related health impacts, impacts on the operation and efficiency of energy infrastructure, and the productivity costs resulting from habitat loss and soil degradation. The damage functions that determine these are based on a review of the available literature and are verified at the national level with local experts.

Table 1 summarizes the externalities that are generally computed in GEM and provides costs of externalities from the New Economy for Brazil project for illustrative purposes (though most country-specific GEMs consider a similar set of externalities). The economic valuation (i.e., the unit cost) is normally customized on a country-by-country basis, and the values presented in Table 1 should not be interpreted as "standard values" applicable to each and every country. The specific values listed here serve to demonstrate the extent to which GEM can incorporate externalities and may not be representative of the actual values used in each GEM. Scenario analysis for these externalities produce rich results for policy analyses, especially when combined with spatial analyses.[19] Country-specific reports and technical notes provide more context and depth on the assumptions used.

Table 1 | **Economic valuation of externalities under the New Economy for Brazil**

EXTERNALITY	COMPUTED AS (DEFINITION)	COSTS PER UNIT OF THE EXTERNALITY (2010 PRICES)
Air pollution (excluding from transport)	Sum of costs from nitrogen oxides (NO_X), particulate matter ($PM_{2.5}$), and sulfur dioxide (SO_2) emissions	$PM_{2.5}$ = US$120,000/ton SO_2 = US$31,000/ton NO_X = US$4,600/ton
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/ton Cost of managed waste = US$63.1/ton of managed waste
Traffic/transport related	Sum of cost of air pollution, plus the cost of noise, plus the cost of urban effect, plus the cost of accidents	Cost of air pollution = €0.0052/vehicle/km Cost of noise = €0.0019/vehicle/km Cost of accidents = €0.029/vehicle/km Cost of urban effects = €0.0008/vehicle/km
Water opportunity cost	Forgone 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 Value added per acre-foot used for industrial processing = US$228.02/acre-foot Value added per acre-foot used for thermal generation = US$27.26/acre-foot
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

Notes: Averages are calculated using open-source databases for Brazil. Additionally, we did not have all data from the same reference year. Building the time series from the year 2000, we adjust for inflation with the same gross domestic product deflator and represent both nominal and real monetary indicators. ha = hectare; km = kilometer.

Source: Romeiro et al. 2020.

Conditions and disclaimers for GEM

GEM allows for disequilibrium conditions[20] and thus focuses on supply-side factors affecting economic activity, with the latter being mainly driven by expenditure decisions and by the constraints or opportunities posed by climate impacts and natural capital. From this perspective, the estimated value of GDP—a variable that policymakers consistently prioritize—is interpreted under GEM as the *potential realization* for value addition (i.e., generation of GDP) under conditions that include expected climate impacts and the availability of environmental goods and services, in addition to other factors of production that drive economic activity. Demand-side constraints, including labor and human capital, financial market restrictions, and others, are *not* prominently featured in GEM. This follows the point made previously in the "System dynamics" section about GEM's focus on the core elements of the problem and the need to reconcile those gaps with complementary models and tools, with each targeting a specific policy area for a consistent policymaking process.

That said, GEM does include several *balancing* structures in the form of automatic mechanisms that either prevent the model from exceeding given thresholds (such as fiscal deficits, debt ratios, employment rates, or foreign account balances) or assess the role of savings constraints for the attainment of climate development targets.

In applying GEM to national activities, engagement activities and policy discussions focus on identifying policy opportunities, constraints, and the outcomes that matter across groups of stakeholders; the process of reconciling differences and addressing trade-offs is at least as important as the numerical outcomes of the empirical exercise that supports it. In this regard, GEM focuses on generating "what if" scenarios, which yield endogenous outcomes over time for a bundle of variables (from the economic, environmental, and social domains) in response to individual shocks, interventions, or policy packages agreed upon among stakeholders. The participatory modeling process enables stakeholders to develop intuition regarding the cross-sectoral impacts of action and inaction (i.e., direct, indirect, and induced effects of interventions)[21] and cross-sectoral and feedback effects (both reinforcing and balancing), and it opens an opportunity to discuss intertemporal preferences, sources of uncertainty, definitions, and linkages all under a "white-box" framework.[22]

Furthermore, GEM is *not* a prediction tool.[23] GEM is designed to improve the learning process for climate and green development policymaking. It can be ascribed into the category of "virtual worlds," a type of model used for simulations in which policymakers can learn, refresh decision-making skills, conduct experiments, and play (Sterman 2000). GEM results should *never* be interpreted as predictions; rather, they are simulated realizations under "what if" conditions that enable a deeper understanding of the associated, connected effects (desired or not) on certain variables from economic shocks or policy shifts. In other words, GEMs do not aim to assert the likelihood of outcomes under policy pathways but instead demonstrate the behavior of economic systems when such policy actions are introduced.

For example, GEM can be used to explore the implications of other studies, such as the emerging literature on the differential and positive benefits of innovation on areas of RE sources as substitutes to high carbon-based technologies for power generation and of a transition to low-carbon systems (Grubb et al. 2021; Way et al. 2022). GEM strives to reflect these benefits but also *reinforcing* impacts via, for instance, improvements in human capital associated with health outcomes that result in higher factor productivity and ultimately in higher economic growth. By the same token, the higher economic growth induced by RE solutions leads to increased energy demand and expenditures. Should the latter lead to increased demand for other high-carbon sources, this would result in higher emissions, negative health impacts, and negative effects in productivity, thus offsetting *some* of the initial economic gains attained by the RE policy (a *balancing* effect). These types of insights can be quickly developed by using GEM in "play mode," a feature of the software that allows the user to see instantaneous changes in model outputs when inputs are modified.[24]

Comparisons with other modeling approaches

Although a full technical comparison of GEM and other modeling approaches would be useful to this discussion, it is out of the scope of this Technical Note due to the number of assumptions needed to be compared and the vast modeling differences considered. Moreover, boundaries between model classifications are relatively fluid, and there is not one standardized system of model categories (Nikas et al. 2019), which makes model comparisons more of an exercise in semantics. The United Nations Environment Programme (2014) provides a more comprehensive comparison of modeling approaches, and Pallaske et al. (2023) present one more specifically related to GEM.

Regardless, much of the literature agrees that integrated modeling is particularly useful for national development planning (UNECA 2016). To some extent, GEM can be classified as an IAM. However, core definitions of IAMs can describe an array of models and analytical frameworks. Whereas some IAMs operate similarly, they may have significant differences in how they work and what questions they answer (Evans and Hausfather 2018). As such, it is important to define GEM in the context of the larger modeling landscape by highlighting its differences from other modeling approaches and how GEM can complement them.

Wilson et al. (2021) distinguishes two broad types of IAMs based on their level of complexity: there are either more "simple" approaches that perform CBAs or the more complex, process-based IAMs, which look more deeply at the sectoral and technological level. Notable examples of CBA-IAMs include the Dynamic Integrated Climate Economy (DICE) model (Nordhaus and Yang 1996) and are typically used to project the SCC. Examples of process-based IAMs include MESSAGE-GLOBIOM (Krey et al. 2016) and the Global Change Assessment Model (Iyer et al. 2015). GEMs are most closely related to CBA-IAMs because both aim to evaluate the cost and benefits via more simplified representations of energy and land-use systems.

One area where GEMs deviate from most other IAMs is on scale: most of the IAMs highlighted in the literature focus on global climate impacts, whereas GEM is specifically attuned to national- and regional-level assessments. GEM is a tool designed for country-level planning and not a tool designed solely to model the implications of climate change. What a country does in terms of emissions may have negligible impacts on the global and local climate. In essence, "traditional" IAMs answer different research questions than what is needed for development planning, and, as such, are rarely customized to the country context. Many IAMs do not include the possibility running specific intervention options across a variety of sectors, though many do focus on a select number and with more detail.

By harnessing SD, GEM incorporates a broader set of linkages and feedback effects among climate, environmental, and socioeconomic dimensions compared to some other types of models generally used for sustainable development analysis (Pallaske et al. forthcoming; UNEP 2014). Optimization frameworks, for instance, may not incorporate the temporal, sectoral, or spatial constraints or opportunities that policymakers face. Despite this, GEMs may have less detailed complexity within a particular sector or subsystem. For example, GEM energy demand and power generation structures may be less detailed than those typically found in energy optimization models such as Low Emissions Analysis Platform (LEAP) (Heaps 2016) and The Integrated MARKAL-EFOM System (TIMES) model (Loulou et al. 2005).

Similarly, GEM typically includes fewer economic sectors than CGE models. Instead of inherently including more than 60 economic sectors in the model, the GEM approach starts with 3 macro sectors (agriculture, industry, and services) and disaggregates based on the research question posed by government and stakeholder priorities. Like GEM, CGE models are large numerical models that combine economic theory with real economic data to computationally derive the impacts of policies or shocks in the economy. But the largest difference is that CGE equations are largely theoretical, often assuming cost-minimizing behavior by producers, average-cost pricing, and household demands based on optimizing behavior. GEM, in contrast, is dynamic. It is based on the systems, and equations change as other aspects of the sector change. In this way, the CGE approach is limited compared to GEM. However, as previously noted, GEM does not optimize; thus, unlike a CGE model, it cannot answer questions concerning the optimal path forward for a given policy.

Moreover, we stress that GEM is not designed to cover every single aspect in climate or green economy analysis, and it would be conceptually wrong to do so. Many other models also do not claim to be able to capture all necessary elements of the economy to accurately portray trends and behavior; hence, modeling results must always be interpreted with the varying assumptions in mind. It must be reiterated that any model used in isolation produces only limited results. Therefore, GEM is most effective as a complementary part of a policymaker's toolbox to understand different problems and issues in climate development that manifest at different levels of aggregation (macro-, meso-, microscales) and across different sectors and cohorts.

BUILDING GEM

This section covers the various technical elements featured commonly across GEMs, including examples of primary inputs used in a country application and their sources. More detail on GEM construction and customization is also presented in Bassi (2015) and Pallaske et al. (2023) as well as in each respective country GEM Technical Note. This section provides succinct descriptions of relevant processes in GEM construction as well as select GEM structures that are common across country model renditions.

Software and model sharing

GEMs are built exclusively using the specialized SD software Vensim, developed by Ventana Systems. Vensim has been the program of choice because the software features make it convenient for empirical work and partner engagement, especially compounded with Ventana Systems' available expert knowledge support, including on climate modeling (Ventana Systems 2022).[25] Vensim resources include a suitable interface for representing GEM structures and policies, a free model reader, a free model learning version, online learning resources, and relevant technical support from Ventana Systems. GEMs are fully owned by the client institutions—typically ministry representatives but also local experts and international institutions—to which NCE-WRI, in partnership with KnowlEdge SRL, provide implementation support. No copyrights are involved, in alignment with Paris Agreement principles for support (Article 4), capacity-building (Article 11), and public access to information (Article 12) for enhanced action (United Nations 2015).

Models and their findings are shared by clients as they see fit, with NCE and KnowlEdge SRL always promoting wide dissemination for climate action. At least one Vensim license must always be acquired by clients because GEM—even its simplest renditions—may be too complex for the free version to adequately manipulate and expand the model. Client model ownership and discretion on what is shared does not preclude NCE from actively seeking to foster a fully transparent and rigorous research process, fully abiding by the scientific method to ensure as impartial and objective model results as possible.

Under Vensim, GEM models are solved recursively based on user-defined integration techniques, such as Euler or other Runge-Kutta methods used in temporal discretization for the approximate solutions of simultaneous nonlinear equations. Optimization features for sections of the model could be included, but so far they have not been required in country work. GEM has, however, been calibrated to and reconciled with alternative modeling exercises based on optimization tools in previous projects.

Model structures

GEMs are large, data-intensive models, organized in modular, interconnected structures that cover systems and subsystems relevant for the analysis of policies and empirical questions posed by stakeholders. All parameters used in GEM are either estimated based on statistical data, obtained from other models or scientific literature. Priority sources are national databases, and then databases from international institutions to fill in data gaps. Several validation techniques are used to ensure that past behavior of the model is calibrated to match statistical data across all model sectors. The model runs differential equations, and it needs to be fully parameterized at the beginning of the simulation, after which the model computes differences for each time step.

Notably, GEM enables its user to go through the chain of parameters in the model—parameter by parameter—to analyze where and why changes emerged. In short, GEM makes it possible for its user to visualize all variables and equations in an intuitive way (i.e., rather than with lines of code). This aids in the validation of the model (and its parameters) by helping stakeholders understand the key drivers and how the structures lead to model behavior.

Table 2 provides a summary of core model structures and substructures commonly included in GEM. For the purposes of this Technical Note, we highlight select structures that are most relevant to informing mitigation and adaptation policies in the next few subsections, with detailed technical specifications for each module available in Appendix A. In particular, we highlight how climate impacts are modeled through the GHG emissions module.

Table 2 | **Core model structures and substructures commonly included in GEM**

MODULE	DESCRIPTION
Demographics and labor force	Population dynamics from fertility, mortality, and migration patterns; associated dynamics of working-age population, labor participation, and labor supply
Climate scenarios	Changes and variability in precipitation and temperature over time associated with Representative Concentration Pathways
Food demand and supply	Amount of food produced and brought to market and food demand from agricultural productivity and changes in population, by age cohort, respectively
Land use and land-use change	Stocks and flows of different types of land use (e.g., forests, agriculture, settlement, and fallow) and their changes in response to economic activity, population changes, and policy interventions
Carbon stocks	Carbon stock and changes in carbon stocks resulting from land conversion dynamics forecast in the land and oceans modules
Capital accumulation and value addition	Real gross domestic product (GDP), total and by sectors of economic activity, along with dynamics in capital formation and capital stocks; different formulations of value added are possible
Employment	Total and sector-level employment
Factor productivity	Dynamics of total factor productivity (TFP) from changes in determinants (including health, education, infrastructure, impacts from externalities) in energy, agriculture, services, and industry sectors
Expenditure GDP components	Nominal GDP, disposable income and private consumption, savings, and investments
Government accounts	Disaggregation of government revenues, expenditures, fiscal balances, and debt dynamics
Health care	Health expenditure and the access to basic health care services and their impacts on factor productivity and GDP
Education	Enrollment capacity, the number of students, and the duration of education as well as the literacy rate and its impact on TFP and GDP

Source: Authors, based on Bassi (2015).

Table 2 | **Core model structures and substructures commonly included in GEM, continued**

MODULE	DESCRIPTION
Energy demand	Energy consumption estimates as a function of economic activity, population changes, and energy efficiency. Includes energy substitution, by source, as a function of price changes and other policy inputs
Power generation	Power generation capacity requirements (estimated based on total electricity demand [from the energy demand module], electricity trade [imports and exports], the load factor of capacity [for each type of generator], and transmission losses), electricity generation, electricity-related employment, and investments, by type of generating technology
Greenhouse gas (GHG) emissions	Countrywide GHG emissions from all sectors (carbon dioxide, methane, etc.)
Wastewater generation and treatment	Population covered by sewage treatment systems and nitrogen loadings generated, plus wastewater treatment facility capacity and the share of wastewater treated
Roads	Size of the total road network, as well as additional construction and ongoing maintenance activities
Air pollution	Total air emissions from power generation (particulate matter, sulfur dioxide, and nitrogen oxides) and the cost of air pollution and related health impacts
Solid waste	Provides information about municipal solid waste generation and different waste streams
Transportation Externalities	Total vehicle stock, total vehicle-kilometers traveled, and various external impacts related to road transport
Biodiversity	Provides information about the total value of land-based biodiversity and changes therein

Source: Authors, based on Bassi (2015).

The degree of detail within each substructure is agreed on with stakeholders based on the type of policy questions being asked, country characteristics, data availability, and the relevance of digging deeper into a given topic or sector. It should be noted that the model structures and substructures are not stand-alone model components; rather, interconnections exist between the different components. For instance, population drives the demand for food, and total real GDP is one of the drivers for total energy demand (such as electricity), which in turn affects GHG emissions and the required power generation capacity. Furthermore, these connections are not linear but oftentimes form feedback loops (e.g., GDP drives energy demand, which affects total country energy expenditure, which affects TFP and hence GDP).

GEM is characterized by exhibiting both *detail* and *dynamic complexity*. Detail complexity arises from the large number of variables involved in a model (e.g., from a disaggregation of the power generation and energy demand), whereas dynamic complexity emerges from the relationships between the components, where cause and effect may not be clear and may vary over time. A detailed description of the country-specific GEM modules—including data sources, equation specifications, and country-specific scenario definition and results—are provided in their respective Technical Notes.

Using GEM to inform climate mitigation and adaptation

As GEM is designed specifically for a green economy assessment, the implications of climate change are necessary components. GEM has been customized extensively in more than 40 countries to inform low-carbon development (Pallaske et al. 2023), with each of these components informed by local data and expert consultation. This subsection presents the extent to which climate impacts and GHG emissions are generally estimated in GEM.

Climate impacts

GEM does not include an inherent climate model substructure (i.e., a representation of GHG concentration and the associated changes in global temperatures, along with other biophysical effects, such as sea level rise) that is necessary for certain IAMs, such as the Climate-Rapid Overview And Decision Support simulator (C-ROADS) (Siegel et al. 2023a) and Energy-Rapid Overview And Decision Support simulator (En-ROADS) (Siegel et al. 2023b), which are explicitly designed to increase people's understanding of aggregate climate impacts at the global level. As GEM is typically a country or regional model, it is near impossible to estimate the exact contribution of the emissions to the changes of the global or even local climate at this scale. In other words, what a country or region emits has a negligible effect on the severity of the climate impacts on the environmental, social, and economic systems in the model because there are infinite transboundary effects to account for.

Similarly, the policies and investments that are simulated for climate mitigation and adaptation in GEM do not affect overall climate trends. Ultimately, GEMs do not generate endogenous estimates of changes in precipitation and temperature and rely on existing, external climate model scenarios for such inputs. Historical climate data are obtained from the Copernicus Climate Data Store (CDS) (2022) or from downscaled climate models available at the country level when available. GEMs use the monthly forecasts of changes in precipitation and temperature and the probability of extreme events over time that are generated by the IPCC's Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) (IPCC 2014) as inputs to determine the extent of future climate impact on different socioeconomic dimensions (e.g., temperature and precipitation variation effects on land productivity, the extent to which increasing rainfall exacerbates road damage and its maintenance, etc.). Specifically, GEM is always set up with at least three climate SSPs (based on Coupled Model Intercomparison Project Phase 6 in the latest version of the model). A switch variable is included in the model, allowing users to either turn off climate impacts, use a more optimistic scenario (i.e., SSP2), use a more intermediate scenario (i.e., SSP3), or use a high climate impact scenario (i.e., SSP5). This flexibility allows GEM users to simulate different combinations of SSPs to approximate international ambition and compare those pathways against domestic ambition (e.g., conditional versus unconditional NDCs or net zero policy goals).

On average, 20–30 specific climate impacts are included in each country application of GEM. Climate impacts in GEM are estimated with impact-specific damage functions (e.g., on selected assets, such as road damage or loss of efficiency in power generation and distribution; land productivity; people's health, such as from extreme heat; etc.). Although modeling results are reported with annual time steps for the estimation period, GEM aligns simulations with the monthly time steps of climate data and forecasts that reflect the seasonal variability in precipitation and temperature. See "Climate assumptions" in Appendix A for more detail about how GEM accounts for seasonal variability in this module.

GHG emissions

Generally, GEM sources emissions data from official national GHG inventories, which are compiled by each country following United Nations Framework Convention on Climate Change guidelines (UNFCCC 2015), to identify the point sources (e.g., burning fuel for energy, industrial processes, domestic waste, livestock and livestock management practices, and deforestation) and removal (by trees and vegetation coverage and by industrial carbon dioxide [CO_2] removal techniques). This process is informed by the internationally agreed upon methodology (and software) for calculating and reporting national GHG emissions of the IPCC's Task Force on National GHG Inventories (TFI).[26] For the specific model structures for GHG emissions, see "CO_2e emissions" in Appendix A.

GHG emissions under GEM are also defined by the Kyoto Protocol, as needed; namely, carbon CO_2, methane, nitrous oxide, F-gases (hydrofluorocarbons and perfluorocarbons), and sulfur hexafluoride (UNFCCC 1997). Using these inventories aligns GEM outputs with a countries' ambition to meet targets associated with the Global Methane Pledge and other similar initiatives. In all cases, GEM provides a structural representation of the biophysical processes and economic scenarios that result in GHG emissions by source and type and over selected time periods.

Estimation of GHG emissions from land use, land-use change, and forestry (LULUCF) activities and the energy sector provides additional insights on the way in which GEM couples biophysical dynamics with economic analysis (Pallaske et al. 2023). The LULUCF module ("Land use" in Appendix A) provides information about aggregate land use and land-use change over time. This module assesses the potential impacts of development policies on land use and potential conversions of land resulting from their implementation, against an assumed baseline that precludes these policies. The module contains several stocks representing all types of land use, such that the sum of land use, by type, at every point in time, equals total (regional or national) land area. They typically include forest, agriculture, settlement, and fallow land. Depending on the country, forestland can be further divided (e.g., primary, secondary, planted forests), and other types of land can be added (e.g., wetlands, grasslands). IPCC LULUCF guidelines are used for definition, classification, and measurement purposes (IPCC 2006b; Watson et al. 2000).

The carbon stock module ("Carbon stock and emissions from land" in Appendix A) provides information about a country's carbon stock and changes therein caused by land conversion. The module is used to assess how policy-induced land-use changes affect the country's carbon stock and land emissions. Carbon stocks are calculated by multiplying each of the country's different land-use stocks by a respective carbon factor. Dynamics in GEM play out according to historical trends and, if available, national forecasts. Relationships with other countries are only considered if known with certainty, or if impacts are very severe—for example, a new dam in Ethiopia affects potential downstream water supply and flooding in neighboring countries (Dagne et al. 2022, 2023). Key exceptions in considering external effects include trade of energy and food resources; land is usually not impacted by these dynamics.

GEM provides a comprehensive representation of the energy sector (including an endogenous simulation of energy demand, by sector and fuel type), the derived power generation capacity needs and installed capacity (by technology), energy efficiency, the associated policies, and resulting emissions. Unlike many optimization energy models, the GEM energy modules incorporate clear feedback loops with socioeconomic activity that enable the simulation of endogenous effects from population growth, energy prices, and subsidies. In turn, paths for energy sector development and the resulting emissions affect GDP via changes in energy spending, air quality, and human capital. However, GEM offers less detail than many optimization energy models, such as on the breakdown of power generation technologies or on energy policy interventions.

Energy sector emissions and the conceptualization of energy structures follow IPCC Energy Guidelines and definitions (IPCC 2006). The energy sector primarily comprises exploration and exploitation of primary energy sources, conversion of primary energy sources into more usable energy forms in refineries and power plants, transmission and distribution of fuels, and use of fuels in stationary and mobile applications. Emissions arise from these activities by combustion and as fugitive emissions (i.e., emissions that escape via leaks and other irregular releases rather than combustion). The process by which emission factors emerge from energy demand, which is disaggregated by type (e.g., electricity, coal, petroleum, biomass) and its sources, is sketched out in Figure A15 in Appendix A. The power generation structure ("Power generation capacity" in Appendix A) includes the estimation of needs—from energy demand by source and technology (14 in total, including coal, petroleum, and different sources of RE such as solar, wind, geothermal, etc.)—for the buildup of power generation capacity.

Fuel demand is further disaggregated by sector (e.g., transportation, residential, commercial). This allows for the introduction of a diverse number of energy policies, including ones on efficiency; pricing; subsidies; electrification of sectors, including electric vehicles (EVs); and public transportation. In GEM, energy efficiency improvements are typically exogenous assumptions and hence serve as inputs to the model. The rebound effect occurs through feedback loops that run through energy cost (TFP GDP energy demand) and carbon emissions. This implies that energy demand in conjunction with costs and the type of fuel used have a greater propensity for a rebound effect, whereby energy efficiency affects the trajectory of total energy demand.

Sources of larger, differential positive socioeconomic impacts under GEM

Of particular interest to government partners are the simulated channels for differential, positive, potential economic growth relative to reference scenarios that have been empirically estimated using GEM in country-level partnerships. Key assumptions are neither driven by fixed assumptions nor by hard coding; instead, they are estimated endogenously by the dynamics of the model, based on the parameterization of the model and policy assumptions. These endogenous dynamics are affected by both exogenous inputs as well as policy interventions, leading to a counterfactual growth trajectory relative to the baseline. The inputs are informed by statistics, local experts, and scientific studies to ensure that structure and parameters are empirically sound and calibrated. The results can be rationalized and explained based on GEM's conceptual framework and associated model structures, whereby indicators in the causal chains that drive change in the model can be examined one by one.

The gap between the counterfactual scenarios and the baseline in GEM is expected to be larger than those typically reported by several other integrated models used to evaluate development pathways. This is due to the inclusion of a wide range of externality costs (e.g., impacts on habitat quality, effects of sea level rise on infrastructure) in the production function underlying GEM. Larger, differential positive socioeconomic outcomes under GEM low-carbon scenarios relative to reference cases are better understood as the aggregation of two groups of feedback effects: larger benefits from low-carbon interventions than those reported by conventional methods of policy analysis at the country level, and larger costs of inaction (as reflected in reference cases) and delayed action relative to what is reported by models that do not incorporate climate and environmental externalities. Moreover, by introducing policy interventions that contribute to mitigating these pressures or assume adaptation, GEM captures the resulting change in productivity, which results in higher gains (see "Climate adaptation impacts and policy effectiveness" in Appendix A). For instance, GEM would capture the impact of lower emissions on air quality as an improvement in worker health and therefore on labor productivity and GDP growth. Few models used for climate mitigation and adaptation policy assessments adequately capture these dynamics; hence, they do not link emission reduction to improved economic productivity and growth.[27]

Yet such positive differential effects *should not* be interpreted as guaranteed, and they *should* be seen only as changes in *potential* outcomes because demand-side elements and constraints are not fully incorporated in the analysis.[28] Positive differential impacts emerge endogenously in GEM and are associated with technological progress, efficiency and waste reduction gains, reduced depletion and degradation of natural capital, and improved resilience to climate-related hazards, all of which reduces uncertainty for investments and builds up physical and human capital.

Positive effects of low-carbon scenarios

The impacts of low-carbon policies are reflected through variables typically found in standard national accounts and channels, including mainstream IAMs, but also via variables that are often omitted in these assessments. For instance, GDP is positively affected by increases in productivity from accumulation of human capital (associated with education and health) and the buildup of public infrastructure. But it is also positively affected by the higher availability and better quality of environmental goods and services that support economic activity. Furthermore, low-carbon technologies and practices yield several benefits not typically reflected in national accounts, such as better air quality and a lower SCC, which, among others, further improve health and labor productivity (Nordhaus 2017).

Low-carbon technologies, introduced by policy goals, are also able to provide a transitional boost in employment and factor productivity because they are more integrated in a country's productive network relative to high-carbon technologies. Each technology is defined using several different parameters (e.g., efficiency, cost, labor intensity) and is based on assumptions taken from the literature, such as the *World Energy Outlook* (*WEO*) reports from the International Energy Agency (IEA). These unit costs are multiplied by the level of ambition simulated—that is, the amount of tech uptake by scenario (e.g., megawatts of power generation from solar).

Depending on the economic structure and ambition of the country, we either model for the adoption of technology exclusively or we also consider domestic manufacturing (e.g., transport electrification, in which a few countries produce EVs but many invest in the manufacturing of charging stations, grid upgrades, etc.). Moreover, emissions reductions from increased energy efficiency and reduction in waste provide an extra boost because higher value addition is generated out of a given value of intermediate inputs.

Higher resilience associated with sustainable methods and climate change adaptation of production and infrastructure helps reduce the frequency and intensity of climate-related impacts, boosting investment and returns. In light of worsening climate impacts observed in many economies, increasing resilience through climate change adaptation measures is paramount for maintaining or increasing the productivity of economic systems. Additional welfare gains are then reported in GEM via value of externalities associated with a better management of resources, efficiencies, and the use of principles of circular economy.

Traditional approaches and neoclassical models incorporate TFP as a proximate source of GDP growth, in excess of that generated by the accumulation of factor inputs included in each output function. Generally, TFP is introduced in models either as an exogenous input (or a *composite factor* that combines an exogenous parameter or trend) or as an endogenous element that responds to changes in other variables, such as the rate of accumulation of human capital or physical infrastructure. GEM broadens the spectrum of factors affecting GDP, including from changes in the availability of environmental goods and services, due (on the negative side) to the depletion or degradation of natural capital or (on the positive side) from the rebuilding or natural accumulation of such type of capital. Aside from the formation of human capital from health and education, and from accumulation of public services infrastructure, a TFP-comparable variable is included in GEM that is affected by (and affects GDP through) changes in the quantity and quality of the natural capital, changes in air and water quality, elements associated with haphazard industrialization and urbanization (waste, traffic congestion), and the SCC.

