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GREEN GROWTH SIMULATION TOOL PHASE 1:
Concept, Methods and Applications

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PREFACE

The Global Green Growth Institute (GGGI) is developing a Simulation Tool based on coupled system dynamics models for the different indicators of the Green Growth Index. As illustrated in this technical report, such models are very complex but, at the same time, extremely useful in exploring relevant scenarios on future implications of policy and investment decisions on green growth transition. As a former professional “modeler”, as well as a developer and user of complex models and scenarios, I strongly support the development of in-house tools to provide GGGI Member Countries and Partners robust models and scenarios. I believe that will help our Members and Partners in assessing different green growth pathways to achieve global sustainability goals and targets such as the Sustainable Development Goals (SDGs), Paris Climate Agreement, and Aichi Biodiversity Targets, and as defined in their national strategic and action plans such as the National Adaptation Plans (NAPs), Nationally Determined Contributions (NDCs), Low Emissions Development Strategy (LEDS), and National Biodiversity Strategies and Action Plans (NBSAPs).

Complex models are not free of controversies regardless of how much care modelers provide on the development, validation, and presentation. It is their complexity that causes integrated assessment models to be perceived as “black box” – not easy to check or understand by anyone and sometimes not even the experts. One way of opening the black box to facilitate understanding is to present every detail of the complex models, breaking them into pieces of equations that explain the relationships of variables, parameters, and functions. The contradiction is that, on the one hand, it makes the documentation, like this technical report, even more complex. It has numerous pages full of equations, so complex that no one can fully review and understand the usefulness, let alone assess their “truthfulness” or the accuracy of the effort. On the other hand, modeling complex coupled systems will still require gross simplifications of inherently complex processes in almost every specific area (e.g. sector, society, ecosystem, etc.), causing some to argue that the resulting effort is not helpful in increasing the understanding of green growth performance.

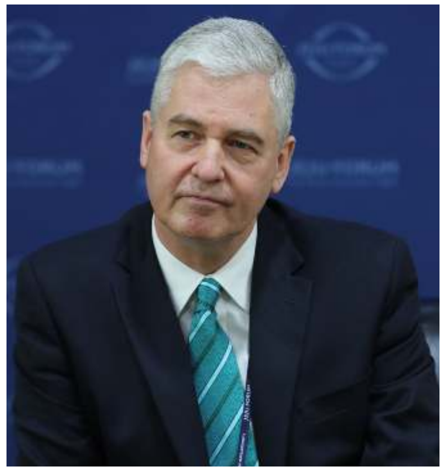
The authors believe, and I support them, that when used responsibly, with sufficient guard rails and without unjustified claims, this form of modeling can help increase the understanding of the behavior of complex systems – at least the trends, directions, and orders of magnitude – and possibly help explore interactions. In fact, this is the upside of using models and scenarios. It can provide knowledge (with some degree of uncertainty) on the otherwise unknown behavior of complex systems. Consequently, many of the policy recommendations coming from international scientific communities including, for example, the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services IPBES) are based on the assessments coming from complex models.

Perhaps more importantly, I believe that the value of modeling efforts to understand complex systems lies, not on “accurately” calculating the state of green growth, but on sitting down with policymakers and interactively exploring the consequences of their decisions – accepting that, in any case, policymakers have to make decisions in the absence of better information, under great uncertainty, on very complex topics such as those embedded in NAPs, NDCs, LEDS, NBSAPs, etc. In other words, even if models are not perfect, as long as they help explore the consequences of decisions and facilitate the interaction among decisionmakers, they can make a positive contribution.

In summary, complex models that will serve as a foundation for the Green Growth Simulation Tool will have to be built using open and collaborative processes to establish credibility. As described in this report, the GGGI’s Green Growth Performance Measurement (GGPM) Team, which is responsible for developing both the Green Growth Index and the associated Simulation Tool, considers the following vital processes to develop the Tool:

- ***Transparency***, through documentation and disclosure of what is in the black box. This technical report is the first of the series of documents to be published to describe the phase-wise development of the Simulation Tool.
- ***A phased approach***, by developing the coupled models step by step. This will allow the modelers to validate the simulation results in every step, as the number of models and degree of their complexity increase due to model integration. For example, this technical report only focuses on the Phase 1 development of the models for the Simulation Tool.
- ***Partnership***, through participation of modelers in relevant research institution with expertise on green growth indicators. During the Phase 1 development, a comprehensive review of peer reviewed articles was conducted, providing information not only on the models to use but also on potential modelers to support the Simulation Tool. This technical report will be a useful reference for the modelers who will collaborate in the next phases of developing the Simulation Tool.
- ***Peer review***, by opening the technical reports, including this one, for comments by relevant experts during the different phases of development. Through the annual peer review of the Green Growth Index, the GGPM team already formed groups of about 100 experts, many of them are modelers from international organizations and experts participating in the IPCC and IPBES assessments, who will be invited to join the peer review. Their reviews will have substantial value because the Simulation Tool is linked to the Green Growth Index.
- ***Participatory scenarios***, by co-designing scenarios with policymakers and other relevant stakeholders to adapt to their needs and preferences. For example, useful scenarios (of policy decisions) are those aligned to the national action plans (e.g. NAPs, NDCs, LEDS, NBSAPs), which are contingent to the country’s social, economic, and environmental condition as well as institutional and investment capacity.

To conclude, I hope this technical report will provide modelers and experts the necessary information to understand the coupled system dynamics models for the different green growth indicators and enable them to actively participate in developing the Green Growth Simulation Tool over several years, in the same spirit as that for the Green Growth Index where a large number of experts globally are continuously supporting its improvement year by year. To all other readers, I hope that the effort to disclose the inner workings of the Simulation Tool will help to convince you that GGGI and the GGPM team are committed to a transparent, interactive, and credible approach in the development of these tools in the years to come.



Dr. Frank Rijsberman
Director General
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Acronyms and Abbreviations

AB	Access to Basic Services and Resources
AFOLU	Agriculture, Forestry and Other Land Use
APEC	Asia-Pacific Economic Cooperation
BAU	Business-as-usual
BE	Biodiversity and Ecosystem Protection
C2E2	Copenhagen Centre on Energy Efficiency
CH_4	Methane
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide equivalent
CV	Cultural and Social Value
DALY	Disability Adjusted Life Years
DMC	Domestic material consumption
DPB	Description of Patterns of Behavior
EE	Efficient and Sustainable Energy
EEA	European Environment Agency
EU	European Union
EQ	Environmental Quality
ESCWA	Economic and Social Commission for Western Asia
EW	Efficient and Sustainable Water Use
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GADM	Global Administrative Areas
GB	Gender Balance
GDP	Gross Domestic Product
GDPC	Gross Domestic Product Per Capita
GE	GHG Emissions Reduction
GEM	Green Economy Model
GGGI	Global Green Growth Institute
GGPM	Green Growth Performance Measurement
GHG	Greenhouse Gas
GIP	Green Industrial Performance
GIS	Geographic Information System
GJ	Green Employment
GN	Green Innovation
GNI	Gross National Income
GT	Green Trade
GV	Green Investment
Global Findex	Global Financial Inclusion
HDI	Human Development Index
HQ	Headquarters
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IEEP	Institute for European Environmental Policy
ILO	International Labour Organization
IM	Integration Module
IMF	International Monetary Fund
INDSTAT	Industrial Statistics Database
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
ir	Integration Relations
ISIC	International Standard Industrial Classification of All Economic Activities
ITU	International Telecommunication Union
JMP	Joint Monitoring Programme
KBA	Key Biodiversity Areas
KS	Kernel Simulation
kcal	Kilocalories
LEDS	Low Emissions Development Strategies
LUC	Land Use Change
Mi	Implementation of mathematical models
ME	Material Use Efficiency
MF	Material Footprint
MJ	Megajoule
MSW	Municipal Solid Waste
N_2O	Nitrous Oxide
NDC	Nationally Determined Contributions
NEET	Not in Employment, Education or Training
OECD	Organisation for Economic Co-operation and Development
OHI	Ocean Health Index
PAGE	Partnership for Action on Green Economy
PM2.5	Particulate matter with a diameter of less than 2.5 micrometers
PPP	Purchasing Power Parity
PST	Problem-solving Technique
R&D	Research and Development
SC	Scenario
SDG	Sustainable Development Goal
SE	Social Equity
SL	Sustainable Land Use
SP	Social Protection
TS	Target Systems
UHC	Universal Health Coverage
UN COM-TRADE	United Nations International Trade Statistics Database
UN ESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UN Women	United Nations Entity for Gender Equality and the Empowerment of Women
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
UNRISD	United Nations Research Institute for Social Development
USD	United States Dollar
WB	World Bank
WHO	World Health Organization

01 INTRODUCTION

Countries are obliged to meet internationally agreed targets on Sustainable Development Goals (SDGs), Paris Climate Agreement, and Aichi Biodiversity Targets to reduce poverty, increase equality, mitigate global warming, and protect environment while achieving economic growth. Thus, the short- and medium- term national development and action plans must be aligned with the long-term sustainability goals. To help the policymakers in their planning and decision-making, an innovative tool is needed to gauge the impacts of current policies and investments on achieving long-term sustainability targets. The Green Growth Index and Simulation Tool are complementary approaches that are being developed through GGGI's Green Growth Performance Measurement (GGPM) Program to measure country performance in green growth. The Index measures the country-level green growth performance based on a common set of performance metrics in four green growth dimensions: efficient and sustainable resource use, natural capital protection, green economic opportunities, and social inclusion (Acosta et al., 2019, 2020). On the other hand, the Tool allows the users to enhance their knowledge on how countries' green growth performance can be influenced by different policy and investment options in major economic sectors: energy, water, waste, transport, industry, agriculture, and forests.