Eq. 1

$$TFP^{i} = f(TECH_{t}^{i}, HEAL_{t}^{i}, EDUC_{t}^{i}, EMIS_{t}^{i}, ENER_{t}^{i}, WAST_{t}^{i}, INFR_{t}^{i}).$$

Where TFP, $TECH$, $HEAL$, $EDUC$, $EMIS$, $ENER$, $WAST$, and $INFR$ are indexes that proxy for factor productivity, technological progress, health status, education, GHG emissions, energy costs, wastewater, and infrastructure (however, for power generation, roads, irrigation, and so forth, the actual type of infrastructure involved changes from country to country). The i superscript refers to sectors of economic activity (e.g., primary, industry, and services) and the t subscript refers to "time." Such characterization provides the basis for understanding differential impacts between policies over social and economic outcomes.

As the equation above shows, technology is also one of the factors affecting TFP. Technology in the model is presented as a stock, and an annual rate of improvement is assumed, for macroeconomic sectors (e.g., industry and services). Depending on the country analyzed, the rate of improvement normally ranges from 1 percent to 1.5 percent per year, a value in the same range as the assumptions made in other comparable modeling exercises for the economy and the energy sector. Additional technologies are then considered in the model (e.g., for energy demand and supply), but these affect TFP indirectly (e.g., via energy consumption and energy spending or via energy consumption and air pollution) and are therefore not directly considered together with the higher-level technology stock for industry and services.

Higher cost of inaction

In this way, GEM challenges business-as-usual scenarios because business can hardly be conducted as usual when faced with growing, more frequent climate impacts. Specifically, GEM includes modules for climate impacts on economic activity—as countries reach their carrying capacity—that yield a worsened baseline and *no-action* paths relative to models that do not incorporate such effects. Climate impacts and other dynamics (e.g., the relevance of natural capital as an enabler of economic activity) are defined at the country level, resulting in customizations of GEM.

Model validation

Optimization models are characterized by their ability to check for internal consistency based on rules and methods for defining initial conditions ("initialization"), values of model parameters, and relationships across the board.[29] Similarly, even though GEM is not an optimization model, it also includes several features to ensure the consistency and robustness of the model and its results. The following steps are undertaken in GEM to validate structures and ensure an accurate representation of model behavior (calibration).

Unit checks

GEM uses a feature of Vensim whereby every single variable and parameter is coded in a model in a way that allows for specifying the units in which they are measured (e.g., hectares or square kilometers for land area, tons of CO_2 equivalent (CO_2e) for GHG emissions, U.S. dollars for GDP, years of average life of capital stock, etc.). After the data are inputted in GEM, Vensim checks whether the units represented on the left-hand side of every single equation are the same as the ones that result from combining the variables and parameters on the right-hand side. This feature offers an opportunity for modelers to assess the logic and validate equations included in the model.

Historical calibration (within period endogenous estimates)

GEMs are typically built covering historical periods that normally start in 2000 (or, at least, not after 2010) and extend through 2050 (and beyond, if needed). Historical data are used for model calibration, including model parameters (e.g., GHG emission factors) and policy inputs (e.g., restoration efforts measured in hectares or square kilometers per year). Calibration explicitly attempts to link structure to behavior.[30] Values of GEM endogenous variables (e.g., GHG emissions, total GDP, employment) are included to assess model performance, such as how well the model is able to reproduce historical behavior of endogenous variables.

Considering that GEM is not built using an optimization algorithm, and that there are no predefined mathematical rules for defining values of model parameters, model calibration follows a heuristic SD approach, which includes the following three elements:

- *Knowledge of system parameters*, which includes knowledge of model parameters with a physical or economic significance that can be directly measured from the biophysical processes that generate them[31] (e.g., GHG emission factors) or can be drawn from the empirical literature or statistical analyses (e.g., elasticities).
- *Automated calibration*, which relies on statistical techniques, including econometrics.
- *An iterative process*, which assesses the model structure's ability to reproduce behavior (testing of a dynamic hypothesis) and, based on those analyses, advancing model structure adjustments based on available information from the last iteration. This process captures short-term effects (i.e., short-lived shocks and policies or interventions not initially captured in the model). Model calibration requires collaboration between modelers and stakeholders, who can shed light on structural and transitional elements affecting model behavior.

The validation of GEM generally follows best practices in the SD field, and it is critical for the uptake and use of the model to validate the underlying drivers of change and causal pathways, such as feedback loops and their relative strength, and how it evolves over time (Barlas 1996). GEM validation involves structural and behavioral validation tests as summarized by Barlas (1996), which are conducted to ensure the validity of simulation outcomes and to generate trust in the accuracy of the forecasts. One way of assessing the validity of the structure of the model (i.e., its equations, determining the strength of causal relations across variables) is to review the root mean square error of the variable selected (e.g., GDP, population, energy demand) in relation to historical data. More than 300 variables of the model are verified against historical data, and GEM is often initialized in the year 2000, which allows for a 20-year time series for the behavioral validation of the model against historical data.

Reality checks

The GEM modeling process assesses the dynamic behavior for variables, which could include system disequilibrium for extended periods. One can think of land stocks (forests, agriculture, urban settlements, etc.), levels of public debt, or persistent unemployment changing over time. In these circumstances, it is important to keep track of the values of variables to make sure they comply with basic physical and economic principles: that the sum of land uses does not exceed total available land at any point in time, that no explosive debt dynamics are reported, and that employment does not exceed the amount of labor force. *Reality checks*, a feature of SD modeling in Vensim, trigger warnings once a variable exceeds a given threshold beyond expected values. Reality checks may be only informative, but they also could be used as endogenous inputs to inform the behavior of other variables. In SD models where behavior is not bound by some automatic equilibrium condition, reality checks can indicate the need to revise model structures—and to understand (and correct) the causes of such behavior—which are typically errors in the formulation of the model. In cases where the model structure is sound but the behavior still exceeds the bounds, the input parameters related to the concept in question are triangulated again to assess whether the parameter chosen is, in fact, scientifically sound.

Model sensitivity to changes in parameters: SyntheSim

Another feature of Vensim is the ability to perform sensitivity analyses to changes in model parameters under ceteris paribus conditions (i.e., all else equal). The Vensim feature SyntheSim allows for an interactive visual assessment of impacts on endogenous variables associated with changes in each parameter over a user-defined range. Using SyntheSim, running sensitivity analyses on even 1,000 or more simulations is relatively quick, setting up and generating new simulations in a matter of seconds.

Stakeholders who contribute inputs to and assess results from GEM can rely on SyntheSim as one of the tools for understanding model behavior in the face of uncertainty in parameters and for assessing changes in outcomes linked to individual input variations. Essentially, this GEM feature allows users to see the implications of alternative weightings through sensitivity analysis. Policymakers and relevant stakeholders would interact with the model via user interfaces,[32] which offer them the ability to either change the extent of certain inputs, or directly by changing variables and equations.

Criteria for defining scenarios under GEM

A step that is as important as *understanding* results from scenario analysis is that of agreeing on *what is pursued* with the scenario analysis itself and on *how to define* such scenarios. A common pitfall in the modeling process is avoiding sufficient discussion with policymakers on how to strategically design reference cases and policy scenarios so they align with problems and questions they have in mind. For instance, the establishment of an NDC implies that a reference case or benchmark exists for defining climate ambition. These are some of the natural questions that emerge: What, in the mind of a policymaker, is a *suitable* benchmark? What makes climate ambition *ambitious*? What inputs should be common in reference cases and policy scenarios, and what should be different? Should a reference case assume that a country will not show progress in areas of, say, energy efficiency even though such improvement in efficiency has been observed in the recent past and in the absence of a low carbon policy framework? These questions need to be discussed with policymakers and reflected in scenario analyses.

Being unaware of the nuances involved in scenario building, policymakers may be eager to jump into comparing reference cases with policy scenarios even before considering what their desirable attributes are in terms of their ability to properly frame relevant policy questions. Unfortunately, no single remedy exists to easily placate policymakers. As such, every GEM rendition encourages exhaustive exchanges among stakeholders to comprehend the best approach for crafting results that cater to stakeholder needs while maintaining necessary empirical rigor and alignment with global climate targets. The process of defining scenarios under the GEMF helps to reconcile initial stakeholder preconceptions and constraints and to develop targets they want to achieve.

Defining scenarios requires an understanding of what is a *desirable benchmark* case against which policies will be tested. Policymaking opportunities and constraints must also be considered, including the initial sequencing and speed; the intermediate and final policy targets; and the cumulative, over-time implications on other variables (such as costs of interventions) as a guide for policy selection and prioritization.

Considerations for building reference cases

Regarding *reference cases* or *baselines*,[33] GEM fosters a discussion and common understanding of policy parameter values and other assumptions that determine the path for this benchmark case. The following elements are discussed with stakeholders:

- **Structural transformation.** GEM scenarios typically run over long-term horizons, usually through 2050. For developing countries, this implies a need to accommodate potential (endogenous) changes in socioeconomic variables associated with structural transformation, even if low-carbon policies are not undertaken (Chenery and Syrquin 1989). These include paths for energy efficiency, agriculture productivity, labor participation, educational attainment, demographic dynamics, and value addition and employment sectoral shares.
- **Policies to include.** A discussion of reference cases implies that countries, in the absence of low-carbon policymaking, would continue or embrace some set of development policies. Under NCE country support, reference cases are built in agreement with stakeholders, so there is a good understanding regarding the nature of the outcomes of the benchmark itself and of differential impacts of low-carbon policies. This process echoes the Stated Policy Scenario of the IEA *WEO* report, which reflects "current policy settings based on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by governments around the world" with a goal "to provide a benchmark to assess the potential achievements (and limitations) of recent developments in energy and climate policy" (IEA 2021).
- **Carrying capacity and climate impacts.** The building of a reference case is normally informed by a country's past performance regarding several indicators (e.g., GDP, employment, GHG emissions) and by policy targets. The role played by past and expected future climate impacts and natural capital is often ignored, and such omissions become more notorious as countries are hit by climate-related hazards and experience carrying capacity constraints, with such impacts being reflected in the variability and trends of TFP. Under the GEMF, stakeholders are offered a conceptual framework that considers alternative reference cases: one where climate impacts and carrying capacity constraints are incorporated (as per balancing loops B1–B7 in Figure 3) and a counterfactual one that assumes that such impacts do not take place. The latter reference case is one that aligns with most modeling exercises and with mental models of individuals who disregard or fail to understand the role of climate hazards and natural capital in attaining given socioeconomic outcomes.

Whether the reference case with climate impacts and constraints becomes the preferred baseline in a policy exercise—such as an NDC update—is a matter that is discussed on a country-by-country basis, though the selected reference case serves as a sound starting point. The differences in welfare-related outcomes (e.g., employment, income, value addition) between reference cases can demonstrate how optimistic many models and associated baselines tend to be in projecting the implication of climate inaction and resulting future impacts (See "Higher cost of inaction").

Considerations for building low-carbon scenarios

Generally, the creation of climate action scenarios is an iterative process in which policymakers provide guidelines and are informed by technical teams seeking to align a country's development ambition with actionable policy interventions. In some circumstances, it is a top-down process that identifies high-level policy interventions (e.g., land, waste, energy efficiency, RE) and provides them as guidelines to line ministries and other national entities. When the approach is a bottom-up process, consultations with many experts and institutions identify policies and interventions that in turn result in given paths for GHG, environmental, social, and economic variables. Some other cases involve a combined top-down/bottom-up approach that seeks to reconcile initially identified targets at a high level with actionable interventions emerging from sector consultations and deep dives. To the extent it is possible, NCE and KnowlEdge SRL foster the latter approach, under an iterative framework that extends over the different stages of the policy process, from setting agendas to deliver on policymakers' short-, medium-, and long-term targets, to formulating associated policies and identifying investments, to implementing and evaluating policies (see Figure 1).

GEM has thus far been a tool for NCE country partners to assess the potential implications of highly ambitious decarbonization scenarios, providing evidence to help policymakers advocate for a rapid change in the pace of implementation and target levels for several proximate policy targets. These in turn come along with high investment needs. Three considerations are worth mentioning regarding the building of low-carbon scenarios under the GEMF:

- **Providing fair comparisons of outcomes across scenarios.** Each GEM scenario includes a unique mix of policies, including their associated investment needs. Expectedly, a scenario that includes higher investment needs (for instance, low-carbon interventions) would yield, in principle, a higher GDP growth than a scenario with a comparatively lower boost in aggregate demand. Since one would like to appraise the merits of low-carbon policies against alternatives based on the former's intrinsic growth potential (and not from higher stimulus effort) it would be appropriate to build the low-carbon scenario in a way that makes total aggregate demand boosts comparable with the alternatives.

- **Abiding by fiscal constraints.** Considering that a country may not wish to exceed some fiscal and debt threshold in order to preserve macroeconomic stability, GEM allows for adding structures that either bind the total amount of public expenditures such that those thresholds are not exceeded (with consequent reduction in low-carbon ambition as a result of the limited fiscal space) or that allows for inclusion of all low-carbon investment requirements (for a given level of ambition) but keeps track of the extra financing needs on top of maximum feasible public expenditures.
- **Abiding by other policy/political constraints.** In many cases, policymakers argue about limits to advance low-carbon ambition beyond a given target in policy variables due to a combination of political, technical, and institutional constraints. This may refer to targets in RE, land restoration, and EV expansion but also in sectors such as coal, palm oil, livestock, and so forth. Quite often, such arguments are based on the past performance of those indicators. Although it can be challenging to increase ambition, including for implementation, NCE strived to advance discussions that help policymakers understand the benefits of higher ambition and expanding the policy frontier.

Cost-benefit analyses

GEM incorporates structures for computing costs of individual low-carbon interventions. These include up-front capital investments and operations and maintenance (O&M) costs. Costs are estimated using both national and international sources from the emerging empirical literature and shared with stakeholders for validation. These discussions come up after the first round of results is shared and questions related to the costs and financing emerge. Model parameters are updated if more accurate cost data are available.

Costs of low-carbon interventions can be compared with the (potential) differential benefits for a set of variables of interest for policymakers, including on value addition, income, employment, human capital, and environmental resources. This economy-wide CBA allows policymakers to explicitly identify welfare-related variables of interest. It provides information about the costs of individual interventions or selected packages as well as the associated benefits, which assists with policy prioritization. GEM scenarios help policymakers understand how policies can have higher potential to attain a given target for a given policy effort and the associated impacts in other variables and domains. For instance, labor productivity is connected to access to health care and education via rising sea levels (reduced land area for health and education infrastructure) and health damages related to air pollution. The avoided costs of such damages add to the benefits of low-carbon interventions.

Overall, we follow this process to create an integrated CBA and financing strategy:

1. Simulate the outcomes for reaching low-carbon targets (both benefits and costs) with no constraints (unless explicitly specified by stakeholders or experts).[34]
2. Estimate the investment required for realizing such outcomes (both gross investment and net versus the reference case) and the investment required for each intervention (both capital and O&M), such as EVs and chargers, public transport, energy efficiency, and so on.
3. Distinguish between public and private investment (both gross investment and net versus the reference case).
4. Compare the required additional private investment with the current budget (including what existing policies advocate for other expenditures, such as spending on health and education) and estimate the potential increase in deficit.
5. Decide what is a reasonable amount of public investment by making assumptions on hard caps (e.g., on deficit, on debt, or on the debt-to-GDP ratio). This part of the analysis considers the potential increase in public revenue from higher GDP (often driven by lower energy spending, lower air pollution, and higher labor productivity).
6. Formulate an investment plan, year by year, for each sector and/or thematic area of investment (e.g., climate mitigation, adaptation, sustainable transport, nature-based infrastructure).

In considering the potential impact of a transition pathway on financial stability, we first estimate the investment needed to realize the stated ambition (e.g., 100 percent RE by 2050), which is disaggregated into public (e.g., public infrastructure) and private investment (e.g., agriculture practices, purchase of vehicles). Then, through GEM, we assess the required public investment in relation to any stated budget or deficit ceilings (we also let the model run without limitations to assess what the impact would be on public debt). Should the public investment required be higher than available resources, we would also provide an assessment of the possible international funding sources and impacts of foreign aid.

GEM does consider trade-offs, but the dynamics of the model change over time. For instance, higher investment in the short-term in the low-carbon scenario results in higher deficits, debt accumulation, and higher interest rates. However, the positive economic outcomes of decarbonization—such as additional productivity that triggers higher value and more investment and growth—that emerge in the medium term lead to larger declines in the deficit and the debt-to-GDP ratio than in the reference scenario. In other words, short-term investment creates medium- and longer-term opportunities. In the case of Indonesia, the client asked to put a cap on the deficit (BAPPENAS 2019; Medrilzam et al. 2021). The resulting trade-off was reduced investment in carbon-intensive projects (both for mitigation and adaptation).

Adding up the costs across interventions against the benefits that such investments will generate yields gross financing needs. A few items are considered by GEM in this regard:

- **Revenues from the transition.** Candidate low-carbon policies include market-based mechanisms such as carbon taxes and the removal of existing fossil fuel subsidies. Applying such instruments earlier in the transition yields significant revenues that can be reinvested into other low-carbon interventions, such as public transportation and clean energy infrastructure, as well as into social programs that can ease externalities that arise from a low-carbon transition, such as training programs for coal workers displaced by growing RE industries.
- **Private sector investments.** Low-carbon interventions are distributed between those that are generally undertaken by the public sector and those that entail some action from private sectors or households. It naturally follows that only a fraction of the required investments is borne by the public sector. GEM identifies and computes costs of interventions that are naturally led by the private sector. They emerge endogenously from patterns of technological progress in areas such as EVs and RE and by comprehending the economic advantages of investing in energy efficiency and waste reduction. Private sector actions can also be driven by regulations or other public policies that result in increased private low-carbon investments.
- **Resource shift.** Under low-carbon scenarios, resources that would otherwise be applied in carbon-intensive sectors are redirected to lower carbon technologies (e.g., materials for coal power plants go toward EV manufacturing). In this regard, in saying that low-carbon gross investment needs to represent a percentage of GDP, one should consider the resources that would be saved from avoiding high carbon scenarios.[35] Public sector green financing needs are thus computed as the difference between the cost of all interventions, minus private sector investments, minus revenues from the transition, minus resources shifted away from high-carbon investments.
- **International bilateral and multilateral financing.** The resource gap that emerges as the difference between green financing needs and the domestic public resources available for green investments corresponds to the required international bilateral and multilateral financing support. GHG emission reductions that can be achieved from sources other than international support could be associated with the unconditional paths often referred to, for instance, in countries' NDCs. The additional GHG emission reduction supported with international funding is often associated with conditional NDC paths.

A SUMMARY OF STRENGTHS AND LIMITATIONS

Many of GEM's strengths have been highlighted throughout this Technical Note, including some of the more useful advantages it has over other modeling approaches and analytical frameworks. GEM's ability to highlight the cobenefits of climate action and its dynamic impacts across sectors have been valuable resources informing low-carbon and net zero initiatives in country programs. Most notably, the results of GEM-Indonesia, developed with the Low Carbon Development Institute, showed significant economic growth and employment gains in parallel with emissions reductions and helped shape the national medium-term development plan to 2024 (Garrido et al. 2019). Though many country-specific macroeconomic models led by development organizations have been utilized by governments and have contributed to policy in similar ways, GEM adds dimensions that are often neglected in more commonly seen economic assessments, especially those relevant to mitigation and adaptation, such as factoring in natural capital and the broader social benefits of green job creation. Moreover, through rigorous consultations with a wide variety of local partners and stakeholders, the GEM methodology is relatively more adaptable to the realities and priorities of the subject country than many conventional approaches.

We have talked mostly about the GEM application at the national level in this note because much of the WRI-NCE work is focused on this scale, but it bears noting that the SD-based modeling approach can be effectively applied to a variety of contexts. For example, an iteration of GEM-Indonesia was deployed to assess the economic viability of peat and mangrove rehabilitation in the Katingan Mentaya Project in Central Kalimantan and the Belitung Mangrove Park; it used a more project-focused assessment called a Sustainable Asset Valuation (Cutler et al. 2021; Pallaske et al. 2023). The approach here connects SD modeling with financial analysis to analyze nature-based-solution options for the Katingan peatlands and Belitung mangroves, thus applying the same methodology intended for national-level planning to a deeper focus on the sectors embedded in the national GEM. This case study also further exemplifies how GEM can be a particularly effective tool with additional inputs from external models to fill analytical gaps.

Yet we also acknowledged in this note that the model has several limitations. Some are inherent to modeling (e.g., model boundaries, results contingent on assumptions) and the task at hand (e.g., limited data availability for key green economy indicators), and they cannot be directly "fixed"; many others, however, can be improved in future iterations of the GEM, with each country or regional application. As mentioned previously, a main limitation is that GEM is not designed to capture all that may be relevant. There are limitations to what we can consider and to what our stakeholders—who cocreate the model and analysis with us—want to consider. Connections with other modeling approaches and tools can also fill many of GEM's gaps, such as those related to spatial analysis or more microeconomic questions.

The following are some of the other policy areas not targeted by GEM:

- **Monetary and relative price dynamics.** GEM is a model of the real economy, connected to natural capital and climate impact representations. It does not include monetary and financial system structures and the associated effects from monetary shocks or monetary policies. Also, it focuses on supply-side elements and thus does not necessarily capture absolute or relative price dynamics that result from explicit interactions with demand. To be sure, such elements could be brought into GEM, as needed, but they are not the main reasons why the model was created. GEM *does* incorporate price dynamics for selected elements, such as those related to the energy sector and how they are affected by policy (from changes in carbon taxation and fossil fuel incentives). Prices then play a role in shifting and changing the composition of energy demand and power generation supply.
- **Balance of payments and trade impacts.** Although GEM includes endogenous estimates for changes in aggregate demand components, including imports, exports, and gross national savings, it does not include a full representation of the external sector (i.e., the dynamics of trading partners and the rest of the world). Balance of payments and the real exchange rate are not part of the model; trade and international capital shocks and policies are not a focus of GEM. The extent to which these issues are relevant to climate impacts and policy indicates the convenience or desirability of bringing into the policymaker's analytical toolbox complementary models and methods. This is especially true for countries that may, for example, have a larger share of GDP attributed to trade and would thus require trade models attached. The model can also be customized in ways that allow the capture of local specificities. Insights from GEM can be combined and reconciled with other models to assess possible dynamics in relative prices (including real exchange rates) and the external sector as well as to analyze possible aggregate demand constraints. GEM outcomes for variables such as GDP, income, employment, and fiscal results are potential realizations as those features are factored in.
- **Detailed, intersectoral input-output relationships.** GEM's representation of economic activity, including by sectors, is done with a lower disaggregation compared with general equilibrium models. The latter often include a Social Accounting Matrix (SAM) that allows a representation of intersectoral linkages that emerge from policies and shocks at levels that are determined by the detail through the SAM. Whereas GEM relies on the SNA (and emerging information from the System of Environmental-Economic Accounting) as the basis to define economic structures (aggregate demand components and value addition, by sectors), it only uses a simplified SAM in model definition.[36] GEM offers detailed representation for selected sectors as needed, depending on country characteristics, but always under a comprehensive framework, such that the sum of value-added for all represented sectors equals total value addition in the economy.
- **Nuanced technological learning.** Though GEM can build in assumptions of accelerated clean energy development as a result of, say, increased investments or removal of fossil fuel incentives, the extent to which technological advancements are shaped in the model are limited by the simplification of sectoral systems. For example, a key dynamic missing with technology is the role that automation (i.e., investment in physical capital) might have on employment levels, when research has shown that much of the job loss in resource extraction industries and natural capital can be attributed to rising automation rather than any environmental or climate policy (Way et al. 2022).

GEM overcomes the reliance on past fixed characterizations of the economy through the intersectoral model relationships and the feedback loops that drive productivity and GDP. If there is a rapid structural transition toward RE, for example, GEM simulates how this might affect energy prices and spending in relation to GDP. This assumes that electricity prices decline followed by energy spending declines, making the economy more competitive and facilitating growth. Returning to the rebound effects mentioned earlier, this additional growth, induced by the RE example above, then leads to higher energy demand and higher spending. Hence, even if decarbonization leads to higher growth, this higher growth must be anticipated and accounted for in the ambition to ensure that targets are achieved.

Moreover, much of the modeling in GEM is reliant on how climate damages are computed, and the literature on quantifying climate impacts evolves rapidly. To the extent possible, the damage functions in GEM consider the latest studies that are relevant to the specific country. That said, there will always be a dispute over the best practices for quantifying climate impacts. This is why working closely with local experts and academics, who will be most in tune with what analytical practices are most appropriate for the circumstances, is instrumental in constructing a robust and practical GEM.

As equity considerations and the need for a more human-centered approach in analytical tools have recently become more prominent, it is also crucial to note how GEM can play a role from a just transition perspective. GEM assesses whether employment and income will be created in a sector and for which investment. It also assesses the extent to which access to services and to natural resources improves under alternative scenarios, favoring different population groups. But GEM by itself is not explicitly designed to shed light on dynamics related to income distribution. This gap has been noted in several of the countries in which GEM has been implemented, and one approach has been to couple a separate microsimulation framework with the GEM assessment (for a description of this module, see "Micro-macro module" in Appendix A). This exercise has so far been formulated and implemented in India and Vietnam, with relevant documentation to be published following the publication of this Technical Note.

Additionally, for large emitters such as China and the United States, a lack of feedback from a model such as GEM could become problematic for scenarios of rapid, deep decarbonization because such countries have a nonmarginal effect on GHG concentrations and thus in temperature changes that in turn can further affect socioeconomic outcomes. A similar issue would arise when the analysis is done for a group of countries with large GHG emissions. Related to this, another limitation of GEM is its lack of analysis on the potential of international leakage, though nationally tracked fugitive emissions are considered when the data are available.

The Future of GEM

GEM is a constantly evolving model and is designed to be refined with the most up-to-date information and science. This includes incorporating emerging innovative economic concepts, including new prosperity measures to discourage reliance on GDP as a key metric. But more importantly, because each country GEM is unique to its regional and policy context, consultations with local policymakers and stakeholders is essential to ensure the model's relevance and effectiveness. As part of building GEMs with national partners, WRI and KnowlEdge SRL train local experts on both SD and GEM to ensure that each country has the capacity to use and update its respective GEM to assess policies being considered to enable a green economy. Part of the training includes demonstrating how to connect GEM to existing policymaking and analytical tools, with the aim of enhancing the empirical evidence needed to drive low-carbon and net zero transitions. It is our aim that GEM and its associated framework, as well as the country programs that are designed to deliver them, contribute to the global effort to address the collective challenge of climate change while maintaining the socioeconomic priorities and needs of each country.

APPENDIX A. TECHNICAL SPECIFICATIONS OF MODEL STRUCTURES IN GEM

This appendix features the equations and causal linkages that compose each module under GEM. This information is integral to understand the assumptions generally underlying the model, how the relationships between variables are calculated, and where data is typically sourced. This is most useful for those seeking a tutorial on how to construct their own GEM; as such, the primary contents are the equations and causal diagrams as they are presented in Vensim. Equations are thus presented not as mathematical formulas but rather as they are plugged into Vensim. Causal linkages in each module are represented as *causes trees*, which show the causes of the variable selected (i.e., the variables that are used to estimate the one selected), or *uses trees*, which show the variables impacted by the one selected.

Population

The population module provides an overview of the development of total population, births, and deaths over time. The population module contains the stock of population, which is affected by the biflow change in population. The stock of population changes based on the integration of the flow value:

$$\textit{Population}_{t+1} = \textit{population}_{t0} - \textit{change in population}_{t0}$$

The change in population depends on the stock of population and the net population growth rate. The flow value can take positive as well as negative values, depending on the net population growth rate. The annual change in population is calculated based on the following equation:

$$\textit{Change in population} = \textit{population * NET POPULATION GROWTH RATE TABLE(time)}$$

The historical population growth rate is obtained from national statistics, and the forecast is calibrated to match the most up-to-date population forecast provided by the United Nations Department of Economic and Social Affairs.

Climate assumptions

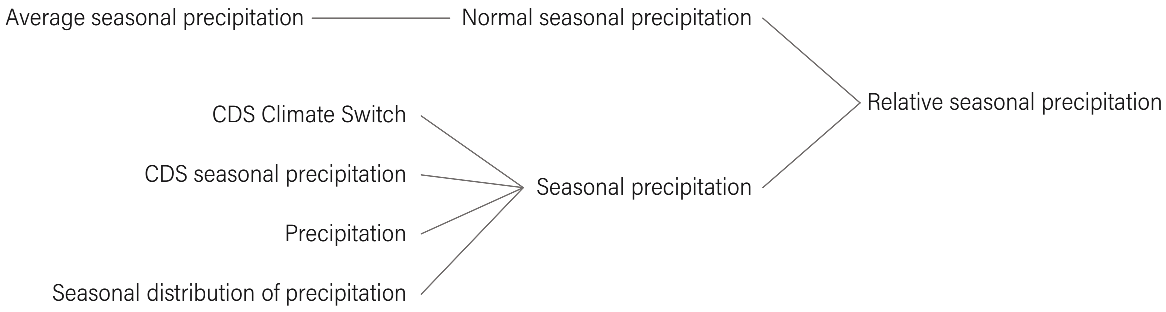
The climate assumptions module serves to simulate changes in precipitation and temperature over time. It provides information about monthly precipitation and seasonal variability in precipitation and temperature.

Climate impacts in the model depend on the relative changes in precipitation and temperature, estimated as an index. Relative seasonal precipitation, which is calculated as seasonal (or monthly) precipitation divided by normal precipitation, is used to assess potential flood risks or water scarcity impacts.

$$\textit{Relative seasonal precipitation} = \textit{MAX(seasonal precipitation/normal seasonal precipitation,0.01)}$$

A MAX function is used to avoid an integration error in case there is a month during which there is no precipitation. In that case, relative seasonal precipitation will take the value of 0.01. All variables that are used to calculate relative seasonal precipitation are presented in Figure A1.

Figure A1 | **Causes tree for relative seasonal precipitation**



Notes: CDS = Climate Data Store.

Source: Authors.

Precipitation is the sum of baseline precipitation, modeled as a stock, and the variability in precipitation. The variability in precipitation is based on past observed variability above and below normal, multiplied by the growth rate of precipitation variability.

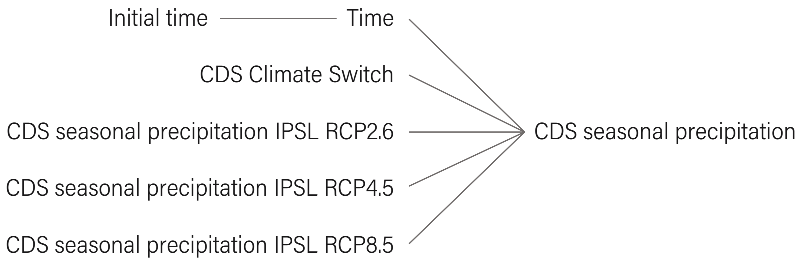
Variability in precipitation =
*(variability above normal + variability below normal) * growth rate variability*

The change in the growth rate of precipitation variability, which is modeled as a biflow, changes the annual variability of precipitation if the Copernicus CDS Climate Switch is active (switch value of 1). This allows for assessing the impacts of increasing or decreasing precipitation variability on a range of variables in the model (e.g., water demand for irrigation, potential flood damages to power generation capacity). A similar formulation is assumed for the stock baseline precipitation. If the *Climate Switch* is active, the change in baseline precipitation, also a biflow, will increase or decrease the annual baseline precipitation, which will affect seasonal precipitation and hence relative seasonal precipitation.

In addition to the endogenous formulation, GEM allows for simulating precipitation and temperature projections obtained from the Copernicus CDS (CDS 2022). The CDS Climate Switch is used to switch between endogenous precipitation and three different CDS climate scenarios. In other words, the CDS Climate Switch allows for the climate data obtained from the CDS to be embedded in GEM. A switch value of 0 indicates the use of the *endogenous* formulation for precipitation. Using switch values of 1, 2, and 3 enables the user to switch between the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively. Figure A2 illustrates the variables used to operationalize CDS seasonal precipitation, also indicated in Figure A1.

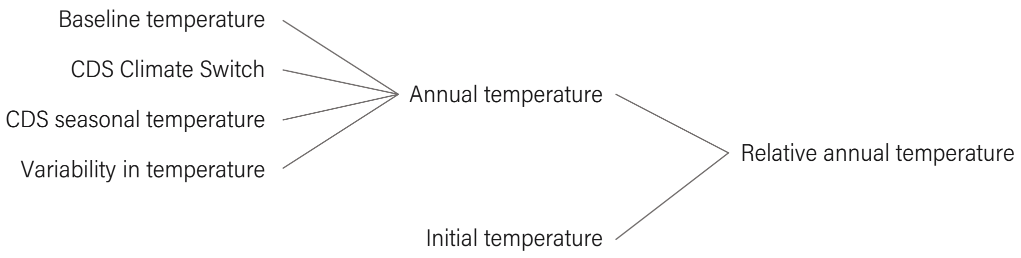
Variables used to calculate the relative annual temperature are summarized in the causes tree displayed in Figure A3. Relative annual temperature is calculated by dividing annual temperature by the initial temperature in the beginning of the simulation.

Figure A2 | **Climate scenarios considered in GEM**



Notes: CDS = Climate Data Store; IPSL = Institut Pierre-Simon Laplace; RCP = Representative Concentration Pathway.
Source: Authors.

Figure A3 | **Causes tree for relative annual temperature**



Notes: CDS = Climate Data Store.
Source: Authors.

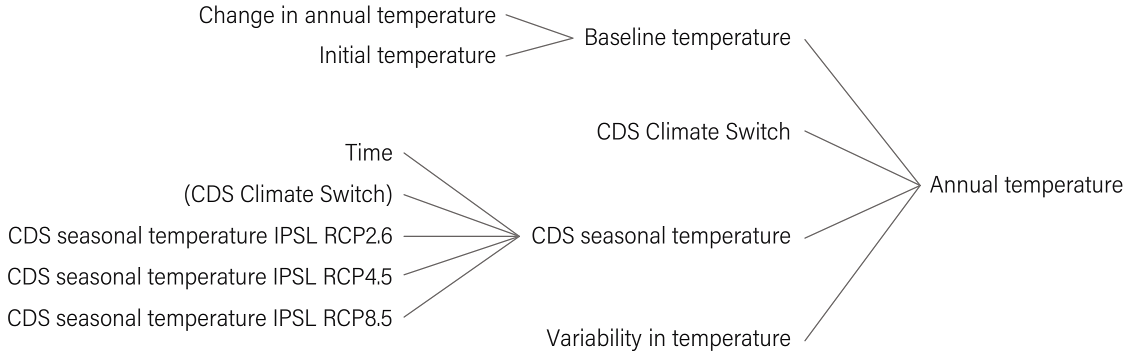
As with precipitation, GEM can simulate temperature projections endogenously using climate projections obtained from the CDS database. In the case of the endogenous formulation, annual temperature is calculated as the sum of the baseline temperatures and variability in temperature. The stock baseline temperature change is based on an assumed fractional increase in annual temperature, which can be defined by the user of the model.

The CDS Climate Switch allows for using climate data from the CDS database as exogenous inputs for the simulations. The switch value ranges from 1 to 3, whereby switch values of 1, 2, and 3 allow for using temperature projections for the RPC2.6, RCP4.5, and RCP8.5 scenarios, respectively. A switch value of 0 indicates that the endogenous formulation is used for the simulation. Figure A4 illustrates the causes tree with variables used to calculate annual temperature.

Land use

The land-use module provides information about aggregate land use and land-use change over time. This module assesses the impacts of development policies on land use and potential conversions of land resulting from their implementation. The module contains four stocks: forestland, agriculture land, settlement land, and fallow land. Five flows are used to capture land-use change over time. Stocks and the respective flows are illustrated in Table A1.

Figure A4 | **Causes tree for annual temperature**



Notes: CDS = Climate Data Store; IPSL = Institut Pierre-Simon Laplace; RCP = Representative Concentration Pathway.

Source: Authors.

Table A1 | **Overview of stocks and flows in the land-use module**

STOCK	INFLOWS	OUTFLOWS
Forestland	▪ Fallow to forest	▪ Forest to settlement ▪ Forest to agriculture
Agriculture land	▪ Forest to agriculture	▪ Agriculture to fallow
Settlement land	▪ Forest to settlement ▪ Fallow to settlement	▪ None
Fallow land	▪ Agriculture to fallow	▪ Fallow to forest ▪ Fallow to settlement

Source: Authors.

Agriculture land, and changes therein, are caused by land conversion for agriculture (forest to agriculture and fallow to agriculture) and the depreciation of agriculture land (agriculture to fallow). The flow forest to agriculture is calculated by the equation below:

Forest to agriculture =
*MAX(MIN((desired change in agriculture land) * (1 – share of agriculture land from fallow land),Forest/TIME TO CONVERT FORESTLAND),0)*

The MAX function ensures that the land conversion flow forest to agriculture cannot take negative values. The MIN function is used to ensure that land conversion is constrained if the desired change in agriculture exceeds the available forest area for conversion. The desired change in agriculture indicates the difference between established and required agriculture land. The multiplication with 1 minus the share of agriculture land from fallow land is done to ensure that the forecasted trajectory of forestland is in accordance with historical data. The desired change in agriculture is the gap between desired agriculture land and currently established agriculture land. The desired amount of agriculture land is hereby based on total population and per capita agriculture land multiplier.

Desired agriculture land =
*population * desired agriculture land per capita*

The stock of settlement land has two inflows, assuming that forest and fallow land can be converted for the expansion of urban areas. Land conversion for settlement land is based on the desired settlement land, which is calculated by multiplying population by desired settlement land per capita. The equations are formulated based on the assumption that, as long as there is fallow land available for conversion, there will be no deforestation for establishing settlement land. The following equation is used for calculating the conversion of fallow to settlement land:

Fallow to settlement =
MAX(0, MIN(desired change in settlement land, fallow land / TIME TO CONVERT FALLOW LAND))

A MIN and a MAX function are used to calculate land conversion from fallow to settlement land. The MIN function ensures that the conversion of land from settlement land cannot exceed the amount of fallow land currently available (same as for the conversion of forestland for agriculture). In cases where the stock of settlement land is higher than the desired settlement land (indicating a negative desired land conversion for settlement land), there would be a flow from settlement land back to fallow land. The MAX function ensures that the current level of settlement land is maintained in case of such an event.

In the case of land conversion for settlement land, forestland serves as a buffer. This means that the conversion of forest to settlement land is only assumed if the amount of fallow land is below the amount required for converting the desired amount.

Forest to settlement =
MAX(0, MIN(desired change in settlement land – waste to settlement, forest / TIME TO CONVERT FORESTLAND))

As in the case of fallow to settlement land, a MIN and a MAX function are used to ensure that land conversion takes place based on land available, and that no reduction of settlement land occurs.

The stock of forestland changes based on land conversion for agriculture and settlement land and the regeneration of forests from fallow land. The outflows of the forest stock, forest to settlement and forest to agriculture, are documented above. The regeneration of forests is the sum of forest regeneration, calculated by dividing the stock of fallow land by the average forest regeneration time and annual reforestation. The equation for the inflow to the forest stock is presented below.

Fallow to forest =
fallow land / AVERAGE FOREST REGENERATION TIME + reforestation of natural forests

Carbon stock and emissions from land

The carbon stock module provides information about carbon stock and changes therein caused by land conversion (Table A2). The module is used to assess how policy-induced land-use changes affect the country's carbon stock and land emissions.

Table A2 | **Overview of data sources for the carbon stock module**

NAME OF VARIABLE	TYPE	SOURCE FOR ESTIMATION
Carbon factor forestland	Constant	Based on IPCC (2006b)
Carbon factor settlement land	Constant	Based on IPCC (2006b)
Carbon factor agriculture land	Constant	Based on IPCC (2006b)
Carbon factor fallow land	Constant	Based on IPCC (2006b)

Source: Authors.

Carbon stocks are calculated by multiplying the four different land-use stocks (forestland, agriculture land, settlement land, and fallow land) by a respective carbon factor. The sum of the four carbon stocks represents the total carbon stock. Figure A5 shows the variables used to calculate the total carbon stock.

Annual emissions from land are calculated based on land conversion. The calculations are based on the five flows described in the documentation of the land-use module and the carbon factors applied to the four land-use stocks. The causes tree in Figure A6 shows the variables used to calculate the net change in carbon stock from land conversion and the CO_2e emissions from land.

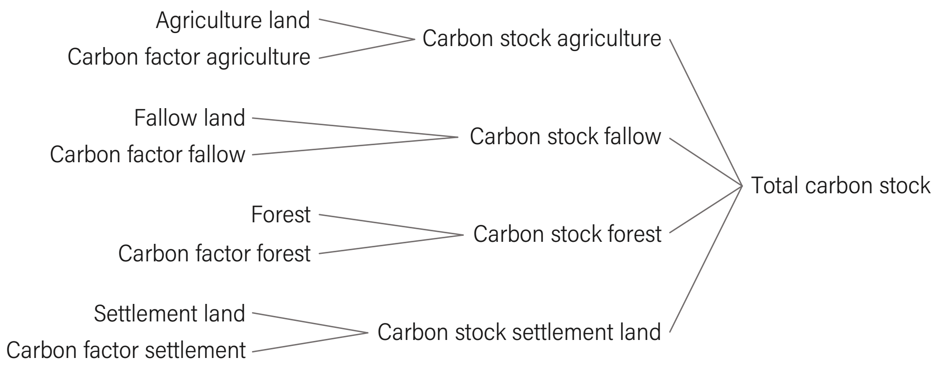
To estimate the change in carbon stock caused by land-use change, the model calculates the net change in total CO_2 that is caused by land conversion. This is done by calculating the difference in carbon stock from the land-use class subject to conversion and the target land-use class. The equation below illustrates the calculation of the change in carbon stock occurring if forestland is converted to agriculture land.

*Change in carbon stock from agriculture to forest = forest to agriculture * adjusted carbon factor agriculture for land-use calculations – forest to agriculture * adjusted carbon factor forest for land-use calculations*

The same approach is applied to calculate the changes in carbon stock for the other four flows. The net change in carbon stock is then calculated as the sum of the individual changes in carbon stock caused by land conversion.

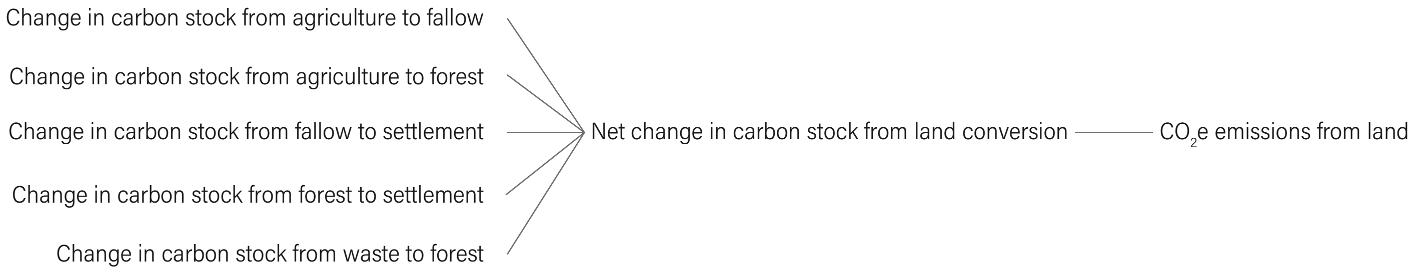
Net change in carbon stock from land conversion = change in carbon stock from agriculture to fallow + change in carbon stock from agriculture to forest + change in carbon stock from fallow to forest + change in carbon stock from forest to settlement + change in carbon stock from fallow to settlement

Figure A5 | **Causes tree for total carbon stock**



Source: Authors.

Figure A6 | **Causes tree for CO_2e emissions from land**



Notes: CO_2e = carbon dioxide equivalent.
Source: Authors.

GDP and employment

The GDP module provides information about the development of total real GDP, the three sectoral GDPs (agriculture, industry, and services), and their respective shares in total real GDP. This module allows for assessing policy impacts on total real GDP and real GDP growth as well potential changes in the economy, indicated by changes in sectoral contributions to real GDP.

The agriculture, industry, and services modules serve to calculate the GDP of the sectors that have not been disaggregated for the analysis of the economy. All three sectors are described in this section. Although the same structural building blocks are used to represent industry and services in the model, the agriculture module is more disaggregated and hence is described in a separate section.

Agriculture GDP

This module provides information about agriculture productivity and employment over time. Key indicators are agriculture real GDP and its growth rate, employment in agriculture, and indicated investment in agriculture. The module allows for assessing the impacts of development policies on agriculture GDP and employment, such as reducing losses during the transport of goods to market.

Agriculture real GDP is calculated based on conventionally and sustainably grown produce and a value-added multiplier. It is calculated based on the respective agriculture production rates, a value added per ton of produce multiplier, and the additional value added from sustainable agriculture. The variable "real agriculture production rate" accounts for preharvest losses and loss of produce during transport to market (see "Crop production").

Real GDP agriculture =
*conventional agriculture production * average value added per ton produced + sustainable agriculture production * (average value added per ton produced * (1 + ADDITIONAL VALUE ADDED FROM SUSTAINABLE AGRICULTURE))*

Total agriculture production is divided into conventional and sustainable produce using the share of sustainable agriculture. The growth rate of agriculture real GDP is calculated using a TREND function, which estimates the change in agriculture real GDP on an annual basis.

Real GDP growth rate agriculture =
TREND(real GDP agriculture, "1 YEAR DELAY TIME," INITIAL REAL GDP GROWTH RATE AGRICULTURE)

Employment in agriculture is calculated based on total agriculture land. The equation below is used to calculate employment in agriculture.

Employment agriculture =
*cropland * (AVERAGE EMPLOYMENT PER HECTARE AGRICULTURE TABLE(time) * (1 – SHARE OF SUSTAINABLE AGRICULTURE) + AVERAGE EMPLOYMENT PER HECTARE AGRICULTURE TABLE(time) * (1 + ADDITIONAL EMPLOYMENT SUSTAINABLE AGRICULTURE) * SHARE OF SUSTAINABLE AGRICULTURE)*

This formulation indicates that agriculture employment is the sum of employment in conventional and sustainable agriculture. The underlying assumption for this equation is that sustainable agriculture has a higher labor intensity per hectare, which is accounted for by using the share of sustainable cropland and a multiplier.

Industry and services GDP

For the industry and services modules, the supply-side approach is used. Throughout this section, the "industry module" will serve as an example to illustrate equations and variables that are used to represent the residual sectors. Table A3 provides an overview of the data sources generally used for calibrating real GDP, employment, and TFP.

Table A3 | **Overview of data sources for the industry and services GDP module**

NAME OF VARIABLE	TYPE	SOURCES
Total employment	Time series	World Bank World Development Indicators (WDI)
Industry real gross domestic product (GDP)	Time series	World Bank WDI or national accounts
Services real GDP	Time series	World Bank WDI or national accounts
Employment in industry	Time series	World Bank WDI
Employment in services	Time series	World Bank WDI

Note: Actual sources may change from country to country, depending on the availability in national databases, core focus areas of the model, and the level of detail of the model in such areas.

Source: Authors.

Capital, labor, and productivity are used to calculate the performance of the residual sectors. The stock of industry capital changes based on the following equation:

$$\textit{Industry capital}_{t+1} = \textit{industry capital}_{t0} + \textit{investment industry}_{t0} - \textit{depreciation}_{t0}$$

Investment in industry is defined as nominal investment industry, which is calculated by multiplying total nominal investment (the sum of private and government investment) by the share invested in industry. The formulation is based on the assumption that the industry will invest in capital to maintain or extend production.

The depreciation of industry capital is calculated by dividing the current industry capital by the average lifetime of industry capital. The depreciation captures machinery that reaches the end of its lifetime or facilities that are outdated. Relative industry capital, an indicator of how much industry capital has changed compared to the beginning of the simulation, is calculated by dividing the stock level of industry capital by its initial value.

In addition, the model simulates the impacts of COVID-19 on productive capital by inducing an additional capital outflow between 2020 and 2023 (assuming three waves of the pandemic). The equation for the depreciation of industry capital is presented below.

Depreciation of industry capital =
*capital industry / average capital life * COVID-19 effect*
on capital industry

Employment in industry is calculated by multiplying industry capital by the labor intensity of the industry sector, an employment factor indicating the employment generated per unit of capital, and the COVID-19 impact on employment.

Employment industry =
*capital industry * real labor intensity industry * COVID-19 effect*
on industry employment

The labor intensity of the industrial sector is affected by the relative labor cost, which affects sectoral employment depending on the cost of labor. If unemployment increases, the cost of labor declines and allows for increased hiring to take place. However, a decrease in unemployment would increase the cost of labor and curb job creation.

Real labor intensity industry =
labor intensity industry / actual relative labor cost

Relative employment in the industry sector is calculated by dividing the employment in industry by its initial value.

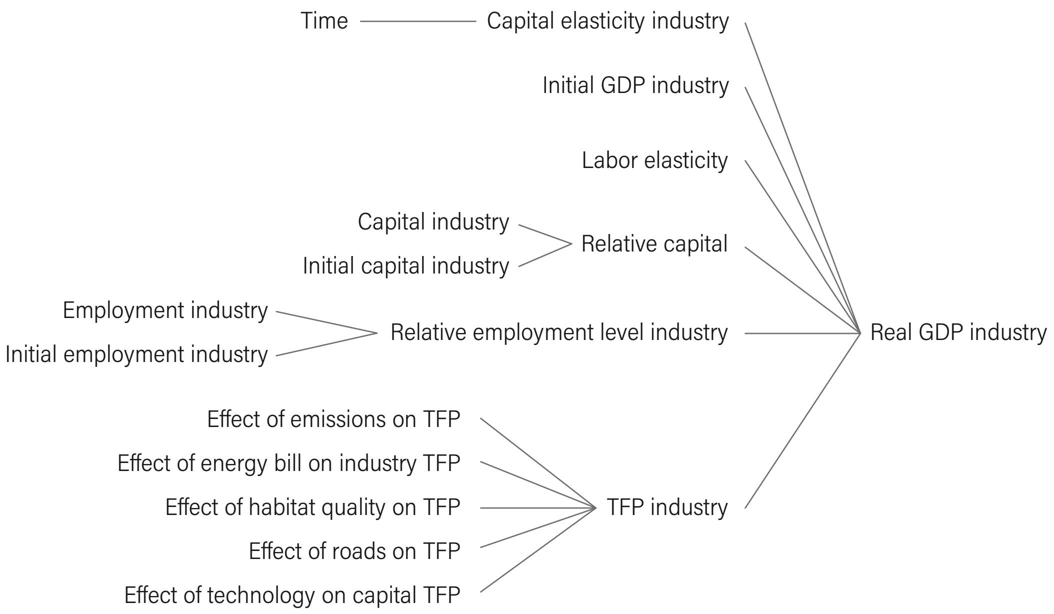
Industry GDP represents the sector's economic performance. It is calculated by multiplying initial GDP industry by production multipliers that account for employment and capital (with a respective elasticity using the Cobb-Douglas formulation) and TFP. The following formulation is used to calculate real industry GDP:

Real GDP industry =
*INITIAL GDP INDUSTRY * relative capital ^ CAPITAL*
*ELASTICITY INDUSTRY * relative employment level ^ LABOR*
*ELASTICITY * TFP industry*

Figure A7 presents a causes tree depicting the variables used for calculating real industry GDP and determining industry sector TFP. TFP depends on the development of the energy bill, technology, roads, and CO_2e emissions. The following equation is used to calculate relative productivity in the industry sector.

TFP industry =
IF THEN ELSE(SWITCH EXTERNALITIES = 1,
*effect of technology on capital productivity * effect of energy bill*
*on industry TFP * effect of roads on TFP * impact of carrying capacity*
and externalities on TFP industry,
*effect of technology on capital productivity * effect of energy bill*
*on industry TFP * effect of roads on TFP)*

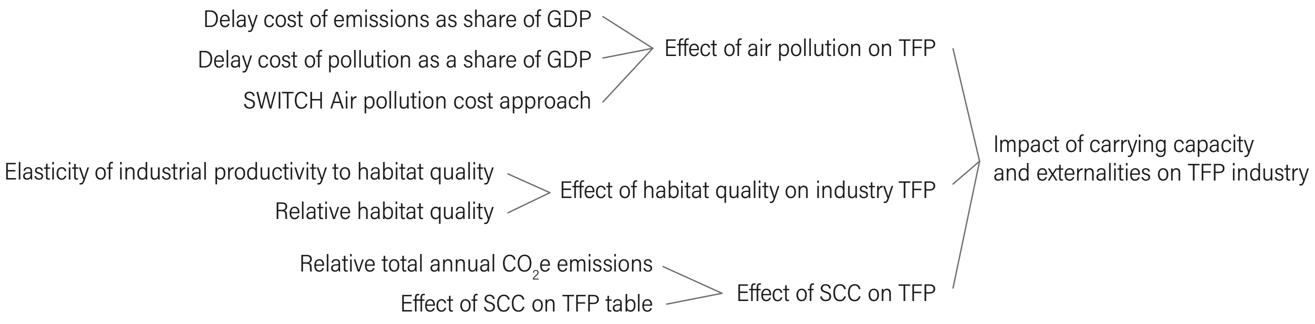
Figure A7 | **Causes tree for the real GDP of the industry sector**



Notes: GDP = gross domestic product; TFP = total factor productivity.

Source: Authors.

Figure A8 | **Causes tree for the impact of carrying capacity and externalities on TFP and industry**



Notes: CO_2e = carbon dioxide equivalent; GDP = gross domestic product; SCC = social cost of carbon; TFP = total factor productivity.

Source: Authors.

The IF THEN ELSE function generates projections including and excluding the impact of externalities on TFP. If the externalities switch has a value of 1 (= switch active), the model will generate forecasts considering the impact of carrying capacity and externalities on industrial TFP. Figure A8 shows a causes tree of variables used to calculate the impact of carrying capacity and externalities on industrial TFP. It considers the effect of country-level SCCs, the effect of habitat quality, and the effect of air pollution. The effect of air pollution hereby allows for choosing whether energy-related CO_2 emissions or the cost of air pollution from power generation are considered for the projections.

Table A4 | **Documentation of effects constituting industry TFP**

EFFECT NAME	EFFECT EQUATION
Effect of technology	*Tech ^ ELASTICITY OF INDUSTRY TFP TO TECHNOLOGY*
Effect of emissions	*DELAY3I(relative annual energy CO$_2$e emissions ^ ELASTICITY OF TFP TO CO$_2$E EMISSIONS, "1 YEAR DELAY TIME," 1)*
Effect of energy bill	*DELAY3I(relative energy bill as share of GDP ^ ELASTICITY OF ENERGY BILL ON INDUSTRY TFP, "1 YEAR DELAY TIME," 1)*
Effect of roads on TFP	*DELAY3(relative km of roads ^ ELASTICITY OF INDUSTRY TFP TO ROADS, "2 YEAR DELAY TIME")*
Effect of habitat quality on productivity	*IF THEN ELSE (time>2020, indicated effect of habitat quality on productivity/effect of habitat quality on productivity in 2020, 1)*
Effect of WBGT on labor productivity	*Effect of extreme temperature on labor productivity ^ ELASTICITY OF LABOR PRODUCTIVITY TO WBGT*

Notes: TFP = total factor productivity; WBGT = Wet Bulb Global Temperature.

Source: Authors.

Table A4 provides the equations used to determine the effects constituting TFP with their respective equations.

Employment and technology

This module provides an overview of total employment and the development of technology over time (Table A5). It assesses the *aggregate* employment impacts of select policy interventions and the changing trends in technological development underlying the analysis. Sectoral employment is described in each sectoral module above for aggregate sectors ("Agriculture GDP" and "Industry and services GDP") and below for energy sector–specific variables ("Employment from power generation") that serve as the inputs for total employment. The total employment output variable is relevant to determine the employment specifically attributed to low-carbon development interventions (outlined in "Green jobs") as well as employment shifts disaggregated by demographics, skill level, and wages (outlined in "Micro-macro module").

Total employment is calculated as the sum of sectoral employment from agriculture, industry, and services. Figure A9 shows the variables used to estimate total employment using a causes tree. The equations used to estimate sectoral employment are described in the previous section.

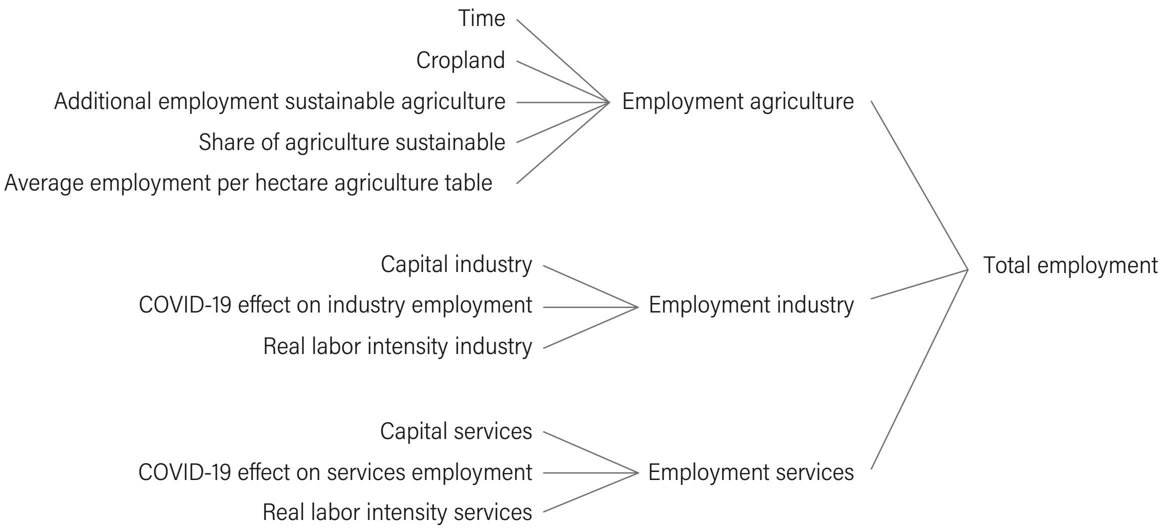
Table A5 | **Overview of data sources for the employment and technology module**

NAME OF VARIABLE	TYPE	SOURCES
Employment in agriculture	Time series	World Bank World Development Indicators (WDI)
Employment in industry	Time series	World Bank WDI
Employment in services	Time series	World Bank WDI
Annual change in technology	Constant	Calibrated based on historical, country-specific data
Labor force participation rate	Time series	World Bank WDI
Average annual salary	Time series	Country-specific sources

Note: Actual sources may change from country to country, depending on the availability in national databases, core focus areas of the model, and the level of detail of the model in such areas.