By coupling the Simulation Tool with the Green Growth Index, policy and investment scenarios can inform the policymakers on how their current decisions will affect their ability to achieve their targets in the future. The Tool's comprehensive framework will allow to develop scenarios that will be useful for tracking progress in achieving SDG and Aichi Biodiversity targets and developing or enhancing climate-related policy instruments such as Nationally Determined Contributions (NDCs), National Adaptation Plans, and Low Emissions Development Strategies (LEDS).

Through the Green Growth Index and Simulation Tool, GGGI aims to:

- **Provide a composite index to measure, track, and communicate green growth performance.** The 2020 Green Growth Index covers 117 countries. It can be used to raise awareness and sustain green growth momentum in the public and private sectors. It ranks and benchmarks the countries' green growth performance through a common set of variables based on publicly available and credible data. Because the index is based on a robust sustainability framework, it can highlight the achievements of the SDGs that are linked to green growth.

- **Improve current knowledge on green growth and its drivers.** The Simulation Tool provides an interactive learning experience and enhances users' knowledge on green growth planning and strategy development. Because the tool can be used to simulate and understand the impacts of different policy and investment options on green growth performance, it can provide input in planning and supporting the formulation of green growth policies in key sectors. The Phase 1 Simulation Tool covers its application in three case study countries, namely, Hungary, Mexico, and Uganda.

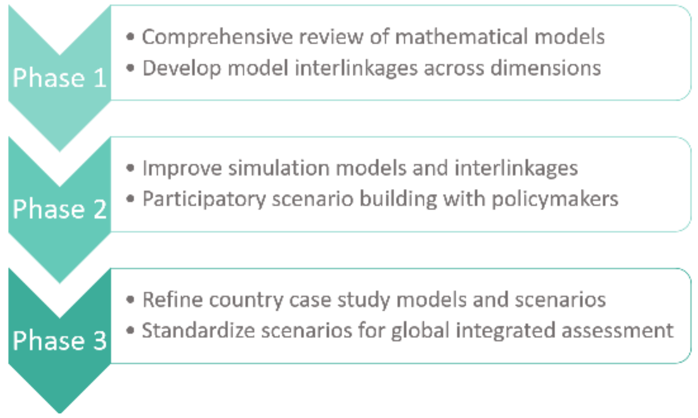
- **Foster a data- and evidence-driven approach in identifying and developing strategies on green growth.** The index and tool are linked to an evidence library, allowing users to have access to the data and empirical evidence underpinning the framework and simulations. This provides credibility to the results and allows them to be used to inform and guide green growth planning. The evidence library can act as a useful starting point for performing further studies and analysis on indicators and sectors related to green growth performance.

The development of the Simulation Tool follows three phases:

Phase 1 (2020) consists of identifying and applying models which provide interlinkages among the indicators and require available data online. Models that require data to be collected from countries were kept first for use in Phase 2.

Phase 2 (2021-2022) consists of conducting stakeholder dialogues to create/identify policy scenarios and collect feedback on the Phase 1 Simulation Tool. It also aims to improve the Phase 1 Simulation Tool by adding models that require data collected from agencies and integrating feedback from stakeholder dialogues.

Phase 3 (2023) consists of refining the models and scenarios by adopting lessons learned from different country applications of the Phase 2 Simulation Tool and standardizing them for more global applications.



This report, which target users who are mainly modelers, presents the development of the Phase 1 Simulation Tool. Chapter 2 discusses the interlinkages of Simulation Tool to the conceptual framework of the Green Growth Index and presents the process and methods for developing the Tool's models and scenarios. Chapter 3 presents the mathematical models, the input and outputs variables for the equations, and sources of data. Chapter 4 discusses selected results from the scenarios analyses for energy and transport sector as well as land and water use for Hungary, Uganda, and Mexico. Chapter 5 briefly discusses the limitations of the Phase 1 Simulation Tool and steps ahead to address them in developing the Phase 2. The Appendices provide details on the review of online tools and peer reviewed articles which, among others, were conducted to identify the mathematical models for the indicators of the Green Growth Index.

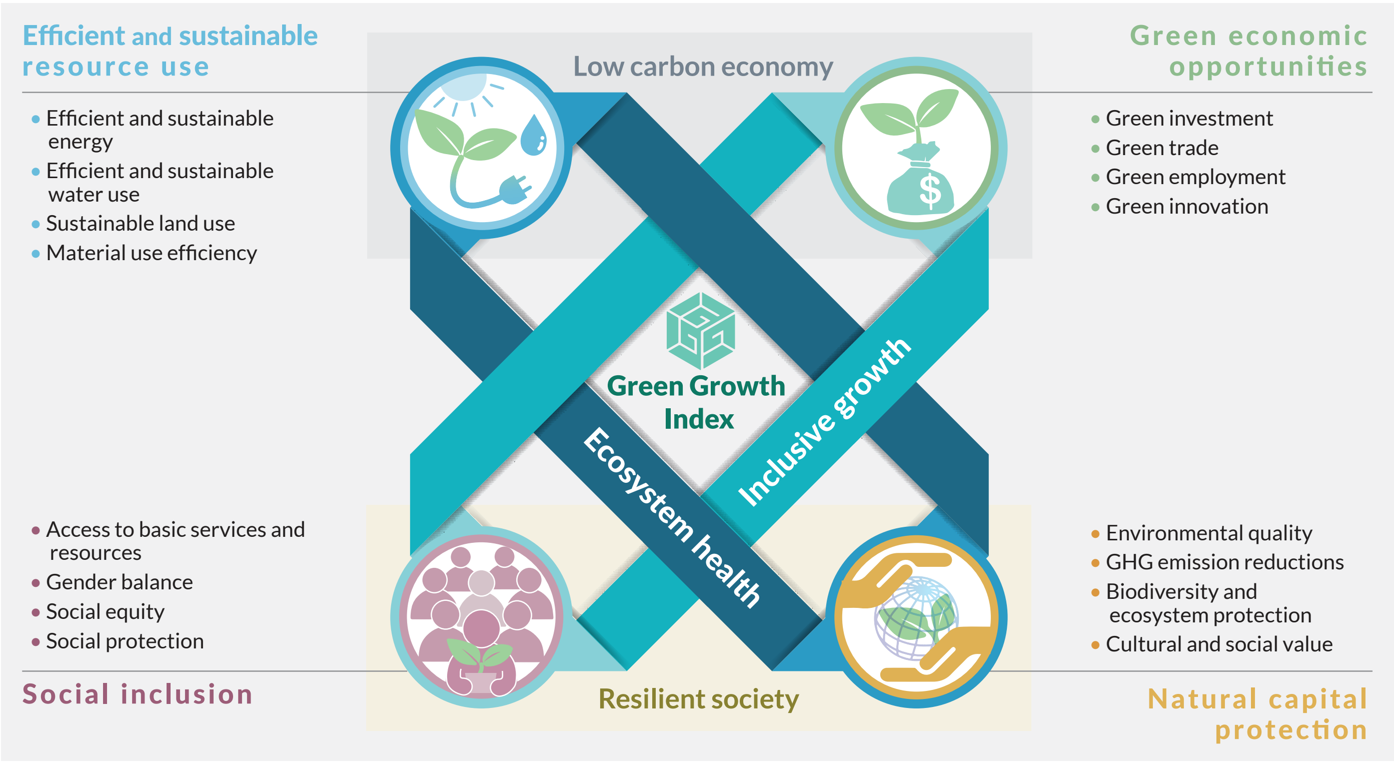
2.1 Underlying concepts

2.1.1 Framework for green growth

The Simulation Tool builds on the four dimensions of green growth – efficient and sustainable resource use, natural capital protection, green economic opportunities, and social inclusion (Figure 1). These dimensions are closely interlinked based on the concepts of low carbon economy, resilient society, ecosystem health, and inclusive growth. The details on these interlinkages are described in the technical report on the Concepts, Methods, and Applications of the Green Growth Index (Acosta et al., 2019) and summarized in the report on Green Growth Index 2020 – Measuring performance in achieving SDG targets (Acosta et al., 2020) as follows: *"Using natural resources efficiently and sustainably will produce more goods and services with less resources. It will protect natural capital including water, energy, land, and materials as well as the ecosystem services they provide. A healthy ecosystem characterized by, for example, fertile soil, multifunctional forests, productive land and seas, good quality freshwater and clean air, and pollination increases economic productivity and creates new economic opportunities. Green Growth advocates the protection of natural capital because it provides sources of economic growth such as green jobs, trade, and investment. And it emphasizes not only people benefitting from growth but also people contributing to the efficient use and protection of natural resources. This makes social inclusion a key mechanism to both achievement and distribution of gains from green growth."*

Each dimension in the Green Growth Index is defined by four indicator categories (Figure 1).These indicator categories are important to transitioning to green growth pathways. The efficient and sustainable resource use covers energy (e.g., transport, industry, residential), water (e.g., freshwater, groundwater), land (e.g., agriculture, forest, cities), and materials (e.g., domestic, imports). The natural capital protection dimension includes improvement of environmental quality (e.g., air, land, water), reduction of GHG emissions (i.e., CO_2 and non-CO_2 emissions), protection of biodiversity and ecosystem (e.g., freshwater, terrestrial, marine, forest), and preservation of cultural and social value (e.g., species and their habitat). Green economic opportunities is created through investment, trade, innovation, and employment. Social inclusion dimension includes access to basic services and resources (e.g., water and sanitation, electricity and clean fuels, internet and mobile communications), gender balance (i.e., political representation, equal pay, access to finance), social equity (i.e., income distribution, urban-rural, youth's future), and social protection (i.e., pension, healthcare, adequate housing). Capturing the interlinkages among the indicator categories within and across the green growth dimensions is an important feature of the Simulation Tool. These interlinkages are represented through simulation models, which mimic the real-world situation.