Source: Authors.

Figure A9 | **Causes tree for total employment**



Source: Authors.

Total employment and the labor force are used to calculate the unemployment rate. The labor force is hereby calculated by multiplying total population by the labor force participation rate. The unemployment rate is calculated using a MAX function to prevent the variable from taking negative values.

Unemployment rate =
MAX(1 – total employment / labor force,0)

Labor force and total employment are used to calculate the labor demand supply balance, which is used to calculate the relative indicated labor cost.

Labor demand supply balance =
total employment / total labor force

The relative indicated labor costs are calculated by dividing the labor demand supply balance by its initial value in the first year of the simulation. This index essentially indicates how labor costs change over time throughout the simulation. The difference between the actual relative labor cost (modeled as a stock) and the relative indicated labor cost accumulates into the stock actual relative labor cost via the flow labor cost adjustment.

Labor cost adjustment =
(relative indicated labor cost – actual relative labor cost) / LABOR COST ADJUSTMENT TIME

The actual relative labor cost is then used to affect the employment intensity in the industry and services sector.

Technology, or "tech" in the model, affects TFP and is modeled as a stock with an initial value of 1 and an annual growth rate. It is an index that increases steadily over time, representing improvements in machinery as well as automation of processes. As a result, the annual improvement of technology results in a compounded improvement in the efficiency and productivity of equipment in the model (as a result of the stock and flow formulation used). The variable representing technology, therefore, exhibits an exponential trend over time.

The annual rate of technology improvement is an exogenous value. This is to allow for the creation of alternative scenarios—which differ in the rates of technology improvement and technology adoption—to accommodate different requests from local stakeholders. For example, different ministries may have different expectations about technology development, and these can be tested with GEM via the simulation of alternative scenarios—a task that can be achieved in a matter of seconds. Furthermore, an exogenous technology growth rate allows the user to estimate the impact of development strategies based on technology adoption and industrial expansion, options that specifically target technology adoption. Although an endogenous formulation would be useful to link investment directly to technology adoption, the use of an exogenous value, coupled with attention to the formulation of coherent scenarios, provides more flexibility in crafting an analysis that responds to the needs of decision-makers.

It is worth noting that the above refers to the use of technology in the estimation of value added at the sectoral level. Specific technologies are represented in the model in relation to investments in climate mitigation and adaptation, as presented in subsequent sections. More specific assumptions are made in this case to future cost reduction and efficiency improvements, based on global trends.

Household accounts

The household account module serves to calculate nominal GDP; disposable income; and private consumption, savings, and investment (Table A6). It provides information concerning the development of these variables over time and assesses policy impacts on household-specific key indicators.

The household module contains household investment and consumption and provides an indication about the real disposable household income. Household revenues are hereby calculated as the sum of nominal GDP, interest on domestic debt, private current transfers, and subsidies and transfers.

Disposable income =
nominal production – "government domestic revenue (excluding grants)" + interest on public debt

Disposable income is calculated as nominal production minus government domestic revenue plus interest on public debt. Disposable income is used to calculate private savings and consumption and real disposable income per capita. Real disposable income per capita is calculated by dividing disposable income by total population and the GDP deflator. The relative value of per capita real disposable income—current real disposable income per capita divided by its initial value—affects the propensity to consume and hence private consumption and private savings.

Propensity to consume =
INITIAL PROPENSITY TO CONSUME(time)
** (relative per capita real disposable income ^ ELASTICITY OF PROPENSITY TO CONSUME TO INCOME)*
** COVID impact on propensity to consume*

In addition to the relative real disposable income, COVID-19 impacts on the propensity to consume are implemented. The impacts of COVID-19 on the propensity to consume are based on COVID-19 employment impacts and an elasticity.

COVID impact on propensity to consume =
IF THEN ELSE (COVID-19 SWITCH = 1:AND DURATION OF COVID IMPACTS TABLE(time)>0, average COVID impact on employment ^ ELASTICITY OF PRIVATE CONSUMPTION TO COVID, 1)

Table A6 | **Overview of data sources for the household accounts module**

NAME OF VARIABLE	TYPE	SOURCES
Nominal production (gross domestic product)	Time series	International Monetary Fund or national (ministry of finance) System of National Accounts, Government Finance Statistics
Disposable income	Time series	
Private consumption	Time series	
Private investment	Time series	
Nominal exports	Time series	
Nominal imports	Time series	

Note: Actual sources may change from country to country, depending on the availability in national databases, core focus areas of the model, and the level of detail of the model in such areas.

Source: Authors.

The IF THEN ELSE function allows for the impacts of COVID-19 to be activated in the simulations. If the COVID-19 switch has a value of 1 (= active) and capital impacts of COVID-19 are active (variable "duration of COVID impacts table"), the model will use COVID-19 employment impacts and the elasticity of private consumption to estimate the impact on the propensity to consume. If the switch has a value of 0, the variable takes a value of 1 (neutral) and no COVID-19 impacts on the propensity to consume are simulated.

The propensity to consume and disposable income are multiplied to calculate total private consumption. Private savings are calculated as the difference between disposable income and private consumption.

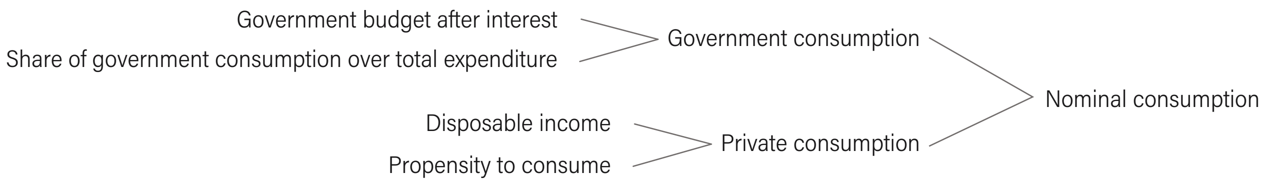
Private savings = disposable income – private consumption

Private investments are determined based on private savings, the share of private savings for private investment and capital, corrected for monetary flows related to government financing, whereby the latter one is based on historical data.

Private savings for private investment =
*private savings * share of savings invested – government domestic financing*

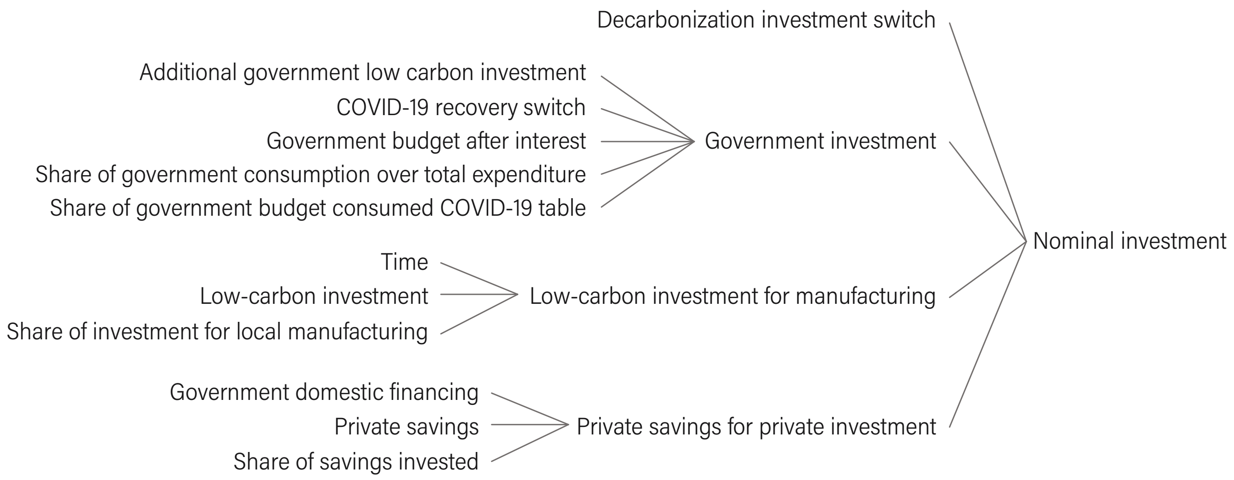
Nominal consumption and nominal investment are calculated as the sum of government and private consumption and government and private investments, respectively. Figure A10 provides an overview of the variables used to calculate nominal consumption, and Figure A11 shows the variables used to calculate nominal investment.

Figure A10 | **Causes tree for nominal consumption**



Source: Authors.

Figure A11 | **Causes tree for nominal investment**



Source: Authors.

The causes trees above illustrate that GEM also provides the feature of simulating government recovery packages for addressing COVID-19 impacts by allowing additional investments to be simulated. If the COVID-19 recovery switch has a value of 1 (= policy active), the model will use a different time series for calculating government consumption compared to business as usual. This change keeps government consumption constant and increases government investment temporarily for the duration of the recovery actions. The above highlights that both nominal consumption and investment are affected by COVID-19 impacts.

Government accounts

The government accounts module provides an overview of government revenues, investments, and debt. It allows for analyzing different public spending strategies and is used as the entry point for simulating a post-COVID government stimulus. Key indicators of the government accounts module and their respective sources are presented in Table A7.

Table A7 | **Overview of data sources for the government accounts module**

NAME OF VARIABLE	TYPE	SOURCES
Government revenues	Time series	International Monetary Fund or national (ministry of finance) System of National Accounts, Government Finance Statistics
Government investment	Time series	
Desired government deficit	Time series	
Public debt	Data	
Interest on public debt	Time series	

Note: Actual sources may change from country to country, depending on the availability in national databases, core focus areas of the model, and the level of detail of the model in such areas.

Source: Authors.

The government accounts module captures government revenues and grants and provides information on total government consumption and investment. Total government revenue is the sum of government domestic revenue and revenue from grants, both calculated as a share of nominal GDP (termed *nominal production* in the model). The causes tree in Figure A12 summarizes the variables used to calculate total government revenues.

The sum of total government revenue and government domestic financing constitutes the government budget. Government financing is defined as total government revenues multiplied by the desired government deficit, a time series function estimated based on historical data. As illustrated in the uses tree in Figure A13, the government budget is used to calculate the government budget after interest, nondevelopment expenditure, and development expenditure.

The government budget after interest is calculated by deducting interest payments on public debt from the government budget. The budget excluding interest serves to calculate government consumption and government investment, using the share of government consumption over total expenditure. Government consumption is calculated by multiplying the share of government consumption over total expenditure by the budget excluding interest; government investment is calculated by multiplying the budget excluding interest by 1 minus the share of government consumption over total expenditure, as illustrated by the equation below.

Government investment =
*government budget after interest * (1 – share of government consumption over total expenditure)*

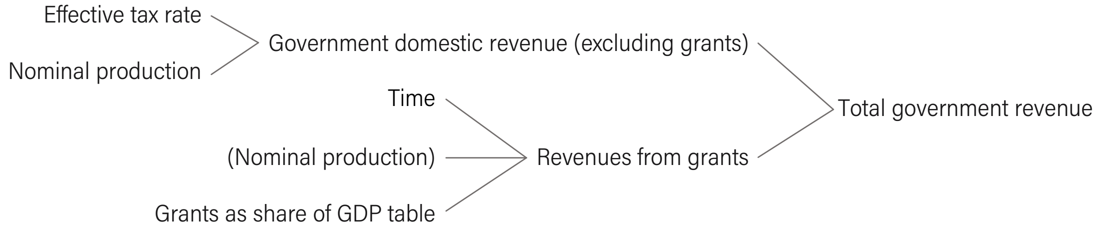
Nondevelopment expenditure is the sum of interest on public debt and the share of government budget used for administrative purposes.

Nondevelopment expenditure =
*interests on public debt + (government budget * ADMINISTRATIVE EXPENDITURE AS SHARE OF BUDGET) * GDP deflator*

Development expenditure, which is used to calculate investments in health care, education, and resource efficiency, is equal to the government budget corrected for the nondevelopment expenditure.

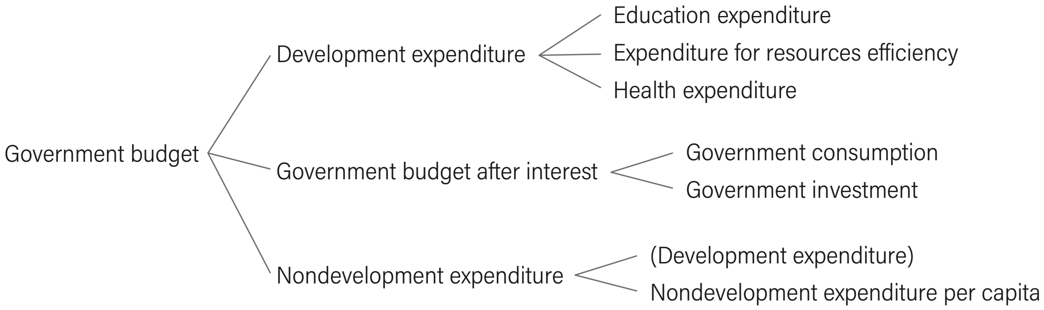
Development expenditure =
MAX(government budget – nondevelopment expenditure, 0)

Figure A12 | **Causes tree for total government revenue**



Note: GDP = gross domestic product.
Source: Authors.

Figure A13 | **Uses tree for government budget**



Source: Authors.

A MAX function is used so that the development expenditure cannot become smaller than zero, which would be equivalent to negative investment.

Investments in health care, education, and resource efficiency are calculated by multiplying the government development expenditure by the desired share of development expenditure invested in health care, education, and resource efficiency, respectively. The desired investment shares for health care and education are calibrated to ensure that the resulting investments are consistent with historical data.

$$\textit{Education expenditure} = \textit{development expenditure} * \textit{desired share of development expenditure for education}$$

Crop production

The crop production module calculates crop production based on total cropland and the crop yield (Table A8). The module is also used to calculate the amount of preharvest losses from agriculture production, and it assesses the impacts of policies aiming to increase the productivity of the agriculture sector while reducing preharvest losses.

The crop production module has one stock (total cropland) that is distributed into conventional and sustainable cropland using the share of sustainable agriculture. Conventional cropland is calculated using the equation below.

$$\textit{Conventional cropland} = \textit{total cropland} * (1 - \textit{share of agriculture sustainable})$$

Sustainable cropland is calculated as the difference between total cropland and conventional cropland. The amount of land by management practice is used to calculate the respective production rates. Both conventional and sustainable agriculture production are calculated by multiplying the amount of land under conventional and sustainable management practices by the respective yield. Total agriculture production is the sum of crop production from conventional agriculture land and crop production from sustainable agriculture land.

Table A8 | **Overview of data sources for the crop production module**

NAME OF VARIABLE	TYPE	SOURCES
Total agriculture production	Time series	FAOSTAT or national statistics (ministry of agriculture)
Crop yield per hectare	Time series	
Share of preharvest losses	Time series	
Fertilizer application	Time series	

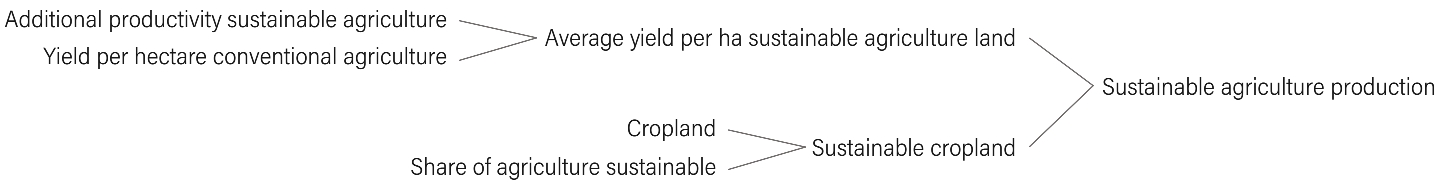
Note: Actual sources may change from country to country, depending on the availability in national databases, core focus areas of the model, and the level of detail of the model in such areas. FAOSTAT = Food and Agriculture Organization Corporate Statistical Database.

Source: Authors.

$$\textit{Total agriculture production} = \textit{conventional agriculture production} + \textit{sustainable agriculture production}$$

In the case of sustainable agriculture production, a productivity multiplier is applied to the yield from sustainable cropland, assuming that sustainable cropland is, on average, 10 percent more productive than conventionally managed cropland. Aside from the parameter "additional production from sustainable agriculture," the causes tree in Figure A14 illustrates both conventional and sustainable agriculture production.

Figure A14 | **Causes tree for agriculture production**



Note: ha = hectare.

Source: Authors.

Fertilizer application

Fertilizer application from agriculture is calculated based on the total land used for crop production and a fertilizer-per-hectare multiplier. GEM estimates fertilizer consumption for conventional and sustainable agriculture land separately. For sustainably managed cropland, the model assumes that the input of fertilizers is 50 percent lower compared to cropland under conventional management practices.

Total fertilizer use =
*cropland * (CHEMICAL FERTILIZER APPLICATION PER HECTARE OF AGRICULTURE LAND(time) * (1 – SHARE OF AGRICULTURE SUSTAINABLE) + CHEMICAL FERTILIZER APPLICATION PER HECTARE OF AGRICULTURE LAND(time) * SHARE OF AGRICULTURE SUSTAINABLE * FERTILIZER REDUCTION ON SUSTAINABLE AGRICULTURE LAND)*

The total fertilizer application use is used as an input for calculating the relative fertilizer application, which is calculated by dividing the current total fertilizer application rate by its initial value in the beginning of the simulation.

Furthermore, total fertilizer application is used to calculate the total annual nitrogen (N) loadings from the application of fertilizers.

Annual demand for N fertilizer =
*total fertilizer application use * N CONTENT OF AG FERTILIZER*

Livestock production

The livestock production module provides an overview of total country livestock populations and the value added from livestock production. The livestock sector contains the following stocks to model livestock populations:

- Cattle
- Buffalo
- Pigs
- Horses
- Sheep and goats
- Poultry

Livestock populations were calibrated based on the historical values obtained from national statistics. Annual changes were calculated and used as table input to reproduce the historical development of the stocks. The "change in cattle" variable, for example, is calculated based on the following equation:

Change in cattle =
(desired cattle – cattle) / TIME TO ADJUST LIVESTOCK

The stock changes based on the integration of the difference between the desired and the actual amount of dairy cattle. The desired amount of cattle is calculated by multiplying total population by a per capita production of cattle multiplier. The value added from livestock production is calculated by multiplying total livestock, which is the sum of all livestock categories, by the real revenues per unit of livestock.

Livestock production value added =
*total livestock * AVERAGE VALUE ADDED PER HEAD OF LIVESTOCK*

Energy demand

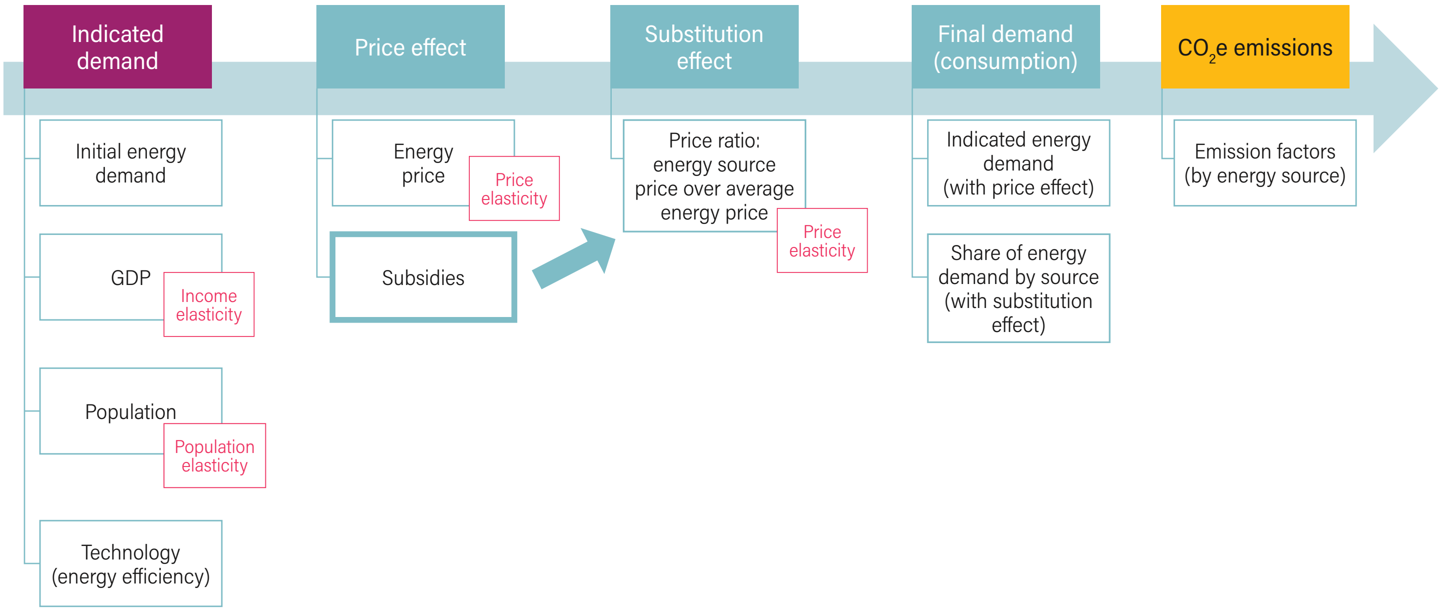
The energy demand module projects national energy consumption by sector and source, from 2000 to 2050. Energy consumption is then multiplied by GHG emission factors to obtain total national emissions from the use of energy.

These are the main structural assumptions of the module (see Figure A15):

- Final energy consumption is estimated considering (1) indicated demand (including the effect of GDP, population, and energy efficiency); (2) the price effect; and (3) the substitution effect. Items 1 and 2 are used to estimate demand for energy services.
- The potential for fuel substitution is represented by the ratio of an energy price over the national weighted average energy price. This implies that an energy source will become more attractive if its price increases less than others when subsidies are removed.
- It is assumed that price effects require a one-year delay to influence energy consumption.

One of the main drivers of the model is energy price, which can be modified in two ways: by setting baseline medium- to longer-term trends (which is an endogenous calculation for electricity) and by removing fossil fuel subsidies. The removal of subsidies increases energy prices, which lowers energy demand in two possible ways: energy becomes more expensive and consumption reduces to offset the growth in expenditure, and, if energy services are required, the use of (previously) subsidized fossil fuels declines and consumption of now comparatively cheaper fuels increases. GHG emissions are affected by both the reduction of energy consumption and the change in fuel mix, and the model analyzes these effects separately. As a result, the model estimates the impact of removing the fossil fuel subsidy on GHG emissions and compares such reduction to other possible intervention options (e.g., investments and/or mandates on energy efficiency and renewable energy). Emission reductions can also be estimated as a result of the reallocation of subsidy savings, such as through investments in RE and energy efficiency.

Figure A15 | **Energy demand, by type, and determinants**



Note: CO_2e = carbon dioxide equivalent; GDP = gross domestic product.
Source: Merrill et al. 2015.

Several variables and equations are used to estimate energy flows (which are measured in terajoule per year [TJ/year]) and emissions (which are measured in tons per year [ton/year]).

To begin with, indicated sectoral energy demand (coal is presented as an example) is calculated using the initial value for 2000, multiplying it by relative GDP and relative population (both indexed to 2000 and raised to the power of a specific elasticity factor) and dividing it by relative energy efficiency (also indexed to 2000). The use of subscripts, "sector" in the example provided below, allows for calculating energy demand for the residential, commercial, industrial, and transport sectors within the same variable.

Indicated coal demand$_{[sector]}$ =
(INITIAL COAL DEMAND TABLE$_{[sector]}$ ** relative GDP ^ ELASTICITY OF COAL DEMAND TO GDP*$_{[sector]}$ ** relative population ^ ELASTICITY OF COAL DEMAND TO POPULATION) / relative energy efficiency*

The price effect is then added, simply taking indicated demand (presented above) and multiplying it by relative energy price (indexed to 2000) and raised to the power of a price elasticity.

The removal of fossil fuel subsidies is reflected in energy price changes. When subsidies are removed, it is assumed that energy prices increase for all sectors (unless it is known that subsidies are allocated to specific users). Users can indicate the extent to which subsidies are removed and the timeline (e.g., full removal, linearly, by 2030).

"Indicated coal demand (with price effect)"$_{[sector]}$ =
indicated coal demand$_{[sector]}$** relative coal price ^ ELASTICITY OF COAL DEMAND TO COAL PRICE*$_{[sector]}$

Next, the substitution effect is considered. The formulation is the same as the one used for incorporating the price effect, but a one-year delay is used to represent the lag existing between price changes and demand (or consumption) changes.

"Coal demand (with substitution effect)"$_{[sector]}$ =
*DELAY N(("indicated coal demand (with price effect)"[sector] * "coal price – substitution" ^ ELASTICITY OF COAL DEMAND TO COAL PRICE*$_{[sector]}$*), TIME TO ADAPT DEMAND TO PRICE CHANGES, ("indicated coal demand (with price effect)"*$_{[sector]}$ ** "coal price – substitution" ^ ELASTICITY OF COAL DEMAND TO COAL PRICE*$_{[sector]}$*), 3)*

The potential for substitution from one energy source to the other, due to price changes (e.g., as a result of fossil fuel subsidy removal), is incorporated here by using the ratio of energy source price (e.g., coal) over the average energy price of the country (estimated as a weighted average of all energy prices). This ratio is also indexed to ensure consistency with the use of elasticities.

$$\text{“Coal price – substitution”} = \text{DELAY N((relative coal price / relative weighted average energy price),1,1,1)}$$

Indicated energy demand (including the price effect) is used to estimate the total indicated energy demand (this is also demand for energy services), which is the total energy that has to be guaranteed at the country level. The potential for substitution is instead used to estimate the actual share of energy consumption by source as a result, a normalization is performed multiplying total indicated energy demand by the shares obtained from the inclusion of the substitution effect.

$$\text{Normalized coal demand}_{[\text{sector}]} = \text{total indicated country energy demand} * \text{normalized coal share of energy demand}_{[\text{sector}]}$$

Energy bill

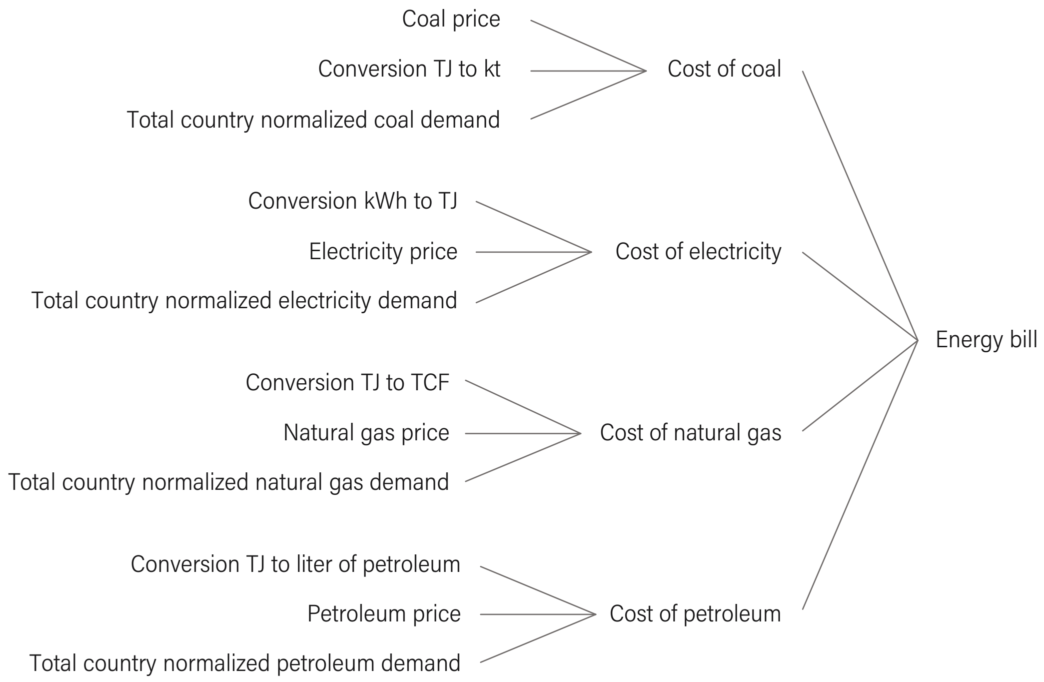
The energy bill provides an overview of the country-level energy cost by type of fuel and the relation between energy cost and total real GDP. The latter is used to estimate energy cost impacts on TFP. The causes tree in Figure A16 presents the variables that are used to calculate the energy bill.

In all cases, the cost of energy is calculated using the normalized country energy demand by fuel, the price of energy, and, where required, a conversion factor to align units of measure. The equation used for calculating the country-level cost of petroleum is described below.

$$\text{Cost of petroleum} = \text{total country normalized petroleum demand} * \text{petroleum price} * \text{conversion TJ to liter of petroleum}$$

The energy bill, calculated as the sum of costs across all fuel categories, is converted from U.S. dollars to local currency units (LCUs) using the exchange rate. The energy bill as a share of GDP is calculated to determine the impacts of energy costs on industry and services TFP.

Figure A16 | **Causes tree for the energy bill**



Notes: kWh = kilowatt-hour; kt = kiloton; TCF = trillion cubic feet; TJ = terajoule.

Source: Authors.

$$\textit{energy bill as share of GDP} = \\ (\textit{energy bill} * \textit{EXCHANGE RATE US\$ TO LCU}) / \textit{total real GDP}$$

The relative energy bill as a share of GDP—an index calculated by dividing the current energy bill as a share of GDP by its initial value in the year 2000—is used to calibrate the impacts of energy costs on industry and services TFP. The uses tree for the relative energy bill as a share of GDP is presented in Figure A17.

Power generation capacity

The power generation module captures the demand for electricity, transmission losses, and required and current power generation capacity. The module uses the total normalized electricity demand as input to assess electricity generation by technology and forecast future capacity requirements. It further provides information about total electricity generation, both by technology and system-wide, and the shares of generation by technology. The power generation module uses the subscript "power generation technology," which enables the use of the same structural components to estimate capacity, generation, and cost for the 14 technologies presented in Table A9.

Power generation capacity is represented using two stocks: power generation capacity under construction and power generation capacity. The installation and usage of power generation capacity is driven by the desired electricity generation rate, which considers both imports and transmission losses.

$$\textit{Desired electricity generation} = \\ \textit{electricity demand in megawatt-hours} * (1 + \textit{TRANSMISSION LOSSES TABLE(time)}) * (1 - \textit{SHARE OF ELECTRICITY IMPORTED TABLE(time)})$$

The desired electricity generation serves as input for calculating the desired electricity generation by technology, which is calculated by multiplying the total desired generation by the shares of generation satisfied by the respective technology. Considering the load factor and the number of hours per year, the desired electricity generation by technology is used to calculate the required electricity generation capacity for each technology.

$$\textit{Required electricity generation capacity by technology} = \\ (\textit{desired electricity generation by technology}_{\textit{[power generation technology]}} / \textit{hours per year} / \textit{load factor}_{\textit{[power generation technology]}})$$

The power generation capacity gap calculates the capacity generation gap by comparing the required power generation capacity with the currently installed capacity. The capacity gap for all technologies considered is calculated by the following equation:

$$\textit{Power generation capacity gap}_{\textit{[power generation technology]}} = \\ \textit{required electricity generation capacity by technology}_{\textit{[power generation technology]}} - \textit{power generation capacity}_{\textit{[power generation technology]}} - \textit{power generation capacity under construction}_{\textit{[power generation technology]}}$$

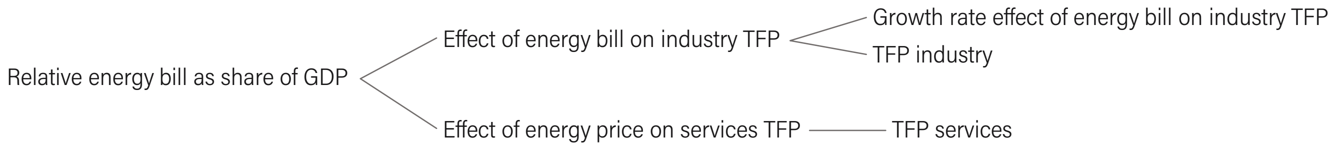
The required electricity generation capacity is compared to the current power generation capacity and power generation capacity under construction to determine whether there is a capacity gap. The MAX function ensures that the capacity gap does not take negative values in case of overcapacity, as a decrease in capacity is assumed to happen through decommissioning only.

Table A9 | **Power generation technologies considered in GEM**

POWER GENERATION TECHNOLOGIES	
Diesel and fuel oil	Hydropower (large scale)
Cogeneration	Hydropower (small scale)
Gas turbine	Solar power (utility scale)
Steam coal	Solar photovoltaic (rooftop)
Nuclear	Wind (onshore)
Biomass	Wind (offshore)
Geothermal	Waste generation

Source: Authors.

Figure A17 | **Uses tree for relative energy bill as a share of GDP**



Notes: GDP = gross domestic product; TFP = total factor productivity.
Source: Authors.

The stock of power generation capacity under construction is changed by the construction rate and the completion rate. The construction rate is increasing the stock level and is calculated by dividing the power generation capacity gap by the time to process capacity orders. The completion rate is an outflow of power generation capacity under construction and an inflow to power generation capacity. The completion rate is defined as a fixed order delay based on the construction rate and the construction time of all technologies, based on the assumption that capacity becomes functional once the construction is completed. Power generation capacity is increased by the completion rate and decreased by decommissioning, whereby decommissioning is calculated as a fixed delay of the completion rate and the capacity lifetime, based on the assumption that capacity depreciates after a fixed lifetime.

Electricity generation is calculated based on the power generation capacity, the load factor, and the hours per year. It represents the total amount of electricity that is produced. The following equation is used to calculate the electricity generation for all capacity types:

$$\begin{gathered}\textit{Electricity generation rate[power generation technology]} = \\ \textit{MAX(IF THEN ELSE (desired electricity generation by technology}_{\textit{[power generation technology]}} < \textit{power generation capacity}_{\textit{[power generation technology]}} \textit{ * hours per year * load factor}_{\textit{[power generation technology]}}\textit{, MIN(power generation capacity}_{\textit{[power generation technology]}} \textit{ * hours per year * load factor}_{\textit{[power generation technology]}}\textit{, desired electricity generation by technology[power generation technology]), power generation capacity}_{\textit{[power generation technology]}} \textit{ * hours per year * load factor}_{\textit{[power generation technology]}}\textit{),0)}\end{gathered}$$

The MAX function is used to ensure that electricity generation does not take negative values. The IF THEN ELSE function ensures that, in case of overcapacity, the MIN function is applied for calculating total generation; otherwise, all generation sources are assumed to generate at full capacity. The MIN function is used to ensure that only the required amount of electricity is produced and constrains generation to the desired generation by capacity type to avoid overproduction. It compares the current generation potential, by technology, to the desired electricity generation, by technology. If the potential generation is higher, the MIN function ensures that the technology in question does not produce more electricity than demanded. The total electricity generation rate represents the sum of electricity generation from all types of capacity and is calculated using a SUM function to add up the electricity production of all technology subscripts. The share of renewable generation is calculated by the following equation:

$$\begin{gathered}\textit{Share of renewable generation} = \\ \textit{(SUM(electricity generation}_{\textit{[other renewables!]}}\textit{) + SUM(electricity generation}_{\textit{[hydropower!]}}\textit{)) / SUM(electricity generation}_{\textit{[technology!]}}\textit{)}\end{gathered}$$

The sum of the electricity that is produced by hydropower and other renewable capacity types divided by the total electricity generation represents the share that renewable capacity has in total electricity production.

Employment from power generation

The employment module captures the employment that is generated through the construction and maintenance of energy generating capacity. It allows for observing the impact that different energy pathways have on the total employment of the energy sector. Furthermore, it also captures the employment generated through the extraction of fossil fuels.

Table A10 provides an overview of the module's key variables and lists the reports and documents that are used for the parameterization of the module.

Table A10 | **Key variables and sources in the employment module**

NAME OF VARIABLE	TYPE	SOURCES
O&M employment per MW of thermal capacity	Time series	Rutovitz and Atherton (2009), national statistics and sector-specific studies
O&M employment per MW of hydropower capacity	Time series	
O&M employment per MW of RE capacity	Time series	
Employment per MW of thermal capacity	Time series	
Employment per MW of hydropower capacity	Time series	
Employment per MW of RE capacity	Time series	

Note: MW = megawatt; O&M = operations and maintenance; RE = renewable energy.

Source: Authors.

Employment from the energy sector is divided into employment from the construction of capacity and employment from the operation and maintenance of capacity. Figure A18 shows the variables that are used to calculate the employment that is generated by the energy sector. The variable electricity employment represents the sum of employment that is generated by construction and operations and maintenance per capacity type.

Construction employment is calculated by the following equation:

$$\textit{Construction employment} = \textit{power generation capacity under construction}_{\textit{[technology]}} * \textit{construction employment per}\ \text{megawatt of capacity}_{\textit{[technology]}} * \text{FRACTION OF CONSTRUCTION TAKING PLACE DOMESTICALLY}$$

The power generation capacity under construction is multiplied by a construction multiplier per megawatt of capacity and the fraction of construction taking place domestically. The fraction of local construction corrects for the manufacturing that is not generated domestically if power generation capacity is imported.

O&M employment is calculated by multiplying power generation capacity by the O&M employment per megawatt of capacity. The variables “construction employment per megawatt of capacity” and “O&M employment per megawatt of capacity” are time series variables that contain employment multipliers for each type of capacity.

Total O&M employment and total construction employment are the sum of the generated employment in O&M and the construction of capacity, respectively, for all capacity types. The variables “total thermal and nuclear employment,” “total hydropower employment,” and “total renewable employment” are indicator variables that provide an overview of the number of people employed based on capacity types.

CO_2e emissions

The CO_2e emissions module calculates countrywide CO_2 emissions from all sectors (Table A11). The module provides information about the development of CO_2e emissions over time and assesses policy impacts on CO_2e emissions per capita and the SCC.

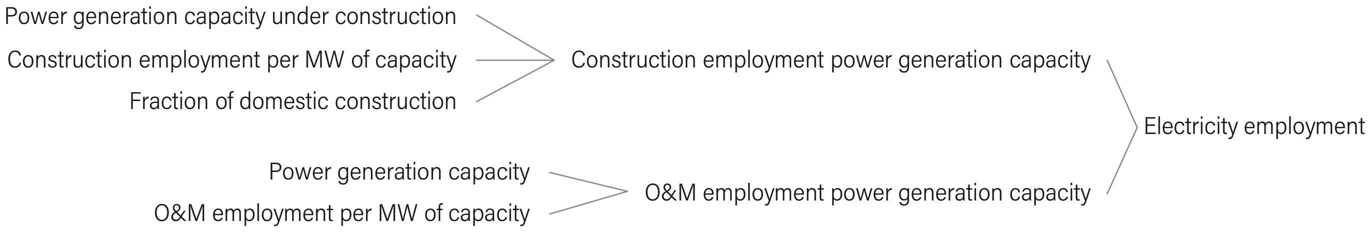
Table A11 | **Overview of data sources for the CO_2e emissions module**

NAME OF VARIABLE	TYPE	SOURCES
CO_2e emissions from energy (historical)	Time series	National GHG inventory and coefficients (if not available in the national inventory) from Intergovernmental Panel on Climate Change and United Nations Framework Convention on Climate Change GHG inventory guidance
CO_2e emissions from industry and waste (historical)	Time series	
CO_2e emissions from land use (historical)	Time series	
CO_2e emissions from livestock (historical)	Time series	
CO_2e emissions from managed soils (historical)	Time series	
CO_2e emissions from waste (historical)	Time series	
Total CO_2e emissions (historical)	Time series	
CO_2e emissions per capita (historical)	Time series	

Note: Actual sources may change from country to country, depending on the availability in national databases, core focus areas of the model, and the level of detail of the model in such areas. CO_2e = carbon dioxide equivalent; GHG = greenhouse gas.

Source: Authors.

Figure A18 | **Causes tree for electricity employment**

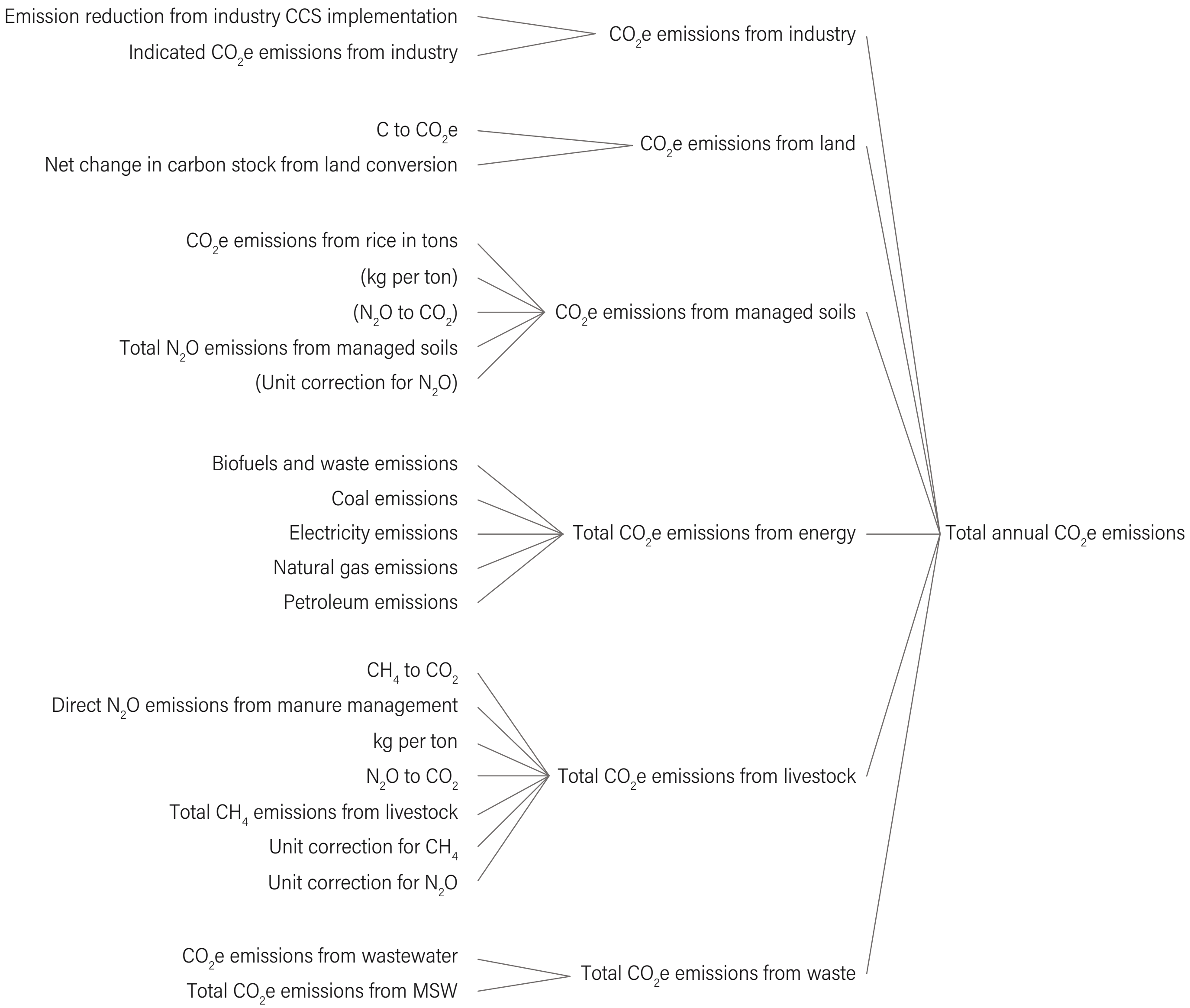


Notes: MW = megawatt; O&M = operations and maintenance.

Source: Authors.

Total annual CO_2e emissions are calculated as the sum of emissions from energy, industry, livestock, managed soils, LULUCF, and waste. The variables underlying the calculation of total and sectoral CO_2e emissions are illustrated in the causes tree in Figure A19.

Figure A19 | **Causes tree for total CO_2e emissions**



Notes: CCS = carbon capture and storage; CH_4 = methane; CO_2e = carbon dioxide equivalent; kg = kilogram; MSW = municipal solid waste; N_2O = nitrous oxide.

Source: Authors.

Emissions from industry are calculated based on the indicated CO_2e emissions from industry and the emission reduction assumed from carbon capture and storage (CCS).

CO_2e emissions from industry =
indicated CO_2e emissions from industry – emission reduction from industry CCS implementation

Indicated CO_2e emissions from industry are calculated based on industrial real GDP and an emissions intensity per unit of industry real GDP.

Indicated CO_2e emissions from industry =
*IF THEN ELSE (LOW IMPACT DEVELOPMENT POLICY SWITCH = 1, real GDP industry * INDUSTRY EMISSIONS PER UNIT OF INDUSTRY REAL GDP(time) * (1 – LCD EMISSION REDUCTIONS FROM IMPROVED PROCESSES TABLE(time)), IF THEN ELSE (LOW IMPACT DEVELOPMENT POLICY SWITCH = 2, real GDP industry * INDUSTRY EMISSIONS PER UNIT OF INDUSTRY REAL GDP(time) * (1 – NZE EMISSION REDUCTIONS FROM IMPROVED PROCESSES TABLE(time)), real GDP industry * INDUSTRY EMISSIONS PER UNIT OF INDUSTRY REAL GDP(time)))*

The IF THEN ELSE function is used to allow for the simulation of policies that would reduce emissions from industry and waste to assess their impacts on total CO_2e emissions. *LCD* refers to "low carbon development" and *NZE* refers to "net zero emissions." If the policy switch is active, the model will simulate a reduction in industry and waste emissions intensity, depending on the scenario simulated. This reduction is a policy input and will be informed by national plans related to reducing emissions from the industrial sector.

CO_2e emissions from energy are calculated as the sum of emissions generated across all sectors through the use of energy (see "Energy demand"); included fuels are coal, petroleum, natural gas, electricity, and biomass. The sum of emissions across all energy uses and electricity production systems yields the total CO_2e emissions from energy.

Total CO_2e emissions from energy =
(SUM(coal emissions$_{[sector!]}$) + SUM(electricity emissions$_{[sector!]}$) + SUM(natural gas emissions$_{[sector!]}$) + SUM(petroleum emissions$_{[sector!]}$) + SUM(biofuels and waste emissions$_{[sector!]}$))

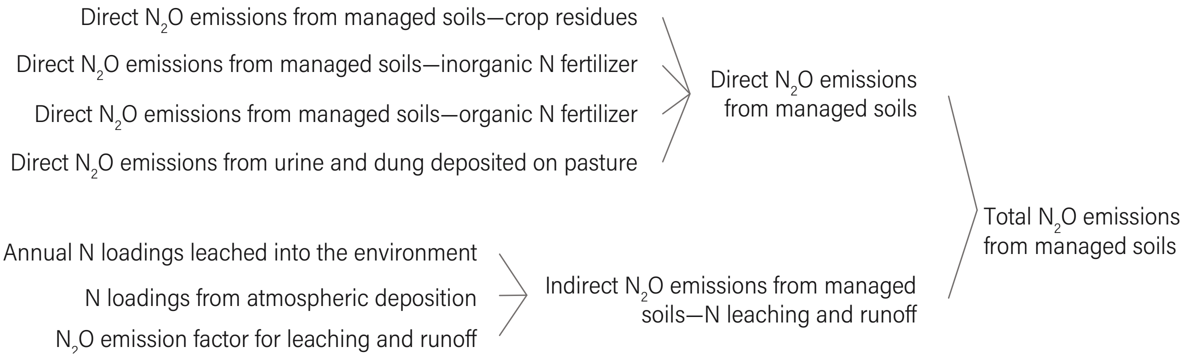
GHG emissions from livestock and managed soils are calculated based on livestock and related manure management as well as fertilizer application. Emissions from livestock are estimated as the sum of methane (CH_4) emissions from enteric fermentation and manure management and direct nitrous oxide (N_2O) emissions from manure management.

Total CO_2e emissions from livestock =
*(direct N_2O emissions from manure management * N_2O TO CO_2 / UNIT CORRECTION FOR N_2O + total CH_4 emissions from livestock * CH_4 TO CO_2 / UNIT CORRECTION FOR CH_4) / KG PER TON*

GHG emissions from managed soils are calculated as the sum of emissions from managed soils and CO_2 emissions from limestone and urea application and N_2O emissions from managed soils. The causes tree in Figure A20 illustrates the variables used to calculate CO_2e emissions from managed soils.

Total annual CO_2e emissions serve to calculate the CO_2e emissions per capita and the country-level SCC. CO_2e emissions per capita are calculated by dividing total CO_2e emissions by population. The SCC at the country level is based on total CO_2e emissions and the SCC

Figure A20 | **Causes tree for the total N_2O emissions from managed soils**



Notes: N = nitrogen; N_2O = nitrous oxide.

Source: Authors.

per ton of carbon emitted (Nordhaus 2017). GEM does not assume an escalation of SCC as proposed by Nordhaus (2017), indicating that the SCC per ton of CO_2e emitted remains constant at US$31 per ton throughout the simulation.

$$\textit{Annual social cost of carbon} = \textit{total annual } CO_2\textit{e emissions} * \textit{SOCIAL COST OF CARBON PER TON OF } CO_2\textit{E} * \textit{EXCHANGE RATE US\$ TO LCU}$$

Emissions from LULUCF are calculated based on the results for land conversion in the aggregate land-use module as well as policies related to land, such as reforestation or forest restoration. The approach used is based on the IPCC's "change in carbon stock" approach (IPCC 2006a). Using this approach, the difference in carbon stock resulting from land conversion on a year-to-year basis is converted into CO_2e emissions using a conversion factor. Furthermore, the implementation of sustainable agriculture practices is projected to increase carbon sequestration from land, meaning that it is added to the equation.

$$CO_2\textit{e emissions from land} = \textit{net change in carbon stock from land conversion} * -1 * \textit{C to } CO_2\textit{e} - \textit{additional sequestration from sustainable agriculture}$$

The causes tree presented in Figure A21 below illustrates the variables used for calculating total emissions from land.

Roads

The roads module provides information about the size of the total road network as well as additional construction and ongoing maintenance activities (Table A12).

The roads module provides information about the current road network and the costs of road construction. The module contains the two stocks that keep track of the total kilometers of roads under construction and the total kilometers of roads (Table A13).

Table A12 | **Overview of data sources for the roads module**

NAME OF VARIABLE	TYPE	SOURCES
Kilometers of road	Time series	World Bank World Development Indicators or spatial maps with primary, secondary, and tertiary roads

Note: Actual sources may change from country to country, depending on the availability in national databases, core focus areas of the model, and the level of detail of the model in such areas.

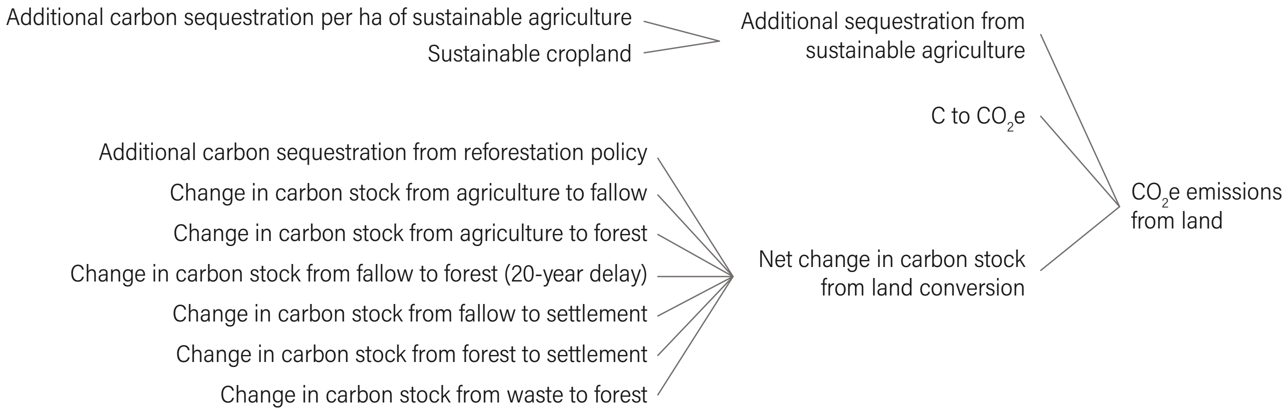
Source: Authors.

Table A13 | **Stocks under the roads module**

STOCK	INFLOWS	OUTFLOWS
Roads under construction	Road construction starts	Road completion
Total kilometers of roads	Road completion	Road disruption

Source: Authors.

Figure A21 | **Causes tree for CO_2e emissions from land**



Notes: C= carbon; CO_2e = carbon dioxide equivalent.

Source: Authors.

The road construction rate increases the kilometers of road under construction and depends on the current and desired size of the road network.

Road construction starts =
MAX(0, desired road network – total kilometers of roads + roads disruption)

The difference between the size of the desired road network and the total kilometers of roads that are already established assesses whether there is an infrastructure gap. The MAX function is used to ensure that there is no artificial reduction in infrastructure if the current road network is larger than the desired road network. In this case, infrastructure is assumed to be phased out at the end of its lifetime.

The total kilometers of roads increases based on the road completion rate and is reduced by the disruption of roads. The road completion rate is calculated by dividing the stock of roads under construction by the construction time for roads. The disruption of roads is calculated by dividing the total kilometer of roads by the average lifetime of roads.

Road density, indicated in kilometers per hectare, is calculated by dividing the total kilometers of roads by the total land in hectares. It serves to calculate the relative kilometers of roads per hectare.

Relative kilometers of roads per hectare =
kilometers of roads per hectare / INITIAL KILOMETERS OF ROADS PER HECTARE

The initial kilometers of roads per hectare represents the road density in the beginning of the simulation. The relative kilometers of roads therefore serves as an indication for whether the road network increases or decreases and affects the average cost per kilometer of road.

Average roads cost per kilometer =
*INITIAL ROADS COST PER KILOMETER * EFFECT OF ROADS DENSITY ON ROADS COST TABLE(relative kilometers of roads per hectare)*

The average cost per kilometer of roads is calculated based on the initial cost per kilometer and the effect of road density on road costs, which is a table function based on the relative kilometer of roads. The table function gradually adjusts the road costs based on whether road density increases or decreases compared to its initial value.

The module further provides information about the costs of road construction and maintenance. The total road construction costs are calculated by multiplying the road construction rate by the average cost per kilometer of road. Road maintenance costs are calculated based on the stock of total kilometer of roads and a road maintenance cost per kilometer multiplier.

Road maintenance cost =
*total kilometers of roads * ROADS MAINTENANCE COST PER KILOMETER*

Air pollution from energy consumption

GEM estimates the occurrence of air pollutants from final domestic energy consumption. In total, GEM estimates 11 pollutants across energy sources and sectors. The emission factors were obtained from the emission factor database of the LEAP Integrated Benefits Calculator (IBC).[37] The following air pollutants are considered in GEM:

- Carbon dioxide (CO_2)
- Carbon monoxide (CO)
- Nitrogen oxides (NO_x)
- Non-methane volatile organic compounds (NMVOC)
- Methane (CH_4)
- Particulate matter ≤ 10 micrometers (μm) (PM_{10})
- Particulate matter ≤ 2.5 μm ($PM_{2.5}$)
- Black carbon
- Organic carbon
- Ammonia (NH_3)

Air pollutants for energy consumption and power generation are calculated separately. Air pollutants from final energy consumption are calculated by multiplying total final energy demand (by fuel source) by a respective emission factor by type of fuel and sector. For example, PM_{10} emissions from biomass use, for each sector considered, are calculated by the following equation.

$$PM_{10}\ \textit{emissions from biomass}_{[sector]} =$$

$$\textit{normalized biofuels and waste demand}_{[sector]} * \textit{PM10 EMISSIONS PER TJ OF BIOMASS BY SECTOR}_{[sector]} / \textit{KILOGRAM PER TON}$$

The same approach is used for all other fuel types (coal, petroleum, natural gas), if historical data on fuel use is available. Air pollutants from power generation are calculated by multiplying the fuel used for the generation of electricity by a respective emissions per TJ of fuel used multiplier.

$$\textit{fuel use for power generation in TJ}_{[power\ generation\ technology]} = \textit{fuel use per megawatt-hour by technology new}_{[power\ generation\ technology]} * \textit{electricity generation rate}_{[power\ generation\ technology]}$$

The emission factors used to estimate air pollutants from energy consumption and power generation are summarized in Table A14.