Figure 1. Conceptual framework for the Green Growth Index



2.1.2 Architecture of simulation models

There are two main theoretical viewpoints on the development and application of (computer) simulations – problem-solving technique (PST) and description of patterns of behavior (DPB). Durán (2019) identified the main differences between them in terms of objectives of the simulation and role of mathematical models in simulation. For PST, the simulations are being used to find solutions to mathematical models that are analytically intractable or complex systems that are mathematically intractable (i.e., pen-and-paper mathematics). In this case, the models (of a complex system) are object of the investigation and the simulation is used as an instrument to implement the mathematical models and solve mathematical problems. For DPB, the simulations are considered as tools that visualize various behavioral patterns of and draw inferences on the properties and dynamics of a system or its sub-systems. As such, the simulation represents the response behavior of the target system and the object of investigation is the system's dynamics. According to Durán's (2019) analysis, the mathematical models in DPB simulations are:

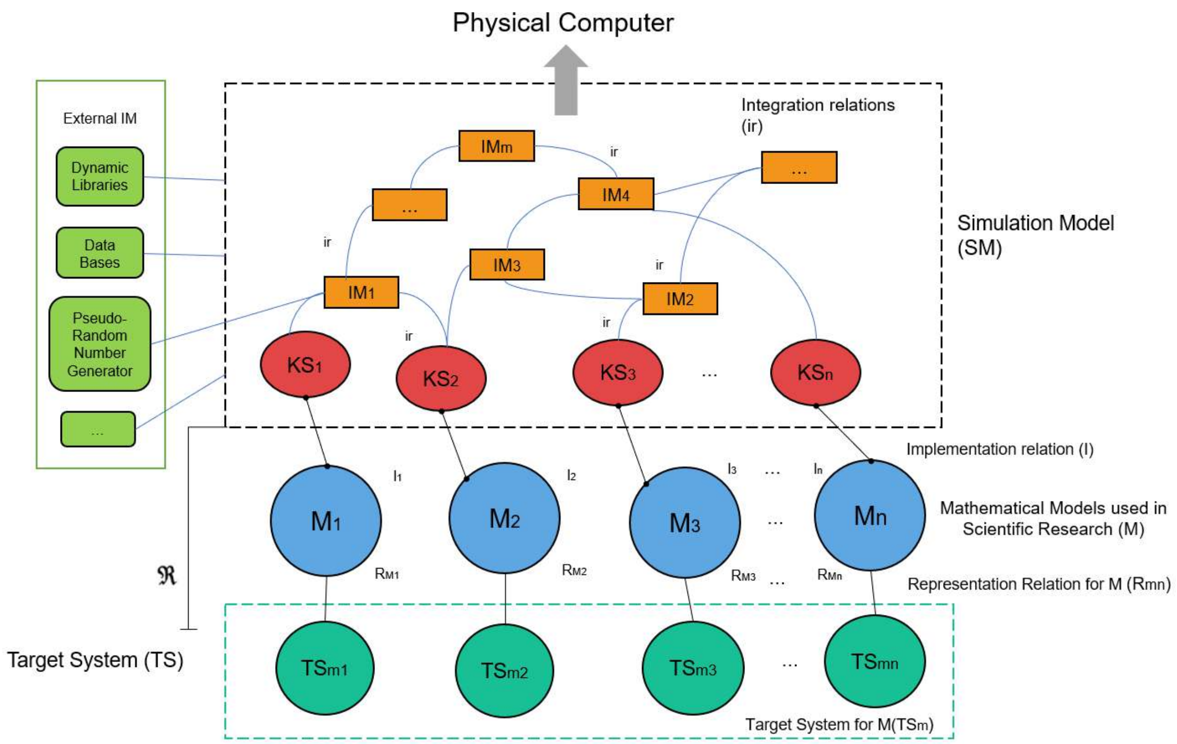
- exogenous to the simulation models, and thus not able to describe the behavior of the target system and its dynamics;
- not the object of investigation, but only a part of a holistic system that includes databases, integration modules, software units, etc.; and
- different from simulation models, which demand a higher level of complexity.

The multi-dimensionality of the Green Growth Index requires analysis that builds on the DPB simulations. The architecture for building the Simulation Tool for the Green Growth Index follows that of Durán (2020: p. 301), which argues that "simulation models can be distinguished from other forms of models by the many algorithmic structures, representation relations, and new semantic connections". Figure 2 presents the architecture for DPB simulations, showing the relationship between the simulation model and mathematical models. Mathematical models are commonly expressed in equations, which show the relationship between different variables – decision, input, state, exogenous, random, and output variables. The variables and their relationships in the equations describe the nature of the target systems. In the Simulation Tool for the Green Growth Index, the target systems are the indicator categories of the green growth dimensions. The mathematical models for the indicator categories (M_1, M_2, ..., M_n) describe the dynamics of the indicators, which are used to represent these systems (i.e., representation relation). For example, in the case of efficient and sustainable energy use, the mathematical models are equations that describe the dynamics in supply of primary energy and consumption of renewable energy. The details on the indicators for each green growth category are presented below (see Chapter 2.1.3 Green growth indicators).

While the mathematical models provide framework for the simulation of the target systems, they remain exogenous to the simulation model (Figure 2). Durán (2020: p. 307) refers to the "implementation of mathematical models (M_i) in the formalism of a programming language" as kernel simulation (KS_i), where each ith corresponds, to specific model. The kernel simulations, thus, translate the mathematical models into a computer language, which is Python software in the case of the Simulation Tool for the Green Growth Index. Because kernel simulation is a core part of a simulation model, the choice of programming language is not trivial. The general criteria for choosing a programming language include the targeted platform, elasticity/simplicity of a language, time to production, performance, and support and community (Reghunadh & Jain, 2011). Python fits to these criteria (see Chapter 2.2.4 Model programming).

The ability of the simulation model to handle complexity is facilitated through the integration modules (IM_k), which have two main functions – First is to integrate the modules that are exogenous to the simulation model including databases for the variables, protocols (or rules) for using data or generating numbers, and libraries for language or other models, and second is to ensure that all integration modules, including both external and internal IM_k, are synchronized and compatible among each other (Durán, 2020). The integration relations (ir) connect the kernel simulations and integration modules, allowing databases and rules to be linked to the appropriate variables. Moreover, they connect the kernel simulations with each other, creating the interlinkages between the different target systems and "clustering numerous models into one simulation model" (Durán, 2020: p. 306). This feature is very relevant for capturing the interlinkages of the four green growth dimensions, and thus the concepts that represent green growth transition (i.e., low carbon economy, ecosystem health, resilient society, and inclusive growth). Thus, the integration relation is an important aspect to consider when conceptualizing the interlinkages among the target systems and identifying the mathematical models that represent these systems.

Figure 2. A general architecture for simulation models based on description of patterns of behavior



Source: Adapted from Durán 2020

2.1.3 Green growth indicators

In building the Simulation Tool for the Green Growth Index, the indicators provide a quantitative basis (i.e., metrics) for identifying and developing the mathematical models. They determine the implementation of the mathematical models by providing knowledge on the data requirements. Although many mathematical models would be available to describe the dynamics of the indicator categories, their implementation could be restricted by data availability. Similarly, the integration relation may not be established if the data providing the links between different indicators are not available. In some cases, however, not only the data but also mathematical models (due to lack of prior knowledge) are not available to describe the links between indicators in different green growth dimensions. Figure 3 presents the 36 indicators in the Green Growth Index, classified according to dimension and indicator categories. The objective of the Simulation Tool is to create as much interlinkages as possible among the different indicators across categories and dimensions, which will enhance the relevance of the Tool in assessing co-benefits of a given policy or investment decision related to specific indicator. The interlinkages have been identified except for those indicators with asterisks. In many cases, this task was challenged by lack of data from online sources and mathematical models from literature. This justifies the development of the Simulation Tool by phases, allowing stepwise identification of solutions to the problems. It will be important to further engage in expert consultations in the next phase of developing the Simulation Tool to address these gaps. The Phase 2 development of the Tool will aim to link the different mathematical models for the different indicators across dimensions to allow co-benefit assessments (Figure 4).

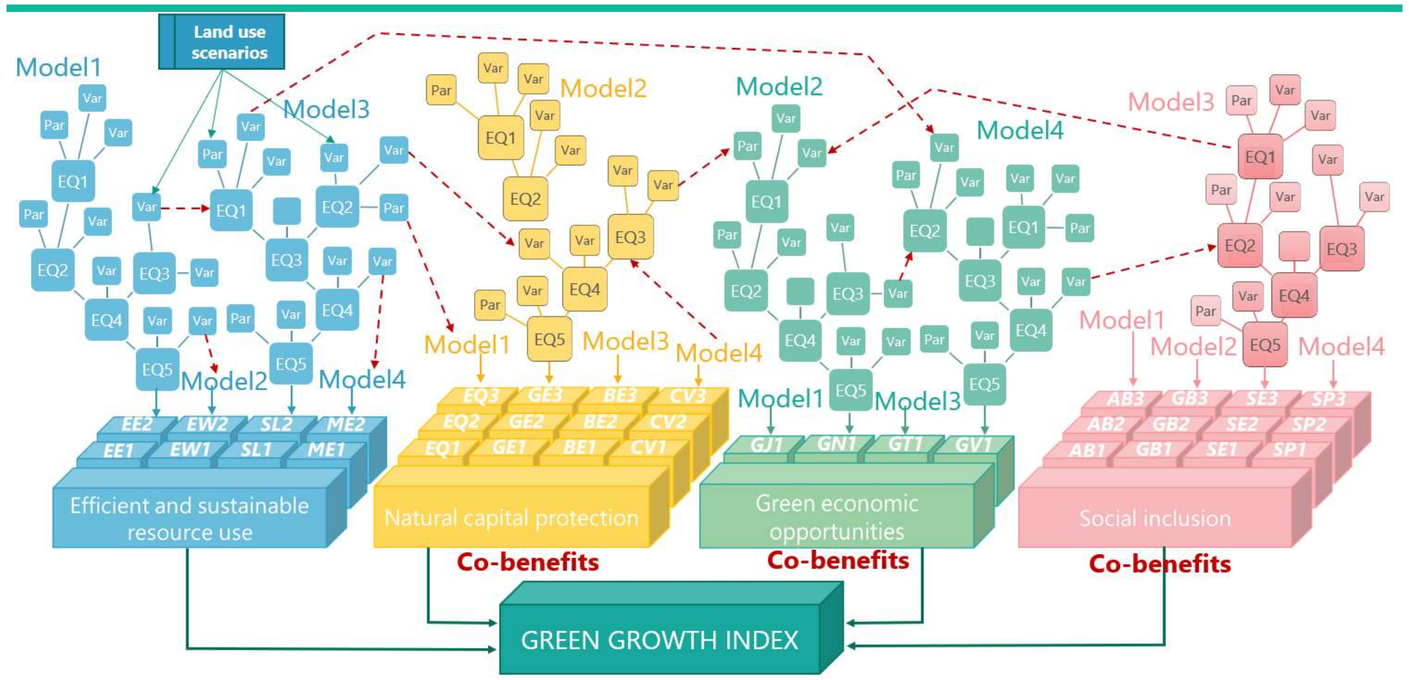
Figure 3. Indicator framework for the Green Growth Index

Green Growth Index

Dimensions [Goals]	Indicator categories [Pillars]		Indicators [metrics]
Efficient and sustainable resource use	Efficient and sustainable energy	EE1	Ratio of total primary energy supply to GDP (MJ per $2011 PPP GDP)
		EE2	Share of renewable to total final energy consumption (Percent)
	Efficient and sustainable water use	EW1	Water use efficiency (USD per m^3)
		EW2	Share of freshwater withdrawal to available freshwater resources (Percent)
	Sustainable land use	SL1	Soil nutrient budget (Nitrogen kilogram per hectare)
		SL2	Share of organic agriculture to total agricultural land area (Percent)*
	Material use efficiency	ME1	Total domestic material consumption (DMC) per unit of GDP (Kilogram per GDP)
		ME2	Total material footprint (MF) per capita (Tons per capita)
Natural capital protection	Environmental quality	EQ1	PM2.5 air pollution, mean annual population-weighted exposure (Micrograms per m^3)
		EQ2	DALY rate due to unsafe water sources (DALY lost per 100,000 persons)
		EQ3	Municipal solid waste (MSW) generation per capita (Tons per year per capita)*
	Greenhouse gas emissions reductions	GE1	Ratio of CO_2 emissions to population, including AFOLU (Tons per capita)
		GE2	Ratio of non-CO_2 emissions to population, excluding AFOLU (CO_2e per capita)
		GE3	Ratio of non-CO_2 emissions in agriculture to population (CO_2eq tons per capita)
	Biodiversity and ecosystem protection	BE1	Average proportion of key biodiversity areas covered by protected areas (Percent)*
		BE2	Share of forest area to total land area (Percent)
		BE3	Above-ground biomass stock in forest (Tons per hectare)
	Cultural and social value	CV1	Red list index (Index)*
		CV2	Tourism and recreation in coastal and marine areas (Score)*
		CV3	Share of terrestrial and marine protected areas to total territorial areas (Percent)*
Green economic opportunities	Green investment	GV1	Adjusted net savings, including particulate emission damage (Percent GNI)*
	Green trade	GT1	Share of export of environmental goods (OECD and APEC class.) to total export (Percent)
	Green employment	GJ1	Share of green employment in total manufacturing employment (Percent)
	Green innovation	GN1	Share of patent publications in environmental technology to total patents (7 yrs moving ave.)
Social inclusion	Access to basic services and resources	AB1	Population with access to safely managed water and sanitation (Percent)
		AB2	Population with access to electricity and clean fuels/technology (Percent)
		AB3	Fixed Internet broadband and mobile cellular subscriptions (Number per 100 people)
	Gender balance	GB1	Proportion of seats held by women in national parliaments (Percent)
		GB2	Gender ratio of account at a financial institution or mobile-money-service provider (Ratio)
		GB3	Getting paid, covering laws and regulations for equal gender pay (Score)
	Social equity	SE1	Inequality in income based on Palma ratio (Ratio)*
		SE2	Ratio of urban-rural access to basic services, i.e. electricity (Ratio)
		SE3	Share of youth (aged 15–24 years) not in education, employment, or training (Percent)*
	Social protection	SP1	Proportion of population above statutory pensionable age receiving pension (Percent)*
		SP2	Universal health coverage (UHC) service coverage index (Index)*
		SP3	Proportion of urban population living in slums (Percent)

*Note: *Interlinkages with other indicators will be improved in Phase 2 Simulation Tool*

Figure 4. Illustration on interlinkages of the green growth indicators resulting in co-benefits



The identification and development of mathematical models require a common understanding of their basic components based on the objective of the Simulation Tool. As the Tool is aimed to be applied to assess the impacts of alternative policy and investment options on green growth performance in major economic sectors, the mathematical models consist of variables that can link sectoral scenarios to the green growth indicators. A simple representation of mathematical models using equations is as follows:

$$Y_t = \alpha + \beta_1 X_{1t} + \beta_2 X_{2t} + \cdots + \beta_n X_{nt} + \delta_t \quad \text{where } \delta_t = \partial \frac{\rho_t}{\rho_{t-1}}$$

In these equations, **Y** represents the green growth indicators, which values in time **t** are influenced by the changes in the values of the exogenous variables $\mathbf{X}_n$ and interrelationships among them. The variable **δ** with its own equation represents an endogenous variable, which value depends on the other exogenous variables. The equations for the green growth indicators consist of the following types of variables:

1. Output variables (i.e., **Y**, **δ**) which values are computed from the equations in the simulation model and depend on the data of the exogenous variables.
2. Input variables (i.e., $\mathbf{X}_n$, **ρ**) are exogenous to the simulation model and their values are available from the databases and dependent on time **t** (i.e., time-series data).
3. Input parameters (i.e., **βn**, **δ**) are also exogenous to the simulation model but not dependent on time as they have fixed values (e.g., regression coefficients). They are also referred to as state variables.

In case the equation is linked to the policy or investment options, which represent the scenarios in the simulation model, then input variables are referred to as input scenarios to emphasize the variables that drive the changes on the green growth indicators. In the above equations, if **δ** represents the equation for the scenarios, then **ρ** becomes an input scenario. The equations in the Phase 1 Simulation Tool represent the dynamic models, where dynamics lie from the time-dependent interrelationships among the variables. Spatial dynamics will be added in developing Phase 2 Simulation Tool, allowing the use of geographic information system (GIS) databases to capture dynamics in land use, biodiversity, and ecosystem. However, many GIS databases are not available online and will need to be collected from government agencies and research institutions.

2.2 Methods

Five consecutive steps were conducted to develop the Phase 1 Simulation Tool for the Green Growth Index – review of online tools and literature, inventory of relevant models, validation of interlinked models, model programming, and case study applications. These steps were aligned to the architecture of simulation models based on DPB (Figure 2). The details on these steps are discussed below.

2.2.1 Review of online tools and literature

For step 1, a comprehensive review of online tools and dynamic models from peer reviewed articles was conducted to understand the nature of the target systems (TS), as represented by the indicator categories, determine best practices in developing online simulation tools, and identify mathematical models that can describe the system's dynamics. The criteria for selecting the online tools and mathematical models include their relevance to the indicator categories and availability of the documentation of online tools and equations in models from literature. The literature review focused on peer reviewed articles to ensure that the mathematical models were already validated by experts. Table 1 presents an overview of the reviewed 128 online tools and 161 peer-reviewed articles. The lists of these tools and articles are presented in Appendix 1 and Appendix 2, respectively. For both tools and articles, most of the models are related to efficient and sustainable resource use and natural capital protection (Table 1). On the other hand, there is a general lack of dynamic models for green economic opportunities and social inclusion particularly in online tools. Generally, many of the mathematical models cover multiple indicator categories. More details on the assessment of the reviewed online tools and peer-reviewed articles are presented in Appendix 3 and Appendix 4.