Table A14 | **Overview of air pollution multipliers for energy consumption and power generation**

FUEL TYPE/SECTOR	CO_2	CO	NO_X	NMVOC	CH_4	PM_{10}	$PM_{2.5}$	BLACK CARBON	ORGANIC CARBON	N_2O	NH_3
	TON/TJ	KG/TJ									
Coal											
Residential	94.6	2,610	34	484	300	490.1	440.4	72.85	196.4	0	38.74
Commercial	94.6	931	173	88.8	10	117	108	6.9	5.2	1.5	0.0093
Industry	94.6	931	173	88.8	10	117	108	6.9	5.2	1.5	0.0093
Transport	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Petroleum											
Residential	67.46	93	306	20	10	21	18	10.1	2.89	1.51	0.108
Commercial	74.1	130	942	50	10	96	96	40	28	0.6	0.168
Industry	74.1	66	513	25	3	20	20	11.2	3.6	0.6	0.154
Transport	69.3	5,808	644.2	741.81	33	161.64	161.64	9.27	116.38	3.2	31.03
Natural gas											
Residential	56.1	26	51	1.9	5	1.2	1.2	0.065	0.54	0.1	0.181
Commercial	56.1	29	74	23	5	0.78	0.78	0.03	0.26	0.942	1.214
Industry	56.1	29	74	23	1	0.78	0.78	0.03	0.26	0.1	1.214
Transport	56.1	271.7	543.48	12.14	92	0.725	0.725	0.036	0.326	2.72	N/A
Biofuels and waste											
Residential	95.6	4,753	134.6	1,654	300	512.35	409.88	51.24	178.4	134.57	53.7
Commercial	112	570	91	300	300	143	140	39.2	72	4	37
Industry	112	570	91	300	30	143	140	39.2	72	4	37
Transport	79.6	5,808	51	0.69	18	1.9	1.9	0.16	0	0	0
Power generation (by fuel type)											
Fuel and diesel oil	77.4	15.1	142	2.3	3	25.2	19.3	0.957	0.359	0.6	0.101
Cogeneration	77.4	15.1	142	2.3	3	25.2	19.3	0.957	0.359	0.6	0.101
Natural gas	565.1	39	89	2.6	1	0.89	0.89	0.022	0.022	0.1	1.829
Coal	96.1	8.7	247	1.4	1	7.9	3.2	0.083	0.167	1.5	0.012
Waste incineration	91.7	90	81	7.31	30	155	133	1.444	0.222	4	0.222

Notes: CH_4 = methane; CO = carbon monoxide; CO_2 = carbon dioxide; kg = kilogram; N/A = not applicable; NH_3 = ammonia; NMVOC = non-methane volatile organic compounds; NO_X = nitrogen oxides; N_2O = nitrous oxide; PM = particulate matter; TJ = terajoule.

Source: Authors.

Cost of air pollution

The cost of air pollution from power generation (documented above) is used to calculate the total cost of pollution by capacity type and the total cost of pollution from power generation. The variables used to calculate the total cost of pollution from power generation are presented in Figure A22, which was drawn from GEM-Vietnam.

Considered are the costs of $PM_{2.5}$, sulfur dioxide (SO_2), and NO_x emissions. The respective number of emissions, by emitting capacity type, is multiplied by an average dollar value of emissions. The equation used to calculate the total cost of $PM_{2.5}$ emissions is illustrated below.

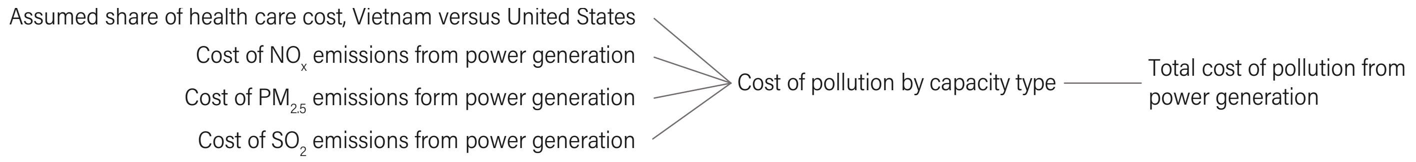
Cost of $PM_{2.5}$ *emissions from power generation*$_{\text{[power generation technology]}}$ = *"*$PM_{2.5}$ *emissions from power generation"*$_{\text{[power generation technology]}}$ ** "total dollar value (mortality and morbidity) per ton of directly emitted* $PM_{2.5}$ *(US\$2010 7 percent discount rate)"*

To calculate the cost of pollution by capacity type in the case of GEM-Vietnam, the cost of the three pollutants is summed up and multiplied by a differential that accounts for the difference in health care costs between the United States and Vietnam because the valuation multipliers are obtained from a study in the United States (EPA 2013). The total cost of power generation is then used as an input to the impact of carrying capacity on TFP in the industry and services modules.

Estimation of policy costs

GEM also forecasts the costs related to implementing low-carbon development policies. The causes tree in Figure A23 presents the variables that were used to calculate the total cost of low-carbon interventions for GEM-Ethiopia.

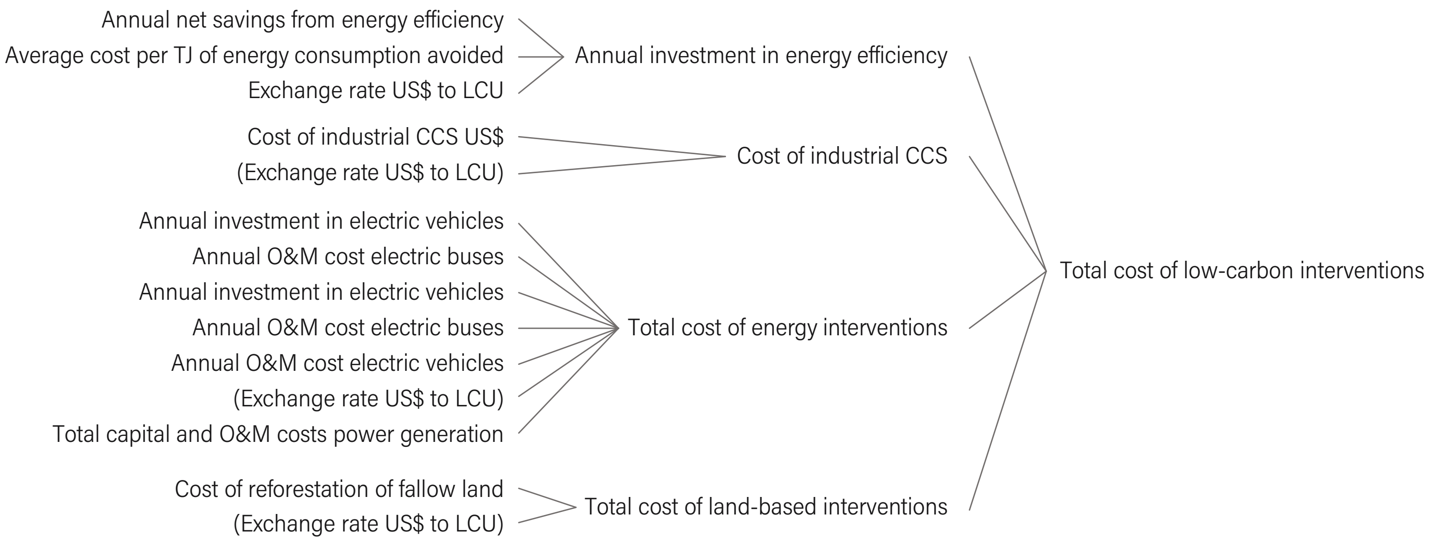
Figure A22 | **Causes tree for total cost of pollution from power generation**



Notes: NO_x = nitrogen oxides; PM = particulate matter; SO_2 = sulfur dioxide.

Source: Authors.

Figure A23 | **Causes tree for total cost of low-carbon interventions (GEM-Ethiopia)**



Notes: CCS = carbon capture and storage; LCU = local currency unit; O&M = operations and maintenance; TJ = terajoule.

Source: Authors.

Cost of energy efficiency

The annual investment in energy efficiency represents investments in energy efficient equipment to achieve the envisaged energy efficiency gains. It is calculated by multiplying the annual reductions in energy demand by an average cost per TJ of energy consumption avoided.

*Annual investment in energy efficiency = MAX(annual net savings from energy efficiency * AVERAGE COST PER TJ OF ENERGY CONSUMPTION AVOIDED,0)*[EXCHANGE RATE [if relevant]]*

The annual net savings are calculated by comparing the total energy demand of the policy scenario to the total energy demand in the baseline scenario. Given that the energy efficiency gains from introducing EVs are already reflected in the total energy demand of the policy scenario, and that related costs are calculated separately, they are deducted from the calculation of savings achieved from the introduction of energy efficiency measures. This is illustrated in the equation below.

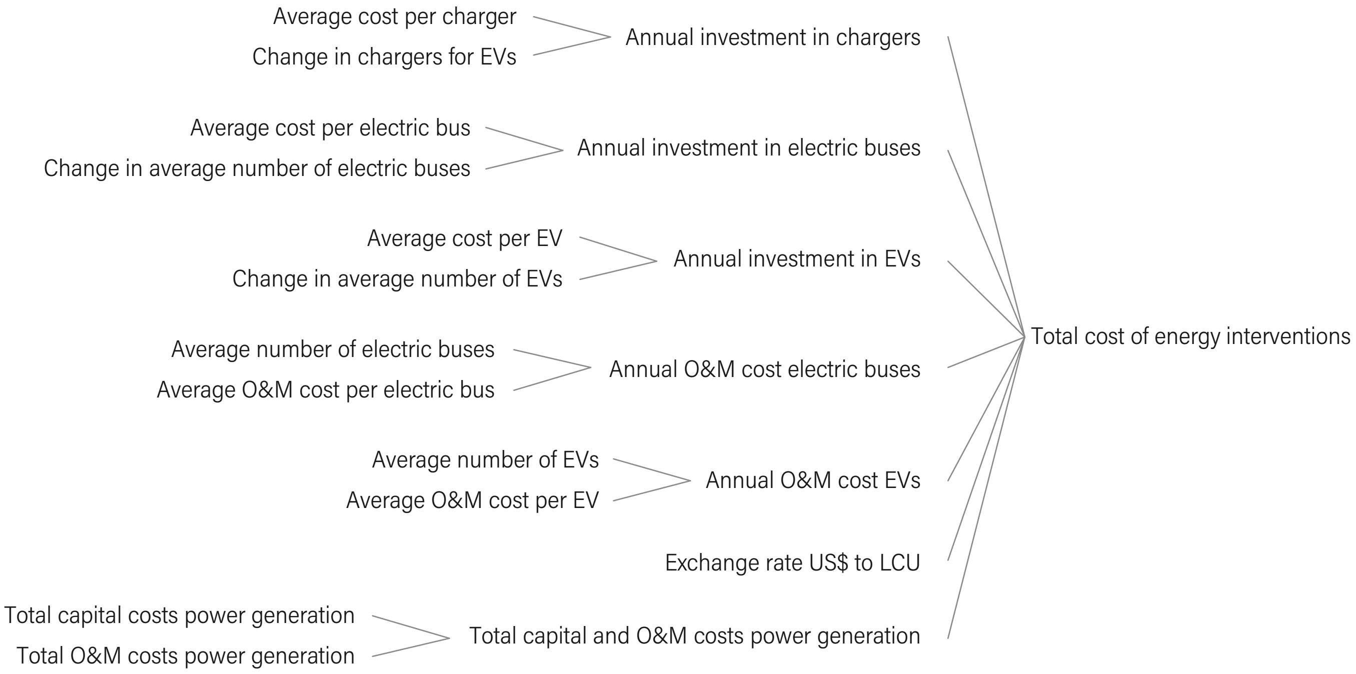
Cumulative net savings from energy efficiency = BASELINE total indicated country energy demand – (total indicated country energy demand + energy use avoided through efficiency gained via electrification)

Cost of energy interventions

The cost of energy interventions considers the costs related to vehicle fleet electrification and the costs incurred by changes in the power generation sector. The costs considered to calculate the total cost of energy interventions, as well as the underlying drivers determining the costs, are presented in the causes tree in Figure A24, which demonstrates the module application in GEM-Ethiopia.

Though the unit cost of technology is defined exogenously, the learning curves and cost reductions over time are considered and gathered from the IEA (e.g., from the WEO or other relevant sources). The cost of technology declines over time in GEM, such as for EVs that reach cost parity by 2030 at the latest. We use this approach because the analysis with GEM is performed at the national level, but technological progress is affected by global dynamics (e.g., the cost

Figure A24 | **Causes tree for the total cost of energy interventions (GEM-Ethiopia)**



Notes: EV = electric vehicle; LCU = local currency unit; O&M = operations and maintenance.

Source: Authors.

reduction of EV manufacturing is primarily driven by global demand and global production of EVs rather than by national trends). If we were to drive technological progress based on installed capacity in a given country, especially a small one where there is uncertainty about whether local production capacity will be introduced, it would likely result in an incorrect (and underestimated) forecast. This is the reason why global studies that forecast low-carbon transitions, for example, are better suited for the initial parametrization of GEM. In addition, alternate simulations are often created to test the sensitivity of the model to changing cost assumptions, with more or less aggressive cost reduction relative to the IEA or other organizations.

The total cost of power generation is calculated as the sum of total capital costs and total O&M costs from power generation. Capital investment for power generation is calculated by multiplying the net construction rate for each power generation technology by the respective cost per megawatt of capacity. The total O&M costs of power generation are the sum of O&M expenditure across all capacity types, which is calculated by multiplying installed capacity by technology by a respective O&M cost per megawatt of capacity multiplier.

"Total capital and O&M costs power generation" =
total capital costs power generation + "total O&M costs power generation"

The residual components of the total cost of energy interventions are related to transport sector electrification. For EVs and electric buses, the annual investment and the annual O&M costs are considered, but for chargers, only capital investment is assumed. The investment costs of vehicles are calculated by multiplying the change in the number of vehicles or buses, calculated as the net addition in vehicles on a year-by-year basis, by a capital cost per EV or bus, respectively. The equation used to calculate the annual investment in EVs serves for illustration purposes.

Annual investment in EVs =
*average cost per EV * change in average number of EVs*

The O&M cost for EVs and buses is calculated by multiplying the estimated number of EVs and buses by a respective O&M cost multiplier.

"Annual O&M cost EVs" =
*average number of EVs * "average O&M cost per EV"*

Cost of industrial CCS

The cost of industrial CCS is calculated based on the amount of emissions avoided by implementing CCS practices and an average cost per ton of emissions avoided. Given that the cost multiplier applies to the absolute amount of emissions avoided, the annual cost of industrial CCS is calculated using a delay function that compares the total cost of each time step to the total cost of the last time step, yielding the annual cost of CCS interventions.

Cost of industrial CCS US$ =
MAX(0, cumulative cost of industrial emission reduction with CCS-delayed cost of emission reduction with CCS)

A MAX function is used to ensure that no artificial savings occur in case industrial processes and product use (IPPU) emissions are higher in the policy scenario despite the implementation of CCS practices. The cumulative cost of industrial emission reduction with CCS is calculated by multiplying the total emission reduction by the average cost per ton of emissions avoided.

Cumulative cost of industrial emission reduction with CCS =
*IPPU emission reduction via CCS * CCS cost per ton of* CO_2 *avoided*

Total cost of land-based interventions

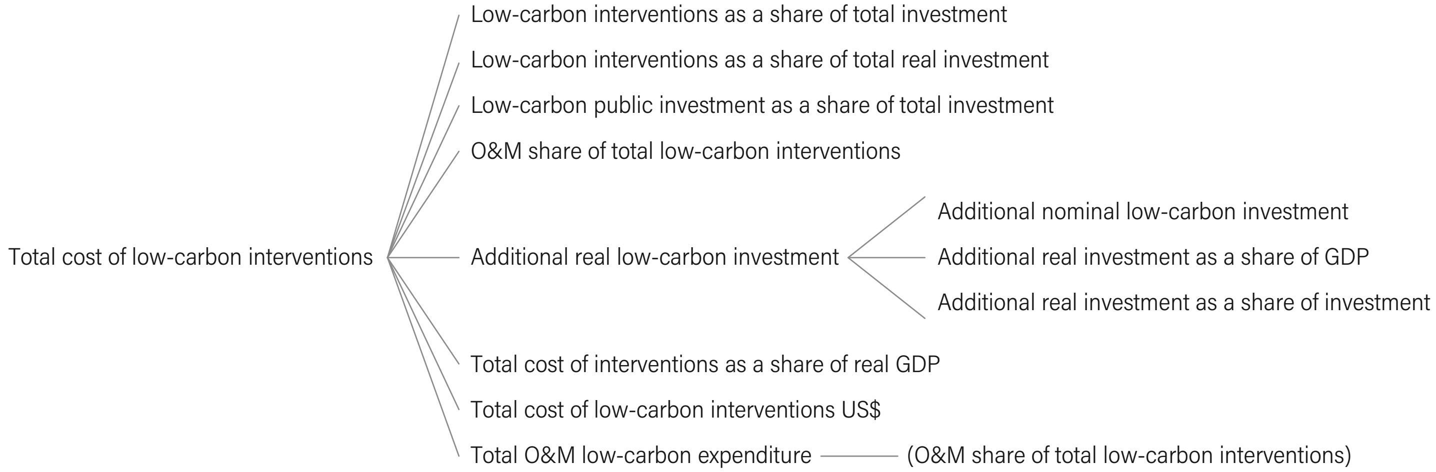
The total cost of land-based interventions is equal to the cost of reforestation. The cost of reforestation is calculated based on the additional reforestation that occurs in the policy scenarios and the average cost of reforestation.

Cost of reforestation of fallow land =
*reforestation * AVERAGE COST OF REFORESTATION*

Macroeconomic indicators related to the cost of decarbonization

The total cost of low-carbon interventions is used to estimate a number of output indicators, such as the share of low-carbon interventions in total investment; the share of GDP; or the additional low-carbon investment relative to the baseline, both in nominal and real terms. The uses tree for the total cost of low-carbon interventions shows the indicators that are calculated (Figure A25).

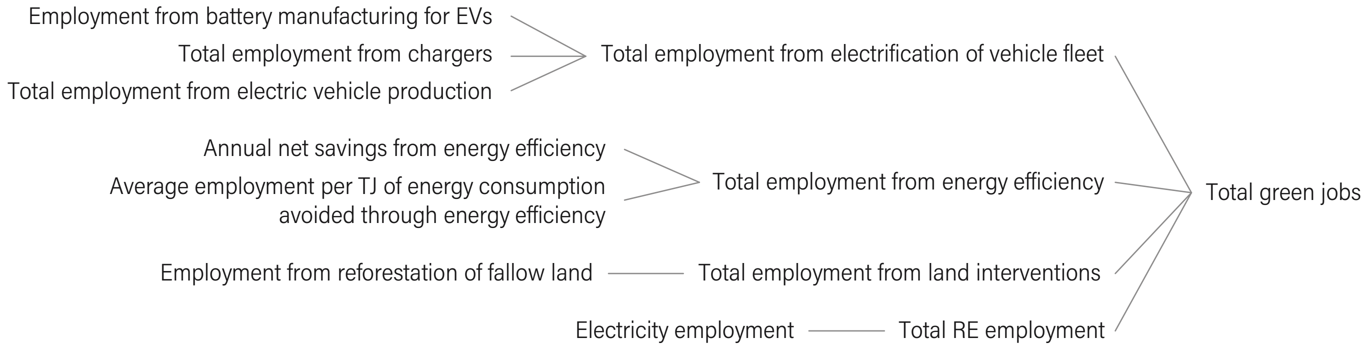
Figure A25 | **Uses tree for the total cost of low-carbon interventions**



Notes: GDP = gross domestic product; O&M = operations and maintenance.

Source: Authors.

Figure A26 | **Causes tree for total green jobs**



Notes: EV = electric vehicles; RE = renewable energy; TJ = terajoule.

Source: Authors.

Green jobs

In addition to estimating the costs for low-carbon interventions, GEM also estimates the employment resulting from decarbonization. The variables considered to calculate total green jobs are presented in Figure A26 in the form of a causes tree. The equation for total green jobs is presented at right.

$$\text{Total green jobs} = \text{total employment from electrification of vehicle fleet} + \text{total employment from land interventions} + \text{total RE employment} + \text{total employment from energy efficiency}$$

The additional number of green jobs resulting from the implementation of decarbonization interventions is calculated by comparing the number of green jobs in the policy scenarios to the baseline number of green jobs that are already present in the baseline scenario. This module also considers and estimates job loss from conventional energy generation. The cost of reskilling can also be built in, if it is a desired intervention to examine.

Additional green jobs =
total green jobs – BASELINE green jobs

Employment from energy efficiency

The employment resulting from improving energy efficiency is calculated based on the annual net savings from energy efficiency and the average employment per TJ of energy consumption avoided through energy efficiency.

Total employment from energy efficiency =
*annual net savings from energy efficiency * AVERAGE EMPLOYMENT PER TJ OF ENERGY CONSUMPTION AVOIDED THROUGH ENERGY EFFICIENCY*

The annual net savings from energy efficiency represents the annual reductions in energy demand achieved by implementing energy efficiency measures. It is the same variable that is used to calculate the cost of energy efficiency.

Employment from renewable energy

The employment from renewable power generation capacity is the sum of construction and O&M employment across all renewable capacity types considered.

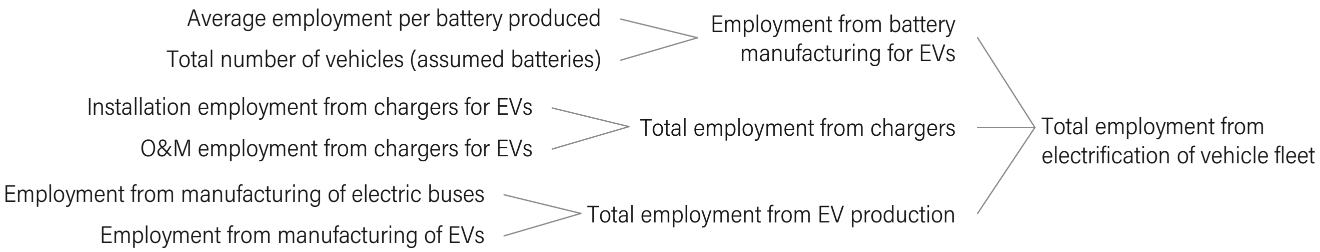
Total RE employment =
SUM(electricity employment[all renewables!])

The causes tree in Figure A18 above shows the variables that underlie the calculations for total electricity employment.

Employment from vehicle fleet electrification

The employment from electrifying the vehicle fleet considers the employment emerging from the manufacturing of EVs and buses, the employment generated from the installation and maintenance of chargers, and the employment from battery manufacturing for EVs (see Figure A27).

Figure A27 | **Causes tree for total employment from vehicle fleet electrification**



Notes: EV = electric vehicle; O&M = operations and maintenance.

Source: Authors.

Manufacturing employment from the production of EVs and buses is calculated by multiplying the annual change in the number of EVs and buses by a respective employment multiplier per unit produced. The following equation for employment from EV manufacturing serves for illustration purposes.

Employment from manufacturing of EVs =
*change in average number of EVs * AVERAGE EMPLOYMENT PER EV*

Employment from the installation and maintenance of chargers is calculated based on the change in chargers and the total number of installed chargers and a respective employment multiplier for the installation and maintenance of chargers.

The employment from battery manufacturing for EVs is calculated based on the total number of vehicles, which is assumed to be equivalent to the number of batteries that need to be manufactured and the average employment per battery produced.

Employment from battery manufacturing for EVs =
*"total number of vehicles (assumed batteries)" * AVERAGE EMPLOYMENT PER BATTERY PRODUCED*

Employment from land-based interventions

Employment from land-based interventions is equivalent to the employment that emerges from the additional reforestation of fallow land that is envisaged in the policy scenarios. Employment from reforestation is calculated by multiplying the amount of fallow land reforested by an average employment multiplier per hectare of reforestation.

Employment from reforestation of fallow land =
*Reforestation * AVERAGE JOB PER HECTARE OF REFORESTATION*

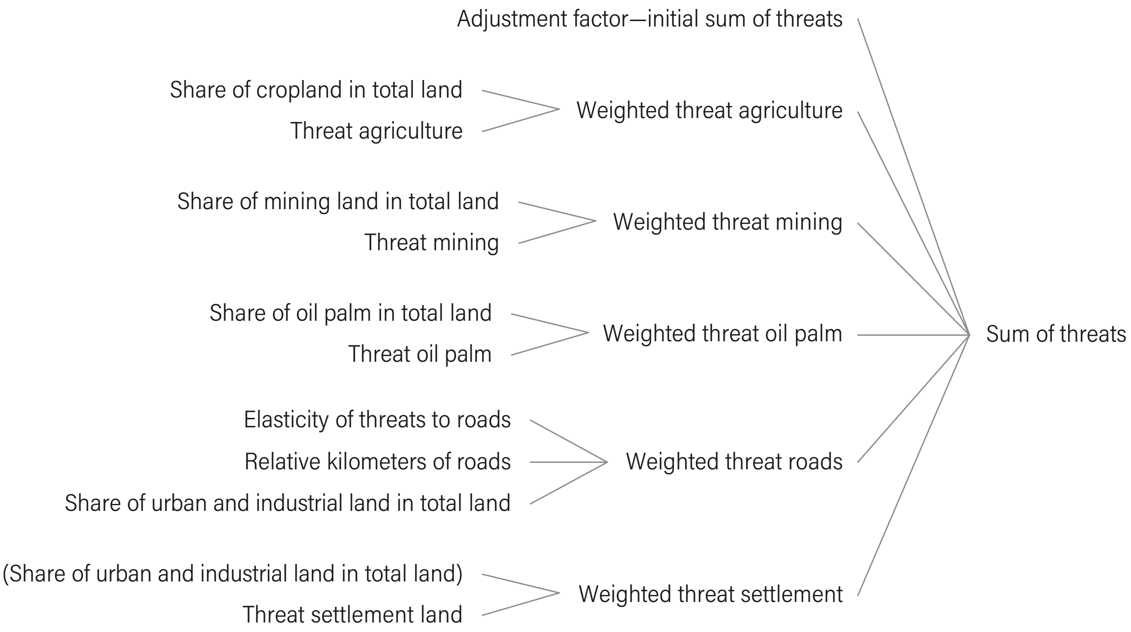
Habitat quality

The habitat quality module calculates the habitat quality indicator and provides insights into the threats affecting habitat quality. The habitat quality indicator is calculated based on initial habitat quality and the effect of threats on habitat quality.

Habitat quality =
*INITIAL HABITAT QUALITY * (1 – effect of threats on habitat quality)*

The effect of threats is calculated based on the relative sum of threats compared to the sum of threats in the initial year of the simulation. The causes tree in Figure A28, drawn from GEM-Indonesia, provides an overview of the threats to habitat quality considered in the model, which include factors specifically relevant to Indonesia's low-carbon development, such as oil palm plantations. An adjustment multiplier is applied to the sum of threats to ensure that the values are aligned with the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST®) suite of tools.

Figure A28 | **Causes tree for sum of threats to habitat quality (GEM-Indonesia)**



Source: Authors.

All threats are weighted according to their threat values and the share of land used by each of the land-use categories that provide a threat to habitat quality. The equation used to calculate the weighted threat from agriculture is presented below.

Weighted threat agriculture =
*THREAT AGRICULTURE * share of cropland in total land*

Spatial assessment of habitat quality

InVEST® is used to assess ecosystem services supply. This enhances the outputs generated by the spatial dimension and supports analyzing how different development trajectories affect the provisioning of ecosystem services in the medium and longer term (Natural Capital Project 2023). For GEM assessments, the habitat quality (HQ) model and its results are used as a proxy for the integrity of landscapes and hence their ability to also provide ecosystem services in the future.

This section describes the results of incorporating the outcomes of the spatial assessment into GEM. For this analysis, the HQ index was included into GEM and calibrated to match the projections generated using InVEST. The HQ index is assumed as an input to the TFP equation, so that changes in habitat quality automatically affect industry and services real GDP. To include the HQ index and its impacts on productivity, information must be exchanged between GEM and the HQ model to ensure that model outputs are aligned.

The first step involves the use of historical geographic information system (GIS) databases, which contain land-use and land-cover data for various years, and the InVEST HQ model. Using InVEST, the HQ score for a selected past GIS data is estimated, starting with the GIS from which the land cover is taken to initialize the different land-use stocks in GEM. Typically, GIS data are available for every five years; hence, assuming a 2005 base year, additional InVEST HQ scores would be estimated for 2010, 2015, and the latest data point available (e.g., 2018). Based on the evolution of the past HQ score between the different years, the HQ index (2005 = 1) is calculated for 2010, 2015, and 2018. The HQ index is therefore an indicator of the evolution of relative HQ as a consequence of land-use changes over time.