Table 1. Summary of review of online tools and dynamic models by indicator categories

Dimension	Indicator Categories	Online tools		Peer-reviewed articles	
		Number	Share to total	Number	Share to total
Efficient and sustainable resource use	Efficient and sustainable energy	17	25%	25	31%
	Efficient and sustainable water use	9		16	
	Sustainable land use	3		5	
	Material use efficiency	3		4	
Natural capital protection	Environmental quality	9	37%	13	26%
	GHG emissions reduction	23		16	
	Biodiversity and ecosystem protection	12		9	
	Cultural and social value	3		3	
Green economic opportunities	Green investment	1	3%	16	15%
	Green trade	0		0	
	Green employment	2		2	
	Green innovation	1		4	
Social inclusion	Access to basic services and resources	4	8%	2	9%
	Gender balance	1		4	
	Social equity	1		5	
	Social protection	4		4	
Multiple indicator categories*		30	23%	26	16%
Other**		5	4%	5	3%
TOTAL		**128**	**100%**	**161**	**100%**

*Tools that relate to more than one green growth indicator categories
**Tools that did not explicitly fall into any indicator categories

2.2.2 Inventory of relevant models

For step 2, an inventory of relevant models was conducted by mapping them out to specific green growth indicators, identifying how to link different models from various literature that belong to a given target system (i.e., indicator category), and checking the availability of online data for the variables of the interlinked models. Flow diagrams were manually laid out to visualize the interlinkages among the different mathematical models, which were identified to be suitable for describing the dynamics of the indicator categories. These flow diagrams were also useful for implementing the mathematical models into kernel simulations and establishing the integrated modules (Figure 2). The models which cannot be implemented due to lack of online data were reserved for the Phase 2 application of the Simulation Tool.

As shown in Table 1, the mathematical models for few indicators were difficult to find. To address this gap, additional literature review was conducted to determine the drivers of change for those indicators. The knowledge gained from the review helped in identifying the variables that can be used to run regression analyses, which results determined the input variables, input parameters, and their interrelationships in the regression equations. In this way, mathematical models based on conceptual and empirical assessments were generated for the indicators.

2.2.3 Validation of interlinked models

For step 3, three validation approaches were conducted. First, the interlinked models for the target systems, which were identified for the Phase 1 application, were validated by implementing them in Excel software and comparing the results to the actual data. When the model results from Excel approximated the actual data of the indicators, the mathematical models were translated into Python programming codes and implemented in the Simulation Tool. Second, the flow diagrams created from manual layout (as conceptualized from the mathematical models) and those from the programming codes ("graphmodels" as illustrated in Chapter 2.2.4 Model programming) were compared for consistencies. Third, the experts from the international expert group for the Green Growth Index were consulted on the relevance and validity of the mathematical models for specific indicators. Further consultations are planned to be conducted during the Phase 2 application of the Simulation Tool.

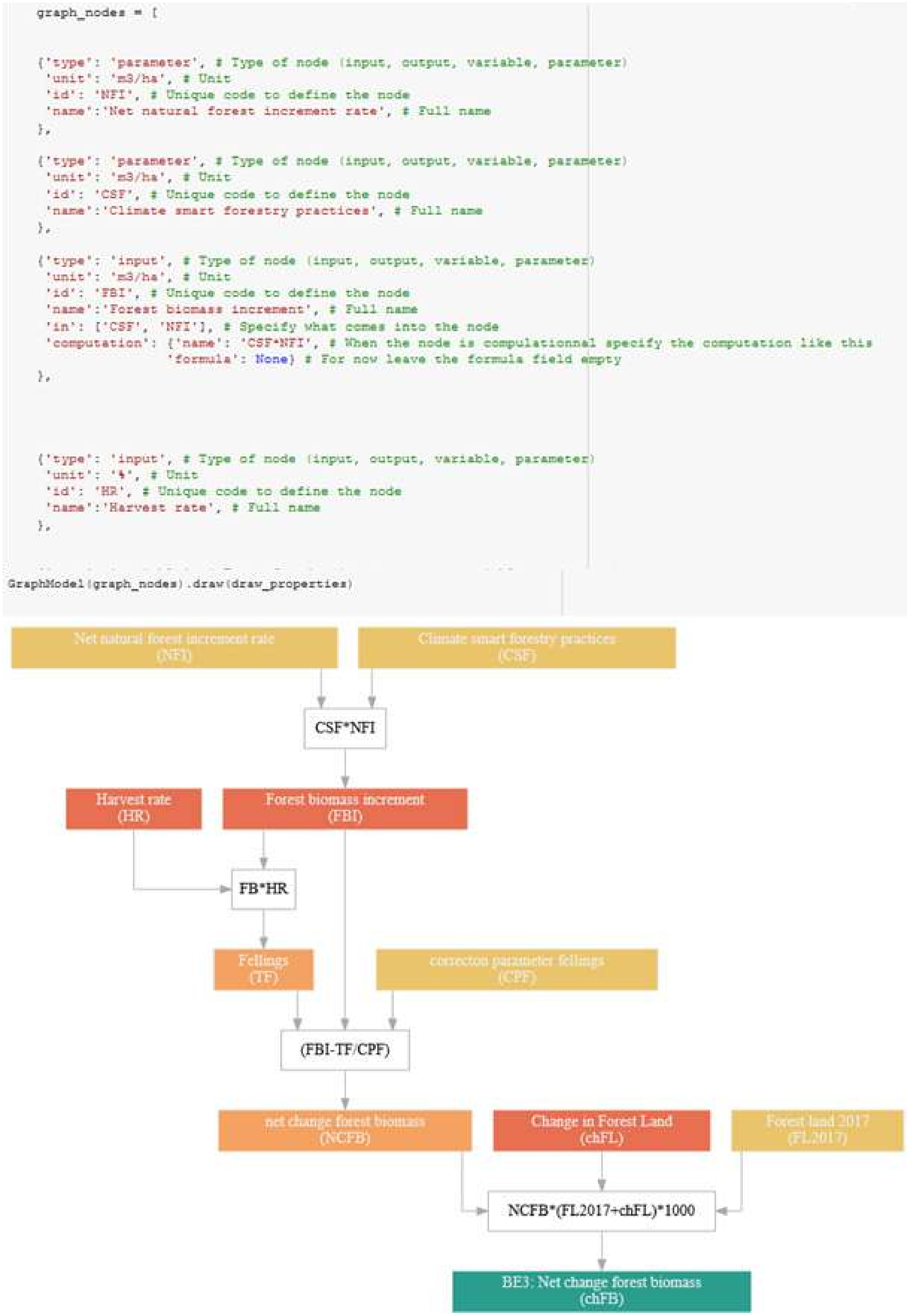
2.2.4 Model programming

For step 4, the mathematical models were implemented in simulation models using the Python programming language. Figure 5 presents a screenshot of the codes for the Simulation Tool and its corresponding "graphmodel". The reasons for choosing Python program to build the Simulation Tool for the Green Growth Index are as follows:

- It is compatible to different platforms including Windows, Mac, Linux, etc.
- It is a readable and an understandable language and has a language library.
- It is an easy to learn language, thus reducing time for production (i.e., less time to go live).
- It is known for its solid and high performance (i.e., run at quite acceptable speeds).
- It is free of charge, thus allowing good community of practice of sharing knowledge and libraries.

Another important consideration for choosing Python is its versatile applications including web and desktop apps, thus allowing the development of graphical interface for showing simulation results and complex calculation systems, facilitating the integration of different mathematical models for the interlinked systems of the green growth dimensions. After the application of Phase 2 Simulation Tool in a country, policymakers will be trained to run scenarios on the Tool and use it for different planning and policy purposes. An interactive interface will be created based on the scenarios identified by the policymakers.

Figure 5. Example of implementation of mathematical models in programming codes



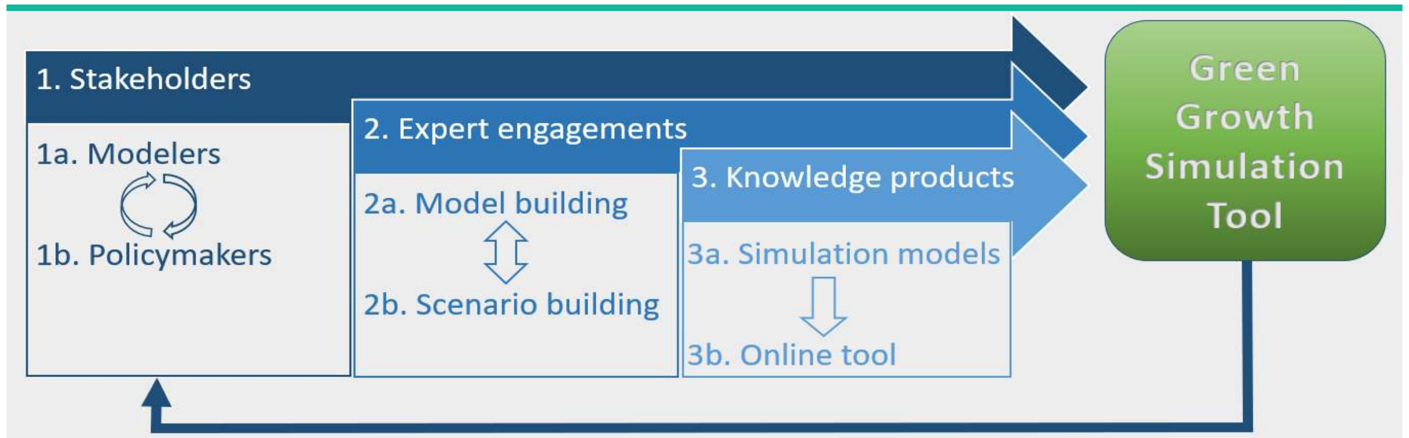
2.2.5 Case study applications

For step 5, the final step, the Simulation Tool was applied in selected countries to illustrate the results of scenario analysis. Three countries were identified as case studies in this report – Hungary, Uganda, and Mexico (see Chapter 4 Scenario analysis case studies).

2.3 Design elements

The development phases of the Green Growth Simulation Tool are guided by three elements – stakeholders, expert engagements, and knowledge products (Figure 6). The Simulation Tool consists of two interlinked knowledge products, the simulation models that facilitate the analysis of scenarios and an online tool that allows choice of scenarios and visualization of scenario outcomes. The knowledge products as well as the form of expert engagements required to develop these products depend on the types of stakeholders. The main stakeholders are modelers and policymakers who will contribute as both developers and users of the Simulation Tool. The stakeholders' roles as well as the description of the other two elements are discussed in details below.

Figure 6. The elements guiding the development of the Green Growth Simulation Tool



2.3.1 Stakeholders

Modelers

Modelers play an important role in both developing and using the simulation models. In the Phase 1 development of the Simulation Tool, the modelers were mainly represented by the GGPM team and selected members of the Green Growth Index International Expert Group. Through comprehensive literature assessment[1], they laid the groundwork for the Phase 2 development (Chapter 2.2 Methods). The assessment results are presented in this technical report, which is the first published knowledge product for the Simulation Tool. For Phase 2, the modelers from renowned research institutions, which have developed simulation models relevant to the green growth indicators, will be invited to contribute to further develop the Simulation Tool. More members of the Green Growth Index International Expert Group with modeling experience and expert reviewers of the 2020 Green Growth Index, most of which are members of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Task Force on Model and Scenarios and ongoing Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, will also be invited to collaborate in the development of the Phase 2 Simulation Tool.

The application of simulation models from the Green Growth Simulation Tool was identified as one of the pilot case studies for implementing the Nature Futures Framework scenarios (Rosa et al., 2017)[2]. The Framework, which was developed by the IPBES Task Force on Model and Scenarios, emphasizes positive futures for different nature perspectives including nature for nature (i.e., environment), nature for society (i.e., economic), and nature for culture (i.e., social). Because the green growth framework is multidimensional (Chapter 2.1.1 Framework for green growth) and the indicators' simulation models are interlinked to measure co-benefits (Chapter 2.1.3 Green growth indicators), the Green Growth Simulation Tool will allow assessment of synergies in the three nature futures perspectives. The modelers from different research institutions are expected to participate in the development and use of the simulation models of the Simulation Tool for the Nature Futures Framework scenarios in 2021.

Policymakers

The policymakers are important targets users of the Green Growth Simulation Tool. However, to make the Tool's results relevant to them, it will be important to engage them in identifying and developing scenarios that are relevant to their countries' policy decision-making and investment plans. Thus, they will also play a key role in developing the Simulation Tool, providing valuable inputs to scenario building. The modelers from the GGPM team and, if possible, relevant research institutions will be collaborating with the policymakers to integrate those scenarios in the simulation models of the Tool. The policymakers will consist of experts from relevant government agencies in countries where Phase 2 Simulation Tool will be applied.

[1]The unpublished document on the methodology developed by the Vivid Economics and Economist Intelligent Unit for the pilot version of the Simulation Tool also provided relevant knowledge for the Phase 1 Simulation Tool.
[2]During the online workshop on modelling Nature Futures Framework (NFF) scenarios, which was organized by the IPBES Task Force on Models and Scenarios on 12-15 January 2021, several members of the Task Force and participants to the workshop agreed to take up the Green Growth Simulation Tool to implement the NFF's biodiversity and ecosystem related scenarios.

In 2021, for example, GGGI will collaborate with the Ministry for Innovation and Technology in Hungary to adapt and apply Green Economy Model (GEM) low-carbon scenarios (Bassi, 2020). The application of the Simulation Tool will investigate how these scenarios are aligned with the SDGs, which governments are committed to achieve by 2030 and beyond. The scenario analysis will be conducted in the context of the European Green Deal and Hungary's national climate neutrality commitment. By assessing the co-benefits using the Simulation Tool, it will be possible to determine the potential contribution of the green deal on reducing biodiversity loss and social inequality. These co-benefits are added social, economic, or environmental benefits above and beyond the direct benefits of reducing greenhouse gas (GHG) emissions and the economic indicators already covered in the analysis performed with GEM.

2.3.2 Expert engagements

Model building

Table 2 presents the characteristics of the models used for developing the Simulation Tool. The models are based on the concepts and theories (i.e., mathematical, theory-driven, deductive) relevant to green growth, capture dynamic changes into the future (i.e., processed-based, dynamic, continuous, predictive), and represent quantifiable relationships that are not random (i.e., quantitative, deterministic, linear or non-linear). Cain (2014) explains that some mathematical models, although guided by theories, have been derived from statistical mechanics, thus blurring the distinction between mathematical and statistical models. Moreover, the use of statistical models to estimate parameters in mathematical equations is increasingly becoming popular among mathematical modelers, causing overlaps in using the terms mathematical and statistical models (Porgo et al., 2019). Model building in the Phase 1 Simulation Tool involved comprehensive review of mathematical models from online tools and peer-reviewed articles, assessment of relevance to green growth of these models, and validation of interlinkages among the models (Chapter 2.2 Methods). For many green growth indicators for efficient and sustainable resource use, natural capital protection, and green economic opportunities, mathematical models which explain the behavior of the systems are available. In some cases, this does not hold for social inclusion indicators. And for these cases, mathematical models are represented by deductive models, mainly based on statistical analyses conducted to identify the relationship of the indicators to relevant explanatory variables. This method, which was applied to address the model gaps for social inclusion, aligns with the ideas from Cain (2014) and Porgo et al. (2019).

Because system dynamics models are complex due to causality and feedbacks, they "require participation of users and expert judgment" (IEEP et al., 2009: p. 33). During the Phase 2, two groups of expert engagement will be conducted for model building – modelers and reviewers[3]. First, a modeling group will be formed to actively support the model building. Experts in this group are either the developers of the mathematical models or modelers working on similar models, which have been identified and reviewed as relevant for the Simulation Tool during Phase 1. Collaboration with this group of experts is important in building model for the Simulation Tool for the following reasons:

- It will ensure that the model assumptions are adaptable to the green growth context.
- It will help align the models to the characteristics defined in Table 2.
- It will provide access to information and data on the models that were not published.
- It will gather interdisciplinary expert opinion on how to link models for different green growth indicators.
- It will support the validation of the integrated (coupled) models and applicability of scenarios.
- It will enhance the credibility of using the models, which were initially designed for other purposes, to address green growth issues.

Second, a group of expert reviewers with modeling experience will be formed to provide comments and suggestions on the model structure and assumptions as well as review the technical reports on the concept, methods, and application of the Simulation Tool. Various online methods for expert engagement will be used including virtual meetings, webinars, and surveys.

Scenario building

While engaging with modelers and reviewers in model building process will ensure that the mathematical models are sophisticated, accurate, precise, realistic, general, and theory-based, engaging with policymakers will ensure that the mathematical models are made relevant to policy process and they can use them (Clapham Jr. et al., 1979). "Coupling models with scenarios to explore future possibilities and options" increasingly plays an important role in policy process (Ferrier et al., 2016: p. 12). Scenarios are defined in different ways depending on the objectives of their use. Table 3 presents the main characteristics of the scenarios relevant to scenario building of the Simulation Tool. Based on a comprehensive review of literature and assessment of definitions of scenarios, Spaniol and Rowland (2019) suggested that future temporal property, possibility or plausibility, and presentation as "sets" are the three core concepts that define scenarios. Five desirable qualities need to be taken into account when building scenarios – consistency, contrast, comparability, applicability, and appeal (Dammers et al., 2019). A set of consistent scenarios should also be able to explore the developments on conflicting issues or social discrepancies. While good scenarios show contrasting directions, they should also remain comparable for eliciting key messages. Finally, scenarios should be applicable and appeal to the target groups to encourage engagement. According to Dammers et al. (2019), the relevant objectives for building scenarios include achieving new policy insights, supporting communication among policymakers, and encouraging engagement of policymakers. The types of scenarios must address the objectives of the target groups in building or using them. The three most commonly used types of scenarios for policy include baseline trend or predictive scenarios, normative or visions scenarios, and explorative or descriptive scenarios. The baseline trend scenarios, also known as business-as-usual (BAU), serve as point of reference for the other types of scenarios. The normative scenarios, also known as ex-ante assessment, assess the different options to reach a specified goal, for example, how can governments reach their targets on GHG emission reduction as expressed in their NDCs. The explorative scenarios forecast the impacts of a range of plausible policy options on the condition of the system under investigation. For both Phases 1 and 2 development of the Simulation Tool, the baseline trend and explorative scenarios are applied.

[3]To acknowledge expert collaboration and knowledge ownership, the modelers will be invited to be as lead authors and expert reviewers as contributing authors to the publications on Phase 2 Simulation Tool.