GEM contains a simplified structure of the HQ calculations that are performed using the InVEST model, which also forecasts the evolution of the HQ index based on land-use changes. The HQ index generated using past GIS data and the InVEST HQ model are used to validate that the changes in HQ forecast by GEM align with the forecasts generated by spatial data.

Subsequently, future land cover data obtained from GEM is used to create a land-use transfer matrix that indicates how land use by land-use class has changed between the last historical data point and the final year of the simulation(s). In conjunction with the InVEST scenario generator, this land-use transfer matrix creates an artificial future GIS that corresponds to the state of the landscape if land conversion is implemented as forecast by GEM. This future GIS is then input into the InVEST HQ model to generate the HQ score for the future landscape (usually for the year 2050 or 2070). Once estimated, the HQ score of the future landscape is used to calculate the HQ index for the final year of the simulation, still with 2005 as the base year. This (future) index score provides insight into how the index score in GEM, given the land-use change forecast, needs to change by 2050 and is hence used to calibrate the HQ index in GEM. The process of generating a future GIS and calculating the future HQ score is repeated for all scenarios simulated to ensure that future HQ index values can be calibrated in alignment with InVEST forecasts.

Micro-macro module

The micro-macro module provides a point of connection between the macrosimulations generated by GEM (considering impacts on GDP and income as well as employment creation) and the microsimulations used to assess specific impacts of policy implementation on households (e.g., by age cohort, skill group, and job type). In previous (unpublished) exercises for India and Vietnam, GEM scenarios were used as inputs for country-specific global income distribution dynamics models, originally developed by the World Bank (Bourguignon et al. 2008; Bussolo et al. 2012), to disaggregate the macroeconomic employment results.

No single model can effectively address micro- and macroeconomic dynamics and impacts of policy implementation while offering a cross-sectoral representation of the economy that is based on physical, human, social, and natural capital. This is the type of analysis that is needed to carry out a complete assessment of low carbon development strategies, which combine interventions across a variety of technologies and practices, sectors, and economic actors.

GEM's micro-macro module uses employment as a main input, disaggregated into agriculture, industry, and services employment and then further disaggregated into skilled and unskilled jobs for agriculture, skilled and unskilled jobs for industry, skilled and unskilled jobs for unsophisticated and sophisticated services, and skilled and unskilled jobs in public administration.

This further disaggregation is performed using data from household surveys, which offer an initial breakdown by sector. It is expected, however, that the amount of skilled and unskilled labor changes over time, toward an increase of the former, especially in the industrial and services sectors. To capture this change, an index of "per capita disposable income" is used together with an elasticity, indicating that the more the country develops (using income as a proxy), the more will be the request for skilled jobs:

Share of skilled labor industry =
*MIN(1, 0.142471 *relative per capita real disposable income ^ ELASTICITY OF SKILLED LABOR INDUSTRY TO PER CAPITA DISPOSABLE INCOME)*

*skilled labor industry = employment industry * share of skilled labor industry*

The number in the equation (0.142471) is the initial share of skilled labor in the industrial sector, adjusted from data to capture the historical trend from the first year of the simulation. In other words, the value is reduced in the initial year of the simulation to make sure that the share matches the recent data obtained from the household survey (e.g., in the year 2020), taking into account the historical increase in per capita income.

The number of employed skilled and unskilled people is then used to estimate wages. The wage is calculated as a multiplication of number of people employed and the unit wage per year, based on the sector and skills (Figure A29).

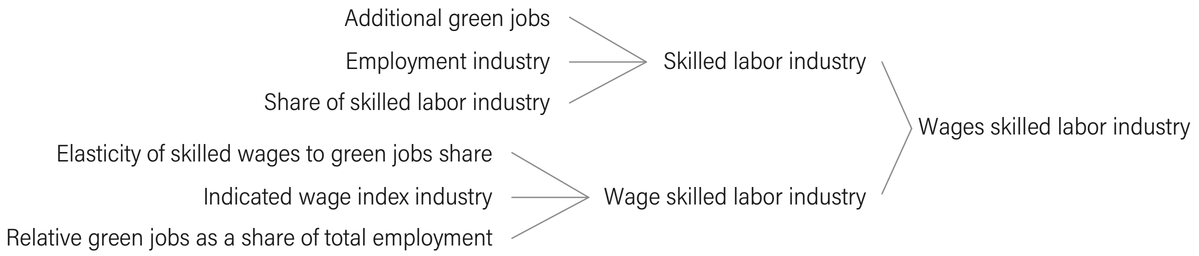
The individual wage level is estimated following these steps:

1. Data are used to obtain the current wage level.
2. A salary escalation is applied in GEM to capture differences between wages as reported in the data (e.g., from 2015) and current values (e.g., based on assumptions on a salary escalation trend). If data are from 2020 or 2021, and inflation has been very low, this adjustment may not be required.
3. An adjustment is applied to account for the labor demand/supply balance. In other words, in the case of labor force scarcity, wages are expected to be higher. Conversely, in a case of high unemployment, wages are expected to be lower than in a baseline scenario.
4. An adjustment is made to qualify whether labor shortages could emerge equally or differently in the agriculture, industry, services, and government sectors. This adjustment compares the annual rate of change in employment in the different sectors to determine if one or more of these is characterized by comparatively higher or slower growth.
5. An additional impact is applied for skilled jobs, using the forecast number of green jobs being created in the economy. In other words, if more green jobs are introduced, it is assumed that these are skilled jobs and will therefore command a wage premium over other, more traditional jobs.

As a result, wages are based on data that are affected by the strength of the labor market nationwide and in specific sectors and by the effort to create jobs that require new skills (in the specific case of GEM and net zero scenarios, these are green jobs).

The equation for the wage calculation is shown below. The number in the equation (9,263; Step 1 above) is the monthly wage obtained from data for skilled labor in the public sector. This is multiplied by 12 to obtain the annual wage per employee. The adjustment for green jobs is then applied (Step 5 above). The second equation shows the use of the adjustment in Step 4. In contrast, the tree diagram in Figure A30 shows the economy-wide labor market situation, capturing the adjustments in Steps 2 and 3.

Figure A29 | **Causes tree for estimating wages for a single sector and skill type**



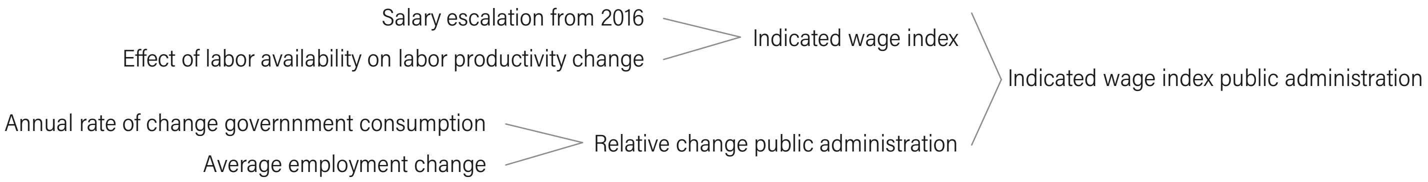
Source: Authors.

*Wage skilled labor public administration = 9,263 * 12 * indicated wage index public administration * relative green jobs as a share of total employment ^ ELASTICITY OF SKILLED WAGES TO GREEN JOBS SHARE*

*indicated wage index public administration = indicated wage index * relative change public administration*

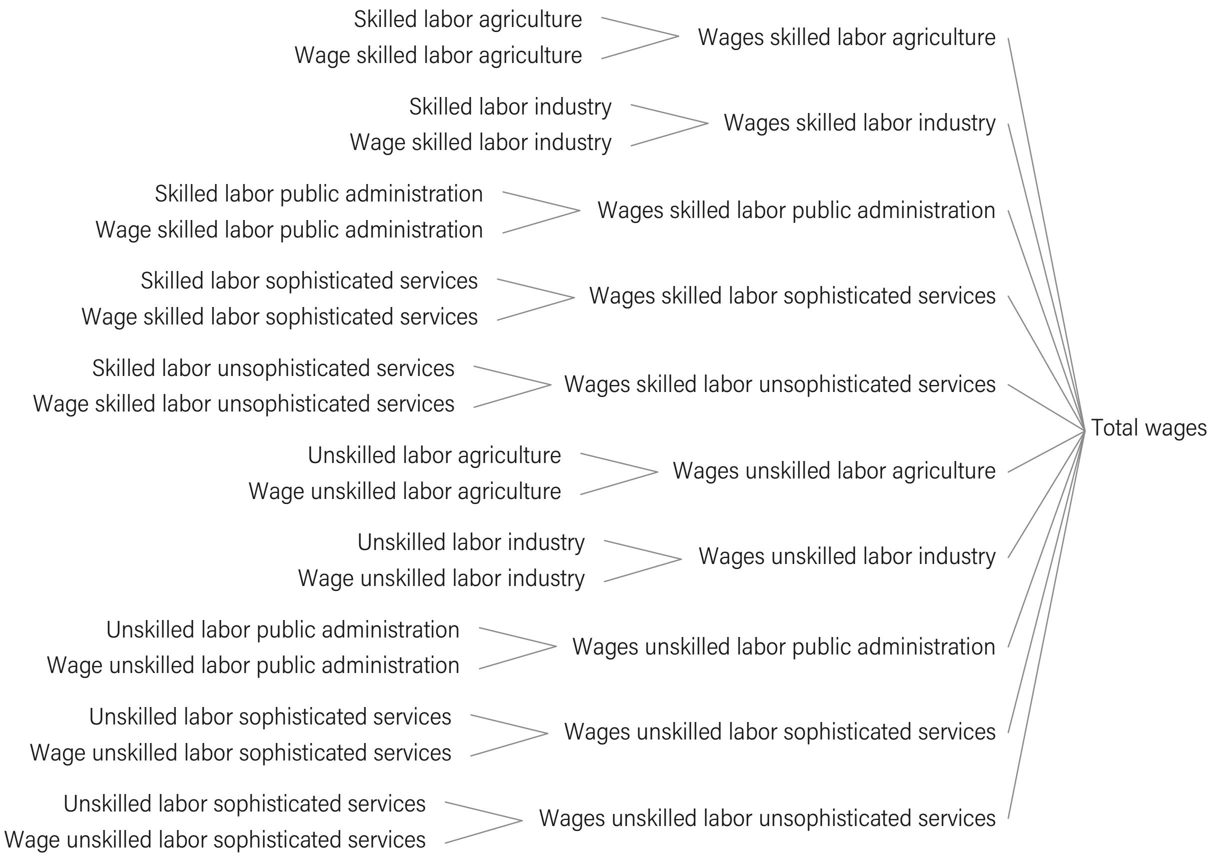
The total wages at the country level are then calculated as the sum of all annual wages (estimated as employment, multiplied by annual wage per person) for all people employed in the country across sectors and with different levels of skills (Figure A31).

Figure A30 | **Causes tree for the consideration of salary escalation and labor market dynamics in wage estimates for public administration jobs**



Source: Authors.

Figure A31 | **Causes tree for estimating total wages at the national level**



Source: Authors.

Climate impacts and climate policy effectiveness

As indicated in the previous sections, GEM is equipped with data on precipitation and temperature, obtained from the CDS. These are used to determine the probability of extreme weather events, such as flood and droughts, and for estimating the impact of weather conditions on various additional indicators (e.g., in relation to infrastructure).

Table A15 presents the climate change damage functions included in GEM, across a range of sectors and infrastructure assets. Examples include wind and flood damages on selected thermal and renewable power generation assets as well as the transmission network; heat; water scarcity and flood impacts on crop production; loss of livestock due to high temperature and heat stress impacts on livestock productivity (value added); flood damages to the total road network; and temperature impacts on total labor productivity, such as the impact of Wet Bulb Global Temperatures (WBGTs).

Time series functions were added to ensure that the damages to power generation, roads, crops, and buildings can be scaled according to the actual area at risk at the country level. This allows for a more nuanced simulation of climate damage impacts as well as related costs.

Concerning climate adaptation, the following intervention options are included in the model:

- Wind and flood protection measures for thermal and renewable power generation assets subject to climate change impacts, as well as for the transmission network
- Interventions to address heat- and flood-related impacts on crop production:
    - Drip irrigation to address water scarcity impacts
    - Practices for climate-resilient agriculture production to address water scarcity impacts
    - Net shading to address heat impacts on crop productivity
    - Drainage systems to address flood-related impacts
- Interventions to address the livestock-related impacts of heat stress (on cattle, pigs, and poultry):
    - Technology-based interventions, high cost and high efficiency
    - Nature-based interventions, low-to-medium cost and efficiency.
- Climate proofing of roads to reduce the impacts of floods (fewer kilometers of roads lost)
- Interventions to address heat impacts on labor productivity:
    - Air-conditioning of buildings (heating, ventilating, and air-conditioning component)
    - Retrofitting of buildings (improved insulation)
    - Greening of urban areas (to reduce overall average WBGT)
- Climate proofing of buildings to reduce flood damages

The investment required, and the impact on employment, is estimated for each of these intervention options. The investment is further integrated into the systemic CBA along with interventions for climate mitigation.

Table A15 | **Overview of climate impacts, related intensity, and potential reduction in damage probability**

SECTOR	SUBSECTOR	TYPE	HAZARD	INTENSITY THRESHOLD FOR HAZARD	INTENSITY UNIT	REDUCTION IN DAMAGE PROBABILITY	COST-BENEFIT RATIO
Power[a]	N/A	Thermal power plants	Extreme wind speed	100	mph	75%	3.00
Power[a]	N/A	Thermal power plants	Floods	99.5	Percentile of extreme wet (SPI)	100%	2.50
Power[a]	N/A	Hydropower plants	Floods	99	Percentile of extreme wet (SPI)	50%	1.67
Power[a]	N/A	Solar farms	Extreme wind speed	100	mph	60%	0.80

Notes: mph = miles per hour; SPI = Standardized Precipitation Index.

Source: a. Miyamoto International 2019

Table A15 | Overview of climate impacts, related intensity, and potential reduction in damage probability, continued

SECTOR	SUBSECTOR	TYPE	HAZARD	INTENSITY THRESHOLD FOR HAZARD	INTENSITY UNIT	REDUCTION IN DAMAGE PROBABILITY	COST-BENEFIT RATIO
Power[a]	N/A	Wind farms	Extreme wind speed	70	mph	50%	2.00
Power[a]	N/A	Nuclear power plants	Floods	99.5	Percentile of extreme wet (SPI)	30%	0.60
Power[a]	N/A	Electrical substations	Extreme wind speed	70	mph	67%	1.00
Power[a]	N/A	Electrical substations	Floods	99	Percentile of extreme wet (SPI)	100%	1.00
Power[a]	N/A	Transmission and distribution lines	Extreme wind speed	70	mph	77%	1.15
Transportation[b]	Road infrastructure	Highway bridges	Extreme wind speed	150	mph	60%	0.60
Transportation[b]	Road infrastructure	Highway bridges	Floods	99.9	Percentile of extreme wet (SPI)	60%	0.60
Transportation[b]	Road infrastructure	All roads	Floods	95	Percentile of extreme wet (SPI)	50%	1.67
Agriculture[c,d]	Crop	Various crops (corn, soybeans, cotton, other crops)	Change in temperature (trend)	30	Degrees Celsius	N/A	N/A
Agriculture[e,f,g]	Crop	N/A	Extreme wet	90	Percentile of extreme wet (SPI)	N/A	-0.5
Agriculture[e,f,g]	Crop	N/A	Extreme dry	90	Percentile of extreme dry (SPI)	N/A	10
Agriculture[e,f,g]	Crop	N/A	Extreme dry	90	Percentile of extreme dry (SPI)	N/A	1
Agriculture[e,f,g]	Crop	N/A	Extreme dry	90	Percentile of extreme dry (SPI)	N/A	3.19
Agriculture[h,i]	Livestock	Pigs	Extreme heat	90	Temperature percentile	81%	N/A
Agriculture[h,i]	Livestock	Pigs	Extreme heat	90	Temperature percentile	19%	N/A

Notes: mph = miles per hour; SPI = Standardized Precipitation Index.

Source: a. Miyamoto International 2019
b. Hallegatte et al. 2019
c. Schlenker and Roberts 2009
d. Tanny 2013
e. ECA 2009
f. Yu et al. 2014
g. Azumah et al. 2020
h. Schauberger et al. 2022
i. St-Pierre et al. 2003

Table A15 | **Overview of climate impacts, related intensity, and potential reduction in damage probability, continued**

SECTOR	SUBSECTOR	TYPE	HAZARD	INTENSITY THRESHOLD FOR HAZARD	INTENSITY UNIT	REDUCTION IN DAMAGE PROBABILITY	COST-BENEFIT RATIO
Agriculture[h,i]	Livestock	Poultry	Extreme heat	90	Temperature percentile	81%	N/A
Agriculture[h,i]	Livestock	Poultry	Extreme heat	90	Temperature percentile	19%	N/A
Agriculture[h,i]	Livestock	Cows	Extreme heat	90	Temperature percentile	81%	N/A
Agriculture[h,i]	Livestock	Cows	Extreme heat	90	Temperature percentile	19%	N/A
Worker productivity[j,p]	N/A	N/A	Extreme heat	90	Temperature percentile	90%	1.36
Worker productivity[j,q]	N/A	N/A	Extreme heat	90	Temperature percentile	90%	3.9
Buildings[k]	N/A	N/A	Floods	99	Percentile of extreme wet (SPI)	50%	5.2
Health[l]	Morbidity	Malaria	Extreme wet	CVM	CVM	77%	
Health[m]	Mortality	Heat-related deaths	Extreme heat	CVM	CVM	45%	35
Health[m]	Mortality	Extreme events	Extreme wind speed	CVM	CVM	45%	35
Health[m]	Mortality	Extreme events	Floods	CVM	CVM	45%	35
Health[m]	Mortality	Extreme events	Wildfires	CVM	CVM	45%	35
Cities[n,o]	N/A	N/A	Extreme heat	N/A	N/A	Area 2°C cooler	1.6
Cities[n,o]	N/A	N/A	Extreme heat	N/A	N/A	0.7°C	2.2

Notes: CVM = cardiovascular mortality; SPI = Standardized Precipitation Index.

Source: h. Schauberger et al. 2022
i. St-Pierre et al. 2003
j. Dunne et al. 2013
k. Dottori 2020
l. Andrianantoandro et al. 2021
m. Rogers and Tsirkurnov 2010
n. Nurmi et al. 2013
o. Susca et al. 2011
p. Tiedemann 1970
q. Grimes 2012

ABBREVIATIONS

ARRA	American Recovery and Reinvestment Act
CBA	cost-benefit analysis
CCS	carbon capture and storage
CDS	Climate Data Store
CGE	computable general equilibrium
CH_4	methane
CLD	causal loop diagram
CO	carbon monoxide
CO_2e	carbon dioxide equivalent
C-ROADS	Climate-Rapid Overview And Decision Support
CVM	cardiovascular mortality
DICE	Dynamic Integrated Climate Economy
En-ROADS	Energy-Rapid Overview And Decision Support
EV	electric vehicle
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GEM	green economy model
GEMF	GEM Framework
GDP	gross domestic product
GHG	greenhouse gas
GIS	geographic information system
HQ	habitat quality
IAM	integrated assessment model
IBC	Integrated Benefits Calculator
IEA	International Energy Agency
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPCC	Intergovernmental Panel on Climate Change
IPPU	industrial processes and product use
IPSL	Institut Pierre-Simon Laplace
kt	kiloton
kWh	kilowatt-hour
LCD	low carbon development
LCU	local currency unit
LEAP	Low Emissions Analysis Platform
LULUCF	land use, land-use change, and forestry
mph	miles per hour
MSW	municipal solid waste
MW	megawatt
N	nitrogen
NCE	New Climate Economy
NDC	nationally determined contribution
NH_3	ammonia
NMVOC	non-methane volatile organic compounds
NO_x	nitrogen oxides
N_2O	nitrous oxide
NZE	net zero emissions
O&M	operations and maintenance
PKE	post-Keynesian economics
$PM_{2.5}$	particulate matter equal to or less than 2.5 micrometers in diameter
PM_{10}	particulate matter equal to or less than 10 micrometers in diameter
RCP	Representative Concentration Pathway
RE	renewable energy
SAM	Social Accounting Matrix
SCC	social cost of carbon
SD	system dynamics
SNA	System of National Accounts
SO_2	sulfur dioxide

SPI	Standardized Precipitation Index
SSP	Shared Socioeconomic Pathway
TCF	trillion cubic feet
TFI	Task Force on National GHG Inventories
TFP	total factor productivity
TIMES	The Integrated MARKAL-EFOM System
TJ	terajoule
WBGT	Wet Bulb Global Temperature
WDI	World Development Indicators
WEO	*World Energy Outlook*

GLOSSARY

ceteris paribus Latin for "all else being equal." In a ceteris paribus situation, the effect of one economic variable on another is isolated by holding all other conditions unchanged.

circular economy An economy that reduces the consumption of resources and the generation of wastes and reuses and recycles wastes throughout the production, distribution, and consumption processes (Bourguignon 2016).

delays Time lags between action and impact. As many natural processes play out over large periods of time, the time required for a cause's effect to take place needs to be factored in.

endogenous (dependent) variable A variable in the model whose value is dependent on the states of other variables in the system.

exogenous (independent) variable A variable in the model that behaves independently from changes and shocks in the other variables of the model; typically an external input.

goal-seeking patterns *Goal seeking* implies that the system aligns with existing limits to growth (i.e., carrying capacity) or a desired target set by decision-makers—or, first the latter and then, as a consequence of overexploitation, the former. There are systems that tend toward equilibrium, reaching a given goal. For instance, the number of trout in a lake is a function of the amount of food available in such lake. If we put 10 trout in the lake, and the carrying capacity of the lake is 100, at some point in time we will have 100 trout in the lake—no more and no less (if there are no other disturbances). This is what goal seeking means: adjustment toward an implicit equilibrium (that is not zero; otherwise we have exponential decline).

green economy At the visionary level, a green economy is one that results in "improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities" (UNEP 2011). At the operational level, a green economy can be implemented with three types of investments that reduce carbon emissions and pollution, enhance energy and resource efficiency, and prevent the loss of biodiversity and ecosystem services (EMG 2011). These investments need to be catalyzed and supported by targeted public expenditure and policy reforms, and a green economy recognizes the importance of maintaining a natural capital base as a critical economic asset. Also, to be relevant at the national level and effectively contribute to development planning, a green economy must ultimately align with national priorities and development targets. But it should not favor one political perspective over another; a green economy is one that is relevant to all economies.

green growth Similarly, there is no single definition of *green growth*, but GEM follows the Organisation for Economic Co-operation and Development's definition that "green growth means fostering economic growth and development, while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies" (OECD 2011).

green investment An investment that can be attributed to indicators that promote the green economy, such as reduced carbon emissions and pollution, contributing to energy and resource efficiency, preventing the loss of biodiversity and ecosystem services, and the number of green jobs created (UNEP 2014).

green jobs GEM estimates the number of (full-time) jobs that are created (and lost) by implementing green economy investments. As a result, it estimates the number of jobs required for construction, operation, and maintenance of green infrastructure; for the use of sustainable agriculture practices; and for waste management, recycling, and reuse, among others. The general output is one of labor, but GEM also assesses labor productivity, which is a function of education and health, as determined by human capital investments. As such, GEM further allows comparisons between the job gains with job losses to inform plans for a more just transition. In conjunction with microsimulation tools, GEM supports the assessment of skilled versus unskilled employment at the national level under different scenarios, which can then be used to estimate impacts on income and income distribution.

level of technology This refers to the impact of technology adoption on the model that results in economic impacts (e.g., energy efficiency reduces energy consumption, which reduces energy spending, which increases capital productivity) as opposed to the development and introduction of the technology itself. This is represented as an index in the production function of the model, growing and accumulating over time to represent change in economic productivity. In sectoral models, the technology parameter is more specific—for example, solar panels that carry a given efficiency factor (that changes over time) or vehicles that can use alternate engines and energy sources for energy sector dynamics—but in GEM, it is assumed that the technology itself does not directly result in economic growth but rather its widespread adoption.

module Interchangeable with *structure* and *substructure*, *module* refers to a modeling component within GEM. The technical specifications of each of the structures is outlined in Appendix A.

Social Accounting Matrix (SAM) A SAM is a depiction of economic flows, capturing transfers and real transactions between sectors and institutions (Pyatt and Round 1986). It is an accounting framework laid out as a matrix, where each row and column represents an account, distinguishing between "activities" and "commodities," to reflect a country's balance of payments (Breisinger et al. 2009).

System of National Accounts (SNA) The SNA collects information about the stocks and flows that compose the integrated framework of an economy (UNSD 2008). GEM utilizes a simplified SNA, one that keeps aggregate values consistent despite less detail being provided.

well-being The exact definition of human well-being is difficult to narrow in on, but it generally refers to the overall satisfaction of survey respondents, which are scored on subjective indicators (e.g., happiness, stress, etc.) or based on measured indicators (e.g., physical health, income relative to expectations, etc.) against indexes.

ENDNOTES

1. In 2022, NCE—once a stand-alone initiative—was integrated as a foundational element of WRI's continued country support and is now fully embedded within WRI's Climate Program under its National Climate Action umbrella. Most GEM applications in this technical note were conducted under the previous brand of NCE, but future GEM-related work will be spearheaded as part of the National Climate Action banner.

2. With some of the identified countries meeting more than one of those criteria. Other NCE target countries include Mexico and Nigeria.

3. Definitions of terms in this paper, such as the use of *green*, can have different meanings in different contexts, but all point to the same concepts, which ultimately need to be customized to the context of the country or region in question to be relevant for policymaking. However, to avoid semantic confusion, key definitions under GEM are available in the Glossary.

4. See, for instance, Bale (2019) and Duboz et al. (2018) for descriptions of participatory modeling in the context of energy and health policy, respectively.

5. The country-specific GEM Technical Notes are available on the New Climate Economy website, https://newclimateeconomy.net/. Select Technical Note citations can be found in the references, specifically for Ethiopia (Dagne et al. 2023), India (Golechha et al. 2022), Indonesia (BAPPENAS 2019; Medrilzam et al. 2021), and St. Lucia (GGGI 2021).

6. Projected global GHG emissions from NDCs announced prior to the 26th Conference of the Parties would make it likely that warming will exceed 1.5°C and make it harder after 2030 to limit warming to below 2°C.

7. Climate-compatible paths with 1.5°C are defined as those that yield cumulative GHG emissions not exceeding the so-called carbon budget estimated by January 1, 2018, at 420 gigatonnes of carbon dioxide equivalent ($GtCO_2e$), for a two-thirds chance of limiting warming to 1.5°C relative to preindustrial levels, and at about 580 $GtCO_2e$ for an even chance (medium confidence) (IPCC 2018). The Mercator Research Institute on Global Commons and Climate Change provides current estimates data on the remaining global carbon budget, using the most recent information from the IPCC (MCC n.d.).

8. More often than not, a *silo* mentality is commonly found across institutions that should otherwise work closely together in the policymaking process. The inadequate sharing of information and misalignment in the use of tools exacerbate coordination among entities.

9. Understandably, this discussion then raises questions about future discount rates, of which there continues to be ample debate even among advanced economies.

10. Such as computable general equilibrium models, spatial models like the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) for the estimation of land use change and ecosystem service provisioning, energy optimization models, macroeconometric models, micro-econometric models, and statistical analyses.

11. The Lucas Critique (Lucas 1976), which argues that it is naive to try to predict the effects of a change in economic policy on the basis of relationships observed in historical data, offers one such case of counterintuitive responses to policies.

12. In the case of sectoral models and analyses, such as those that focus on energy systems, model-based assessments have been found to be more accurate than expert elicitation in capturing observed values (Meng et al. 2021). For GEM, both approaches are equally significant in customizing the assessment to the local context to accurately connect the social, economic, and environmental dynamics within a country.

13. Given the model size and number of variables involved, GEMs are characterized by the existence of a very large number of feedback loops. *Some* of them can become dominant for the dynamic of given variables. The strengths of loops depend on the very (country-specific) characteristics of systems and the nature of policy interventions.

14. CLDs focus on feedback loops and the direction of impacts and (especially when they are being introduced to audiences) do not include representations of stocks and flows. Figure 6 assumes that stakeholders have an initial basic understanding of CLDs and can further develop intuition regarding core relationships and the role of policies under GEM.

15. In this context, *goal seeking* is an SD terminology that implies that the system aligns with existing limits to growth (i.e., carrying capacity) or a desired target set by decision-makers. See the Glossary for more detail.

16. Funding constraints are still modeled in GEM, but these are driven by the scenarios.

17. A simplified SNA aggregates flow while retaining the overall consistency of the accounts (e.g., instead of including 20 tax revenue sources, we consider 3). This implies that the total tax revenue is the same, but in a simplified SNA, less detail is provided.

18. Demand-side elements (e.g., labor market frictions and restrictions, financial intermediation constraints, etc.) play a role in outcomes associated with climate policy but are not the focus of GEM. Any of these features or problems can be incorporated systematically either in GEM ("expanding model boundaries") or in associated models, as needed, because the focus of analysis moves past the comprehension of climate, environmental, and socioeconomic dynamics and associated low-carbon, green policies and into specific problems or policies (e.g., migration issues, health, taxation, etc.) that can be linked to the former.

19. GEM is not equipped with robust spatial capability. Thus, the spatial analysis is conducted in parallel based on GEM results and is connected to spatial models to fill one of the limitations of GEM. However, mitigation and adaptation policies have impacts at the local level, and the economic valuation of ecosystem services should take into account where change happens in the country. This is why we use maps and spatial models for ecosystem services.

20. GEM does allow for short-term disequilibrium but leans more toward medium- and longer-term equilibrium. Consistency is ensured by using the SNA and the Social Accounting Matrix (via the GDP identity) to make sure that there is consistency between demand and supply. Still, equilibrium is not a strength of GEM; CGE models are better at this by design.

21. Though direct, indirect, and induced effects are typically associated with input-output approaches, in the context of GEM, they refer to the degree of proximity of an impact. For instance, investments in RE have a direct impact: creation of capacity (megawatts). The indirect impact is employment creation, and the induced impact is the economic growth that results from the income generation and (possible) cost savings on energy spending.

22. The term *white box* is used as opposed to the more commonly known *black box*. In science, computing, and engineering, a black box is a device, system, or model that produces useful information without revealing any information about its internal workings. The explanations for its conclusions remain opaque, or "black." Black boxes also refer to functional relationships between system inputs and system outputs that are lumped together with parameter models. The parameters of these functions do not have any physical significance in terms of equivalence to process parameters, making it difficult to understand or rationalize cause-effect relationships.

23. The terms often used to describe the outputs of models, such as *forecast* and *prediction*, are used differently in the various fields that estimate future events. Although the terms are sometimes interchangeable, especially in climate science, here we refer to *predictions* as future estimates determined with unconditional probability, and we refer to *forecasts* (which, in this case, are interchangeable with *projections* and *scenarios*) as those based on historical trends and realistic assumptions and contingent on changing dynamics.

24. GEM scenarios are generated very quickly once policy parameters are defined or agreed upon. It takes only a few seconds to run a given GEM scenario, so policymakers can get real-time answers to questions on "what if" a given parameter or set of parameters are changed. The term *play mode* is used to refer to a process whereby a modeler runs GEM in front of an audience that provides inputs on desired or suggested policy variables and observes the consequences of such actions on paths and levels of endogenously computed variables of interest.

25. Because GEM is an SD-based model, it could theoretically be constructed and run via other SD software packages, such as Stella, Powers, iThink, and Powersim. We use Vensim primarily because it offers several packages that are better suited to the needs of different audiences (from a few key features to a complete software package for advanced modeling) at different price points. Powersim is the only other software in which a GEM has been replicated, though only approximately.

26. A list of methodological reports can be found on the IPCC's TFI website, https://www.ipcc-nggip.iges.or.jp/public/index.html.

27. CBA-IAMs most closely aligned with GEM, such as DICE, include climate damage functions, which, in theory, do capture such feedback. This depends on how the damage functions are formulated; for instance, if the impact is on GDP or on assets that are then used to generate value added (in this case, GEM focuses on the latter). However, most models used for policymaking—in the context of a green economy and climate mitigation and adaptation—are not CBA-IAMs. In our experience, many emerging economies rely on standard energy optimization models (e.g., LEAP, TIMES) or CGE models for green growth development, and these models often do not consider climate impacts. That being said, we also do not claim that GEM features the most appropriate damage functions—though we do our best to ensure they are—and the model is open for calibration to new research and data as it becomes available.

28. Acknowledging that policymakers are likely to be interested in demand-side elements associated with low-carbon policymaking, including the impacts on fiscal balances and debt dynamics and the role of savings and expenditure policies in attaining, for instance, net zero emissions outcomes. An ongoing exercise is that of reconciling GEM with other integrated assessment methods seeking to identify decarbonization paths that are constrained by demand-side factors.

29. For instance, in CGE models, calibration involves assigning parameter values to technical and behavioral representations (e.g., production and utility functions) so that the model replicates the benchmark data (for instance, that observed in a base-year equilibrium). Most of those parameters are drawn from the Social Accounting Matrix, but others (e.g., elasticities) can be derived from model assumptions (e.g., initial year price levels) or via an iterative process seeking for model "closure."

30. *Model calibration* is the process of estimating the model parameters to obtain a match between observed and simulated behavior. Calibration explicitly attempts to link structure to behavior, which is why it is a more stringent test than solely matching structure or behavior (Oliva 2003).

31. As opposed to synthetic parameters that are created to establish linkages among variables based on observed behavior and that are estimated, precisely through calibration techniques.

32. The C-ROADS and En-ROADS simulators are global (and the only publicly available) examples of such user interfaces (Siegel et al. 2023a, 2023b).

33. Under the GEM, the terms *reference case* and *baseline* are used interchangeably. The one term generally avoided is *business as usual* because under no-action or insufficient action climate and green scenarios, businesses (and individuals) will find it increasingly harder to advance their activities "as usual" due to climate impacts.

34. Constraints are scenario driven. If the deficit is assumed fixed at 2 percent per year, for example, and that value cannot be surpassed, public investment can be limited in GEM. This is something that can be set manually, normally in consultation with the government. There are constraints that shape the resulting decarbonization pathway to be both more realistic and achievable (e.g., the potential area for reforestation to create a sink capacity or the consideration of what is socially acceptable).

35. Computing this is an exercise that normally involves a deep dive into public and private sector budgets and investment plans.

36. The main reason why SAMs are not fully exploited and included is because they provide information regarding the structure of the economy *at some point in the past* (the period for which the SAM was defined). As countries embark or continue their process of structural transformation, such structure is deemed to change substantially, making the SAM increasingly inaccurate as simulations are conducted years and decades into the future (which is a characteristic of many climate-economic models).

37. LEAP's IBC emission factor database is available at https://leap.sei.org/default.asp?action=IBC.

REFERENCES

AFD (Agence Française de Développement). n.d. "GEMMES: A New Modelling Tool That Incorporates the Energy Transition." https://www.afd.fr/en/page-programme-de-recherche/gemmes-new-modelling-tool-incorporates-energy-transition. Accessed March 23, 2022.

Andrianantoandro, V.T., M. Audibert, T. Kesteman, L. Ravolanjarasoa, M. Randrianarivelojosia, and C. Rogier. 2021. "Cost of the National Malaria Control Program and Cost-Effectiveness of Indoor Residual Spraying and Insecticide-Treated Bed Nets Strategies in Two Districts of Madagascar." Working Paper 17. Clermont-Ferrand, France: Centre d'Études et de Recherches sur le Développement International. https://uca.hal.science/hal-03249411.

Azumah, S.B., W. Adzawla, A. Osman, and P.Y. Anani. 2020. "Cost-Benefit Analysis of On-Farm Climate Change Adaptation Strategies in Ghana." *Ghana Journal of Geography* 12 (1): 29–46.

Bale, C. 2019. "Participatory Modelling: A Review of Applications in Energy Whole-Systems Modelling to Support Decision Making." Working Paper. Leeds, UK: University of Leeds.

BAPPENAS (Ministry of National Development Planning). 2019. *Low Carbon Development: A Paradigm Shift towards a Green Economy in Indonesia*. Jakarta: BAPPENAS, Government of Indonesia.

Barlas, Y. 1996. "Formal Aspects of Model Validity and Validation in System Dynamics." *System Dynamics Review* 12 (3): 183–210. https://doi.org/10.1002/(SICI)1099-1727(199623)12:3%3C183::AID-SDR103%3E3.0.CO;2-4.

Bassi, A.M. 2015. "Moving towards Integrated Policy Formulation and Evaluation: The Green Economy Model. Environmental and Climate Technologies." *Environmental and Climate Technologies* 16 (1): 5–19. https://doi.org/10.1515/rtuect-2015-0009.

Bourguignon, D. 2016. "Closing the Loop: New Circular Economy Package." Briefing. Brussels: European Parliamentary Research Service. https://www.europarl.europa.eu/RegData/etudes/BRIE/2016/573899/EPRS_BRI%282016%29573899_EN.pdf.

Bourguignon, F., M. Bussolo, and L.A. Pereira da Silva, eds. 2008. *The Impact of Macroeconomic Policies on Poverty and Income Distribution: Macro-Micro Evaluation Techniques and Tools*. Washington, DC: World Bank. https://openknowledge.worldbank.org/server/api/core/bitstreams/64bb932a-5845-5f40-b14a-df8d5b34d6d9/content.

Breisinger, C., M. Thomas, and J. Thurlow. 2009. *Social Accounting Matrices and Multiplier Analysis: An Introduction with Exercises*. Washington, DC: International Food Policy Research Institute. http://dx.doi.org/10.2499/9780896297838fsp5.

Bussolo, M., R. de Hoyos, D. Medvedev, and D. van der Mensbrugghe. 2012. "Global Growth and Distribution: China, India, and the Emergence of a Global Middle Class." *Journal of Globalization and Development* 2 (2): 1–29.

Cambridge Econometrics. 2022. *E3ME Model Manual*. Cambridge, UK: Cambridge Econometrics. https://www.e3me.com/features/.

CDS (Climate Data Store). 2022. "European Centre for Medium-Range Weather Forecasts." Copernicus Climate Change Service, Climate Data Store. https://cds.climate.copernicus.eu/.

Cutler, E., R. Bechauf, A.M. Bassi, and M. Guzzetti. 2021. *How to Make Investments in Land Rehabilitation Economically Viable: Lessons Learned from Peatland and Mangroves in Indonesia, a SAVi Assessment*. Winnipeg, Canada: International Institute for Sustainable Development. https://www.iisd.org/publications/report/savi-indonesia-peatland-mangroves.

Dagne, A., C. Elliott, J. Corfee, and S. Tsehay. 2022. "Mainstreaming Climate Change in Ethiopia's Planning Process." Working Paper. Washington, DC: World Resources Institute. https://doi.org/10.46830/wriwp.21.00032.

Dagne, A., J. Corfee-Morlot, C. Elliott, A.M. Bassi, G. Pallaske, I. Payosova, M. Pellerin, and M. Guzzetti. 2023. "Ethiopia's Path to Net Zero and Climate-Resilient Development: Policies, Costs, and Co-benefits." Working Paper. Washington, DC: World Resources Institute. https://doi.org/10.46830/wriwp.22.00008.

Dottori, F., L. Mentaschi, A. Biamchi, L. Alfieri, and L. Feyen. 2020. *Adapting to Rising River Flood Risk in the EU under Climate Change*. EUR 29955 EN. Luxembourg: Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC118425.

Duboz, R., P. Echaubard, P. Promburom, M. Kilvington, H. Ross, W. Allen, J. Ward, G. Deffuant, M. de Garine-Wichatitsky, and A. Binot. 2018. "Systems Thinking in Practice: Participatory Modeling as a Foundation for Integrated Approaches to Health." *Frontiers in Veterinary Science* 5 (December): 303. https://doi.org/10.3389/fvets.2018.00303.

Dunne, J.P., R.J. Stouffer, and J.G. John. 2013. "Reductions in Labour Capacity from Heat Stress under Climate Warming." *Nature Climate Change* 3 (June): 563–66. https://doi.org/10.1038/nclimate1827.

ECA (Economics of Climate Adaptation). 2009. *Shaping Climate-Resilient Development: A Framework for Decision-Making*. San Francisco: ClimateWorks Foundation; Washington, DC: Global Environment Facility; Brussels: European Commission; New York: McKinsey & Company, Rockefeller Foundation; London: Standard

Chartered Bank; Zurich: Swiss Re. https://climate-adapt.eea.europa.eu/en/metadata/publications/shaping-climate-resilient-development-a-framework-for-decision-making.

EMG (United Nations Environment Management Group). 2011. *Working towards a Balanced and Inclusive Green Economy: A United Nations System-Wide Perspective*. Geneva: United Nations. https://wedocs.unep.org/20.500.11822/8065.

EPA (U.S. Environmental Protection Agency). 2013. "Estimating the Benefit per Ton of Reducing $PM_{2.5}$: Precursors from 17 Sectors." Technical Support Document. Research Triangle Park, NC: Office of Air and Radiation, Office of Air Quality Planning and Standards, EPA. https://19january2017snapshot.epa.gov/sites/production/files/2014-10/documents/sourceapportionmentbpttsd.pdf.

Evans, S., and Z. Hausfather. 2018. "Q&A: How 'Integrated Assessment Models' Are Used to Study Climate Change." Carbon Brief, October 2. https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change/.

Forrester, J.W. 1971. "Counterintuitive Behavior of Social Systems." *Technology Review* 73 (3): 52–68.

Garrido, L., Medrilzam, A. Amalia, I. Darliazi-Yananto, M. McGregor, J. Brand, S. Opitz-Stapleton, P. Sayers, R. Nadin, and A. Quevedo. 2019. *Low Carbon Development Report: A Paradigm Shift towards a Green Economy in Indonesia*. Jakarta: Ministry of National Development Planning, Government of Indonesia.

GGGI (Global Green Growth Institute). 2021. *Fossil Fuel Subsidy and Taxation Reform Scenarios Modelling for Saint Lucia*. Seoul: GGGI. https://gggi.org/wp-content/uploads/2021/09/Saint-Lucia-Fossil-Fuel-Subsidy-and-Taxation-Report-Scenario-Modelling-2.pdf.

Golechha, A., A. Raman, A. Srivastava, A.M. Bassi, and G. Pallaske. 2022. "A Green Economy Model for India: Technical Summary of Methods and Data Used." Technical Note. Washington, DC: World Resources Institute. https://doi.org/10.46830/writn.21.00033

Grimes, A., T. Denne, P. Howden-Chapman, R. Arnold, L. Telfar-Barnard, N. Preval, and C. Young. 2012. *Cost Benefit Analysis of the Warm Up New Zealand: Heat Smart Programme*. Wellington, New Zealand: Victoria University of Wellington.

Grubb, M., P. Drummond, J-F. Mercure, C. Hepburn, P. Barbrook-Johnson, J.C. Ferraz, A. Clark, et al. 2021. *The New Economics of Innovation and Transition: Evaluating Opportunities and Risks*. Exeter, UK: Economics of Energy Innovation and System Transition Consortium, University of Exeter. https://eeist.co.uk/eeist-reports/the-new-economics-of-innovation-and-transition-evaluating-opportunities-and-risks/.

Hallegatte, S., J. Rentschler, and J. Rozenberg. 2019. *Lifelines: The Resilient Infrastructure Opportunity*. Washington, DC: World Bank. http://hdl.handle.net/10986/31805.

Heaps, C.G. 2016. *Long-range Energy Alternatives Planning (LEAP) System*. Somerville, MA: Stockholm Environment institute.

IEA (International Energy Agency). 2021. *World Energy Model Documentation*. Paris: IEA.

IPCC (Intergovernmental Panel on Climate Change). 2006a. *Energy*. Vol. 2 of *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Geneva: IPCC. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html.

IPCC. 2006b. *Agriculture, Forestry and Other Land Use*. Vol. 4 of *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Geneva: IPCC. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by R.K. Pachauri and L.A. Meyer. Geneva: IPCC. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf.

IPCC. 2018. *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, et al. Cambridge and New York: Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SR15_Full_Report_LR.pdf.

IPCC. 2022. *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, et al. Cambridge and New York: Cambridge University Press. https://doi.org/10.1017/9781009325844.

Iyer, G., N. Hultman, J. Eom, H. McJeon, P. Patel, L. Clarke. 2015. "Diffusion of Low-Carbon Technologies and the Feasibility of Long-Term Climate Targets." *Technological Forecasting and Social Change* 90: 103–18. https://doi.org/10.1016/j.techfore.2013.08.025.

Kelly, R.A., A.J. Jakeman, O. Barreteau, M.E. Borsuk, S. El-Sawah, S.H. Hamilton, H.J. Henriksen, et al. 2013. "Selecting among Five Common Modelling Approaches for Integrated Environmental Assessment and Management." *Environmental Modelling & Software* 47 (September): 159–81. https://doi.org/10.1016/j.envsoft.2013.05.005.

Krey, V., P. Havlik, O. Fricko, J. Zilliacus, M. Gidden, M. Strubegger, G. Kartasasmita, T. Ermolieva, N. Forsell, M. Gusti, and N. Johnson. 2016. *MESSAGE-GLOBIOM 1.0 Documentation*. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Loulou, R., U. Remne, A. Kanudia, A. Lehtila, and G. Goldstein. 2005. *Documentation for the TIMES Model: Part I*. Paris: Energy Technology Systems Analysis Programme, International Energy Agency. https://iea-etsap.org/docs/TIMESDoc-Intro.pdf.

Lucas, R.E. 1976. "Econometric Policy Evaluation: A Critique." *Carnegie-Rochester Conference Series on Public Policy* 1: 19–46. https://doi.org/10.1016/S0167-2231(76)80003-6.

MCC (Mercator Research Institute on Global Commons and Climate Change). n.d. "Remaining Carbon Budget." https://www.mcc-berlin.net/en/research/co2-budget.html. Accessed July 3, 2021.

Meadows, D.L., D.H. Meadows, J. Randers, and W.W. Behrens. 1972. *Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*. New York: Universe Books.

Meadows, D.H. 1982. "Whole Earth Models & Systems." *CoEvolution Quarterly* 34 (Summer): 98-108. https://donellameadows.org/wp-content/userfiles/Whole-Earth-Models-and-Systems.pdf.

Meadows, D.H. 2008. *Thinking in Systems: A Primer*. White River Junction, VT: Chelsea Green.

Medrilzam, L. Garrido, S. Ida, I. Darliazi-Yananto, E. Suarga, A. Wijaya, M. Davis, A. Harsono, K. Connolly, and Y. Akopian. 2021. *A Green Economy for a Net Zero Future: How Indonesia Can Build Back Better after COVID-19 with the Low Carbon Development Initiative (LCDI)*. Jakarta: Ministry of National Development Planning, Government of Indonesia. https://lcdi-indonesia.id/wp-content/uploads/2021/10/GE-Report-English-8-Oct-lowres.pdf.

Meng, J., R. Way, E. Verdolini, and L.D. Anadon. 2021. "Comparing Expert Elicitation and Model-Based Probabilistic Technology Cost Forecasts for the Energy Transition." *Economic Sciences* 118 (27): e1917165118. https://doi.org/10.1073/pnas.1917165118.

Merrill, L., A.M. Bassi, R. Bridle, and L.T. Christensen. 2015. *Tackling Fossil Fuel Subsidies and Climate Change: Levelling the Energy Playing Field*. Copenhagen: Nordic Council of Ministers. https://norden.diva-portal.org/smash/get/diva2:860647/FULLTEXT02.pdf.

Miyamoto International. 2019. *Overview of Engineering Options for Increasing Infrastructure Resilience*. Final Report. Sacramento, CA: Miyamoto International. https://documents1.worldbank.org/curated/en/474111560527161937/pdf/Final-Report.pdf.

Natural Capital Project. 2023. "InVEST 3.14.0." Stanford, CA: Stanford University; Minneapolis: University of Minnesota; Beijing: Chinese Academy of Sciences; Arlington, VA: The Nature Conservancy; Washington, DC: World Wildlife Fund: Stockholm: Stockholm Resilience Centre and the Royal Swedish Academy of Sciences. https://naturalcapitalproject.stanford.edu/software/invest.

NCE (New Climate Economy). 2018. *Unlocking the Inclusive Growth Story of the 21st Century*. Washington, DC: NCE, World Resources Institute. https://newclimateeconomy.report/2018/.

Nikas, A., H. Doukas, and A. Papandreou. 2019. "A Detailed Overview and Consistent Classification of Climate-Economy Models." In *Understanding Risks and Uncertainties in Energy and Climate Policy*, edited by H. Doukas, A. Flamos, and J. Lieu, 1–54. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-030-03152-7_1.

Nordhaus, W.D. 2017. "Revisiting the Social Cost of Carbon." *Proceedings of the National Academy of Sciences of the United States of America* 114 (7): 1518–23. https://doi.org/10.1073/pnas.1609244114.

Nordhaus, W.D., and Z. Yang. 1996. "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies." *American Economic Review* 86 (4): 741–65. https://www.jstor.org/stable/2118303.

Nurmi, V., A. Votsis, A. Perrels, and S. Lehvävirta. 2013. *Cost-Benefit Analysis of Green Roofs in Urban Areas: Case Study in Helsinki*. Helsinki, Finland: Finnish Meteorological Institute.

Oliva, R. 2003. "Model Calibration as a Testing Strategy for System Dynamics Models." *European Journal of Operation Research* 151 (3): 552–68. https://doi.org/10.1016/S0377-2217(02)00622-7.

OECD (Organisation for Economic Co-operation and Development). 2011. *Towards Green Growth*. OECD Green Growth Studies. Paris: OECD. https://doi.org/10.1787/9789264111318-en.

Pallaske, G., A. Bassi, L. Garrido, and M. Guzzetti. 2023. "Exploring the Virtuous Interdependencies Existing between Climate Action and Sustainability in the Context of Low Carbon Development." In *Handbook on Innovation, Society and the Environment*, edited by F.J.D. López. Cheltenham, UK: Edward Elgar.

Probst, G., and A. Bassi. 2014. *Tackling Complexity: A Systemic Approach for Decision Makers*. Sheffield, UK: Greenleaf.

Pyatt, G., and J. Round, eds. 1985. *Social Accounting Matrices: A Basis for Planning*. Washington, DC: World Bank Group. http://documents.worldbank.org/curated/en/919371468765880931/Social-accounting-matrices-a-basis-for-planning.

Rodrik, D. 2004. "Industrial Policy for the Twenty First Century." Paper prepared for the United Nations Industrial Development Organization. Cambridge, MA: John F. Kennedy School of Government, Harvard University. https://drodrik.scholar.harvard.edu/files/dani-rodrik/files/industrial-policy-twenty-first-century.pdf.

Rogers, D., and V. Tsirkurnov. 2010. *Costs and Benefits of Early Warning Systems*. Geneva: United Nations Office for Disaster Risk Reduction. https://www.preventionweb.net/english/hyogo/gar/2011/en/bgdocs/Rogers_&_Tsirkunov_2011.pdf.

Romeiro, V., A.C. Barros, A. Bassi, A.F.P. Lucena, A.L. Andrade, A. Szklo, B. Pinheiro, et al. 2020. *A New Economy for a New Era: Elements for Building a More Efficient and Resilient Economy in Brazil*. São Paulo: WRI Brasil. https://www.wribrasil.org.br/sites/default/files/wribrasil_neweconomyforanewera_en.pdf.

Rutovitz, J., and A. Atherton. 2009*. Energy Sector Jobs to 2030: A Global Analysis*. Prepared for Greenpeace International. Sydney: Institute for Sustainable Futures, University of Technology, Sydney. https://cfsites1.uts.edu.au/find/isf/publications/rutovitzatherton2009greenjobs.pdf.

Schauberger, G., M. Schönhart, W. Zollitsch, S.J. Hörtenhuber, L. Kirner, C. Mikovits, J. Baumgartner, et al. 2022. "Reduction of the Economic Risk by Adaptation Measures to Alleviate Heat Stress in Confined Buildings for Growing-Fattening Pigs Modelled by a Projection for Central Europe in 2030." *Agronomy* 12 (2): 248. https://doi.org/10.3390/agronomy12020248.

Schlenker, W., and M.J. Roberts. 2009. "Nonlinear Temperature Effects Indicate Severe Damages to U.S. Crop Yields under Climate Change." *Proceedings of the National Academy of Sciences of the United States of America* 106 (37): 15594–98. https://doi.org/10.1073/pnas.0906865106.

Siegel, L.S., C. Campbell, A. Delibas, S. Eker, T. Fiddaman, T. Franck, J. Homer, et al. 2023a. *En-ROADS Technical Reference*. Washington, DC: Climate Interactive; Harvard, MA: Ventana Systems; Lowell, MA: Climate Change Initiative, University of Massachusetts, Lowell; Cambridge, MA: MIT Sloan School of Management. https://docs.climateinteractive.org/projects/en-roads-reference-guide/en/latest/ref-guide.pdf.

Siegel, L.S., C. Campbell, T. Fiddaman, A.P. Jones, and J. Sterman. 2023b. *C-ROADS Technical Reference*. Harvard, MA: Ventana Systems; Washington, DC: Climate Interactive; Cambridge, MA: MIT Sloan School of Management. https://docs.climateinteractive.org/projects/c-roads-reference-guide/en/latest/ref-guide.pdf.

St-Pierre, N.R., B. Cobanov, and G. Schnitkey. 2003. "Economic Losses from Heat Stress by US Livestock Industries." *Journal of Dairy Science* 86 (E. Suppl.): E52–77. https://doi.org/10.3168/jds.S0022-0302(03)74040-5.

Sterman, J.D. 2000. *Business Dynamics: System Thinking and Modeling for a Complex World*. New York: McGraw-Hill Education.

Sterman, J.D., T. Fiddaman, T. Franck, A. Jones, S. McCauley, P. Rice, E. Sawin, and L. Siegel. 2013. "Management Flight Simulators to Support Climate Negotiations." *Environmental Modelling & Software* 44 (June): 122–35. https://doi.org/10.1016/j.envsoft.2012.06.004.

Susca, T., S.R. Gaffin, and G.R. Dell'Osso. 2011. "Positive Effects of Vegetation: Urban Heat Island and Green Roofs." *Environmental Pollution* 159 (8–9): 2119–26. https://doi.org/10.1016/j.envpol.2011.03.007.

Syrquin, M., and H.B. Chenery. 1989. "Patterns of Development, 1950 to 1983." Discussion Paper 41. Washington, DC: World Bank Group. http://documents.worldbank.org/curated/en/427771468739525450/Patterns-of-development-1950-to-1983.

Tanny, J. 2013. "Microclimate and Evapotranspiration of Crops Covered by Agricultural Screens: A Review." *Biosystems Engineering* 114 (1): 26–43. https://doi.org/10.1016/j.biosystemseng.2012.10.008.

Tiedemann, K. 1970. "Economic and Environmental Impacts of Efficient Air Conditioning in Thailand." *WIT Transactions on Ecology and the Environment* 62. https://www.witpress.com/Secure/elibrary/papers/EENV03/EENV03020FU.pdf.

UNEP (United Nations Environmental Programme). 2011. *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication: A Synthesis for Policy Makers*. Nairobi: UNEP. https://sustainabledevelopment.un.org/content/documents/126GER_synthesis_en.pdf.

UNEP. 2014. *Using Models for Green Economy Policymaking*. Nairobi: UNEP. https://www.un-page.org/static/2eb65e4ad79fdbecf183dff03d0bc9f7/2014-using-models-for-green-economy-policy-making-unep-models-ge-for-web.pdf.

UNFCCC (United Nations Framework Convention on Climate Change). 1997. *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. Geneva: UNFCCC Secretariat. https://unfccc.int/sites/default/files/resource/docs/cop3/l07a01.pdf.

UNFCCC. 2015. *Paris Agreement*. New York: United Nations. https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

UNECA (United Nations Economic Commission for Africa). 2016. *Integrated Assessment Methodologies and Tools for Inclusive Green Economy Analysis in Africa*. Addis Ababa, Ethiopia: UNECA. https://archive.uneca.org/sites/default/files/uploaded-documents/Natural_Resource_Management/EGM-IATM-IGEA-2014/green_economy_analysis_in_africa-june2016.pdf.

UNSD (United Nations Statistics Division). 2008. *The System of National Accounts 2008*. New York: UNSD. .

Ventana Systems. 2022. "Vensim.V.9.3.5." Harvard, MA: Ventana Systems.

Watson, R., I. Noble, B. Bolin, N. Ravindranath, D. Verardo, and D. Dokken, eds. 2000. *Land-Use, Land Use Change, and Forestry*. Cambridge, UK: Cambridge University Press. https://archive.ipcc.ch/ipccreports/sres/land_use/index.php?idp=0.

Way, R., M.C. Ives, P. Mealy, and J.D. Farmer. 2022. "Empirically Grounded Technology Forecasts and the Energy Transition." *Joule* 6 (9): 2057–82. https://doi.org/10.1016/j.joule.2022.08.009.

Wilson, C., C. Guivarch, E. Kriegler, B. van Ruijven, D.P. van Vuuren, V. Krey, V.J. Schwanitz, and E.L. Thompson. 2021. "Evaluating Process-Based Integrated Assessment Models of Climate Change Mitigation." *Climatic Change* 166 (3). https://doi.org/10.1007/s10584-021-03099-9.

Yu, C., C. Li, Q. Xin, H. Chen, J. Zhang, F. Zhang, X. Li, et al. 2014. "Dynamic Assessment of the Impact of Drought on Agricultural Yield and Scale-Dependent Return Periods over Large Geographic Regions." *Environmental Modelling & Software* 62: 454–64. https://doi.org/10.1016/j.envsoft.2014.08.004.

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

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