Table 2. Main characteristics of the models relevant to the Simulation Tool

Types of models	Description of the models and comparison to other types of models
Mathematical	Mathematical models are built on "principle-driven" manner, representing the behavior of real world systems in mathematical concepts and language (i.e., equations, inequalities, functions, variables, constraints). This is in contrast to statistical models which are based on quantifying relationship between random variables.
Processed-based	The mathematical models explicitly describe the system's processes or mechanisms based on established scientific understanding and provide clear and predefined theoretical interpretation of model parameters. This is in contrast to correlative models where processes are implicit and parameters, which are estimated from available empirical data, do not have predefined theoretical interpretation.
Theory-driven	Theories and assumptions guide the model building and drive results from the models. This is in contrast to data-driven models where there is no prior knowledge on the system and results are inferred from observable data.
Deductive	Deductive models are based on logical structure based on theories. This is in contrast to inductive models which aim to develop new theory, deriving new knowledge from empirical findings and generalization from them.
Dynamic	Dynamic models are time-dependent, describing or predicting changes in the system over time. This is in contrast to static models which are time-invariant, where all variables are independent of time and remain constant.
Continuous	Time is treated as a continuous variable providing dynamics to the model. Continuous models allow calculation of state or value of variables for any relevant time or over continuous time intervals. This is in contrast to discrete models which allow change in variable at specific time points.
Deterministic	Random variation is ignored, predicting the same outcome from a given initial state. The system's initial state determines all its possible states in the future. Deterministic models describe the system's behavior without taking into account the stochastic processes or chance events. They use parameters with fixed values or describe variable states by unique values. This is in contrast to stochastic (or probabilistic) models which take into account randomness and describe variable states in probability distributions.
Quantitative	Quantitative models provide precise numerical relationships between variables and measure numerical values of the outcome. This is in contrast to qualitative (or conceptual) models which only describe the direction of relationship or general size of the outcome.
Predictive	Predictive models are used to forecast future events or explain future outcomes. This is in contrast to descriptive models which explain observed phenomena.
Both linear and non-linear	Linear and non-linear models are defined by the relationships of variables in equations. A linear equation produces a straight line on a graph, has a constant slope, and exhibits direct proportionality between its inputs and output. In contrast, a non-linear equation generates a curve on a graph, has a variable slope, and represents a system where inputs and output are not directly related.

Sources: Cain (2014), Lawson & Marion (2008), Schulze (2014), Porgo et al. (2019), IPBES (2016), iPracticeMath.com

Table 3. Main characteristics of the scenarios relevant to the Simulation Tool

Characteristics	Description of the scenarios and, when relevant, comparison to other types of scenarios
Core concepts of scenarios[a]	(i) They possess temporal property, which mainly refer to the future; (ii) They are possible and plausible although they are presented as storylines or narratives; and (iii) They exist in sets, which are built to coexist as meaningful alternatives to one another.
Desired qualities of scenarios[b]	(i) Consistent, ensuring logic within a scenario. (ii) Contrast, exploring different directions in future societal, physical, and policy developments. (iii) Comparable, addressing the same issue, policy, and drivers. (iv) Applicable, where intended outcome matches the needs of the target groups. (v) Appeal, reflecting the thought processes and activities of the target groups.
Objectives for building scenarios[b]	(i) Achieve new insights on interactions and impacts of future developments, possible conditions under which discontinuities could take place, impacts of policy alternatives, and main knowledge gaps. (ii) Support communication through input to strategic policy and dialogue on expectations and ambitions for the future. (iii) Encourage engagement to provide support for existing strategic policy, inspire alternative policy, and better manage the conflicts relating to strategic policy.
Types of scenarios[c]	(i) Baseline trend (extrapolatory or predictive) scenarios assume that current trends will continue in the future. They address the question 'what will happen?' (ii) Normative (backcasting or ex-ante assessment) scenarios set a specific goal for the future and assess alternative policy or management options to reach that goal. They address the question 'how do we get there?' (iii) Explorative scenarios (forecasting or descriptive scenarios) are created to forecast the effect of specified policy or management options on future development and conditions. They address the question 'where do we end up?'

Sources: [a]Spaniol & Rowland (2019), [b]Dammers et al. (2019), [c]IEEP et al. (2009), [c]IPBES (2016), [c]Bizikova et al. (2011), [c]Wright et al. (2020)

Participation of policymakers in scenario building is one of the most useful ways to make mathematical models policy relevant and package the complex mathematical models into a simple and user-friendly simulation tool for facilitating policy uptake (see Chapter 2.3.3 Knowledge products on scenario-based simulation tool). With governments' commitments to achieve global sustainability goals, decision-making processes need to look beyond the present to the future by assessing impacts of policy and investment scenarios. Scenario building in Phase 2 development of the Simulation Tool will follow a participatory approach, with policymakers co-designing the scenarios with the GGPM team and modelers. Building such co-designed scenarios, particularly for explorative ones, offer the following advantages:

- Enhancing ownership and legitimacy of the scenarios, making it more likely for policymakers to use the simulation tool and accept the simulation outcomes (Dammers et al., 2019; Prutsch et al., 2018)
- Empowering policymakers, leading to more consistent and robust scenarios that can help them prepare more effectively for future change (Reed et al., 2013)
- Learning among a diverse set of actors, creating potential for developing mutual understanding on complex or conflicting issues and resulting in successful uptake and action (McBride et al., 2017; Nilsson et al., 2019; Prutsch et al., 2018)
- Increasing overall transparency, providing opportunities to include previously excluded social groups and perspectives in the decision-making process (Sus & Himmrich, 2017)
- Developing trust from the process, allowing policymakers to gain knowledge and confidence in the methods used to generate the scenarios (Wright et al., 2020)

Like in model building, various methods will be used to engage policymakers in scenario building such as workshops, webinars, and surveys.

2.3.3 Knowledge products

System dynamics simulation models

In the context of Green Growth Simulation Tool, simulation models are the integration (coupling) of mathematical models using algorithms and require the use of computer to investigate the behavior of complex and interlinked systems (e.g. dynamic, predictive, and non-linear) such as the green growth dimensions – efficient and sustainable resource use, natural capital protection, green economic opportunities, and social inclusion (Chapter 2.1.2 Architecture of simulation models). When simulation models are constructed from various mathematical models developed by modelers for purposes different from the simulation objectives, several aspects are considered by simulation modelers. These include, for example, input-output relationship between model variables (i.e., output from one model is an input to the other model), synchronization of the timing of dynamic interaction between models (Kottemann & Dolk, 1992), multiple scales of system behavior (e.g., local versus national, commodity versus sector, firm versus project, etc.), and different forms of databases (e.g., scalar and vector, spatial and temporal) (Jakeman & Letcher, 2003). The simulation models being developed for the Green Growth Simulation Tool take these aspects into account, making it possible to couple the mathematical models (Chapter 3 Green Growth Simulation models) into coherent programming codes for the simulation models (Appendix 4).

Schulze (2014) differentiates simulation models from optimization models (e.g., linear programming, stochastic dynamic programming, global programming), with the latter aiming to find out the best possible solution (i.e., optimal maximum or minimum value) of a given set of data to support a decision. Simulation models are useful for investigating complex and uncertain systems, where finding optimal solution is not possible. Moon (2016: p. 2) identified typical uses of simulation which align to the objectives for developing the Green Growth Simulation Tool: "*(i) to develop a better understanding and gain insights of a system, (ii) to compare various plans and scenarios before implementation, (iii) to predict behaviors of a system, (iv) to aid decision-making processes, (v) to develop new tools for investigation, and (vi) for training*". The most applied types of simulation models include agent-based (agents interacting with each other and the environment), discrete-event (system changes occur only at discrete points in time), and system dynamics (consists of stock, flow, and stock-flow linkages that change continuously over time) (Monks et al., 2019; Moon, 2016). Based on the main characteristics of the mathematical models used for the Simulation Tool (Table 2) and the objectives for developing it, the simulation models for green growth context are system dynamics.

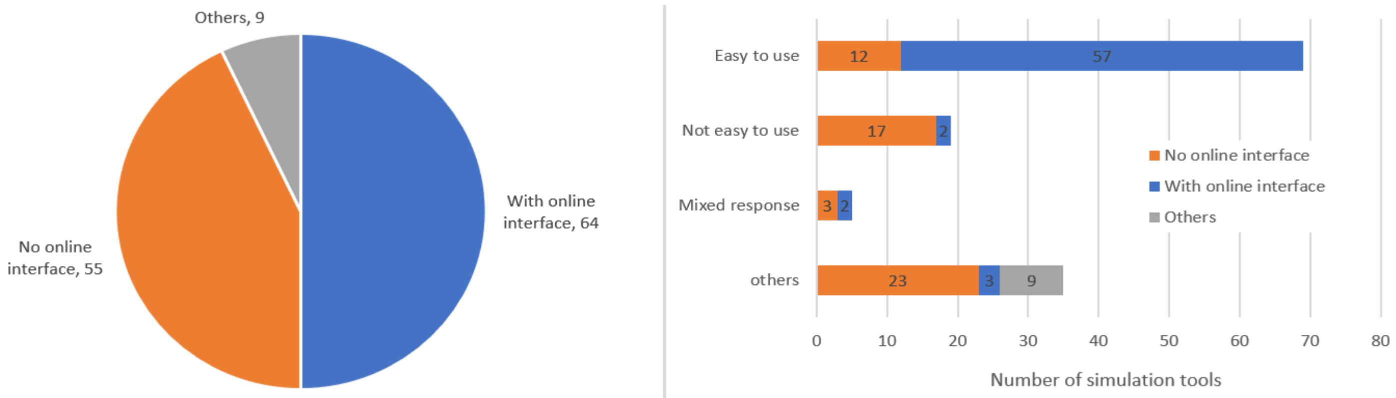
During the Phase 1 development of the Simulation Tool, the main knowledge products are system dynamics simulation models for the four dimensions of green growth (Chapter 2.1.1 Framework for green growth) and algorithms to implement them (Python codes in Appendix 4), which are described and applied in this technical report. So far, there are no published documents yet to discuss the development and application of simulation models for green growth. The target audience for this report are the modelers and experts who will collaborate in further developing the Phase 2 Simulation Tool. Monks et al. (2019) identified reasons for publishing simulation studies such as advancing operational knowledge, enabling reuse of knowledge, furthering conceptual modelling knowledge, reusing data where none exists, and testing of novel simulation methods. In view of these, another technical report will be published for the Phase 2 Simulation Tool to encourage uptake of the simulation models for green growth, creating opportunity for other experts to reuse and build upon them. Simulation models can be used in assessing the status (i.e. current period), trends (e.g. past years), and when combined with scenarios, future outcomes.

Scenario-based online tool

A large number of organizations are now using IT-enabled (often web-based) tools to enhance accessing, storing, retrieving, and distributing information, particularly "*up-to-date, credible, and relevant research information to policymakers*" (Makkar et al., 2015: p. 2). "*The tools and data … are more available than ever before, and more policymakers must know how to use and interpret them, … adopting practices that encourage data-scientific thinking*" (Engler, 2020). However, the ability of the policymakers to use the tools depends on accessibility (i.e., web-based tool, availability of interface) and knowhow (i.e., interpretability of information). So far, there are no studies yet that assess the characteristics of simulation tools. For this reason, the GGPM team reviewed the available simulation tools and identified 128 tools, which are relevant to green growth (Chapter 2.2.1 Review of online tools and literature) and mainly scenario-based (details will be available in Acosta et al., 2021). The objective of the review was to identify the best practices in developing scenario-based online tool, which will be the main knowledge product for the policymakers from the Phase 2 development of the Simulation Tool.

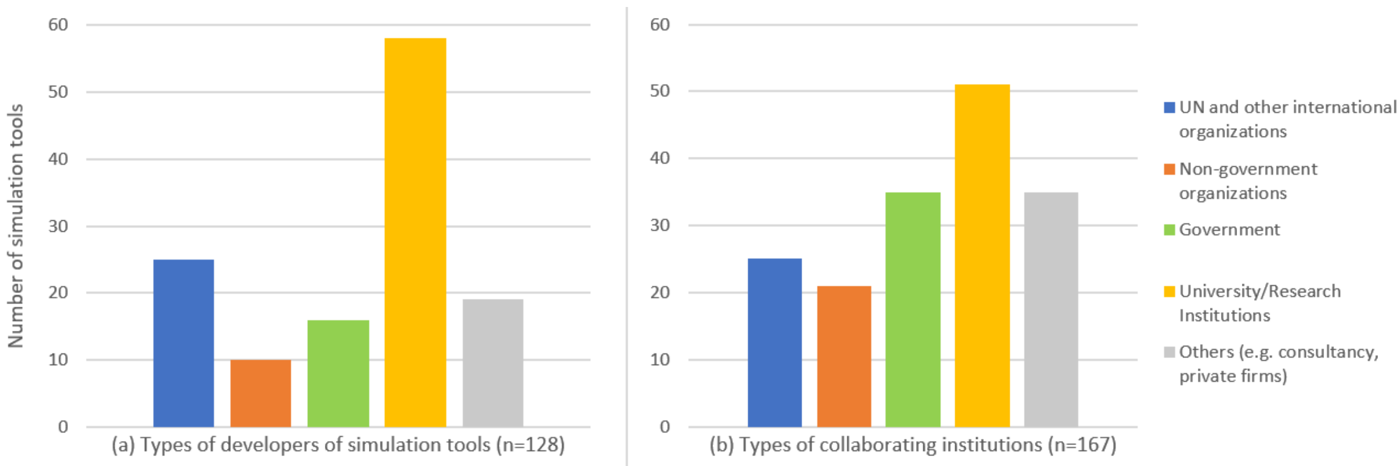
Figure 7 shows that out of the 128 tools analyzed, a total of 119 tools had used model interface, 64 of them can be viewed online (i.e., web-based). The online interface makes the tool more accessible to wider categories of users, which explains why most tool developers choose this form of presentation. The GGPM team conducted a cross tabulation analysis to compare the ease of use of interfaces between online (web-based) and offline (downloadable) simulation tools. The analysis revealed that majority of the online tools with interface are easy to use, while those downloadable tools are difficult to use. On the one hand, the main reasons why online tools with interface are easy to use include the following: (i) it is easy to navigate between the different tabs and pages of the tool; (ii) entering inputs (where required) is simple and explained well; and (iii) many tools have interactive graphics and/or GIS-based maps that users may find easy to understand and visualize. On the other hand, downloadable tools require knowledge of the software or programming, thus making them more difficult to use. Another reason is the difficulty in entering inputs, either due to lack of information provided or complexity and number of inputs requested by the tool.

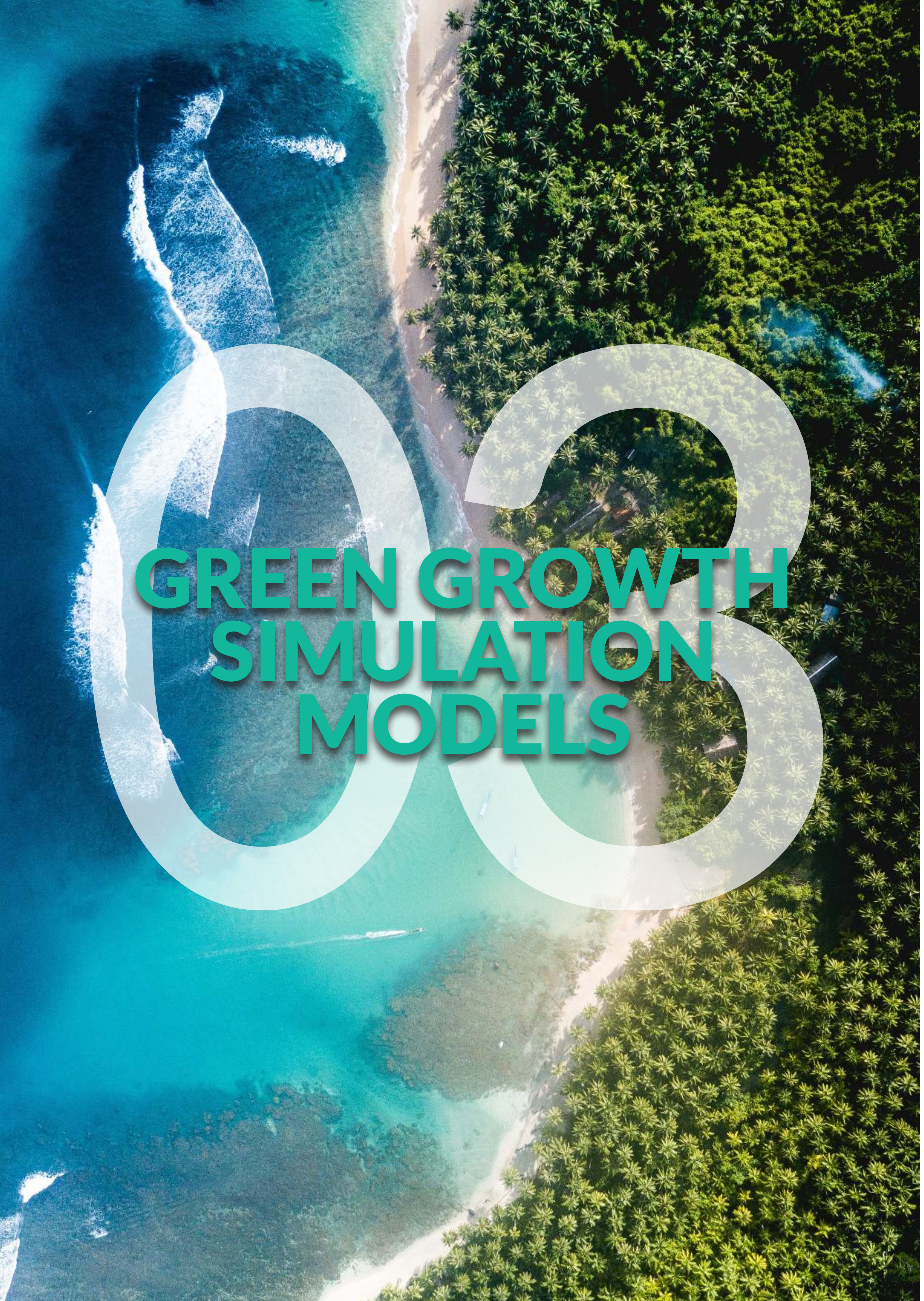
Figure 7. Distribution of simulation tools based on (a) availability of model interface and (b) ease of using the interface



The accessibility of the tools online and availability of user-friendly interface will not be sufficient for policymakers to interpret the results. They still need to understand the models and scenarios, and the assumptions behind them. Here, the participatory approach in scenario building through collaboration between modelers and policymakers plays a critical role. Figure 8(a) shows that most of the scenario-based tools which are related to one or more green growth indicators were developed by universities or research institutions, followed by international organizations. Figure 8(b) shows the most popular types of institution that collaborated with the developers/publishers of the simulation tools. A total of 167 institutions collaborated in the development of the 128 simulation tools. Many collaborations involved universities/research institutions, accounting for 51 of the simulation tools. But a significant number of government institutions also collaborated in the development of online tools. These results reveal that there is significant interest among policymakers in participation in building models and/or scenarios for online simulations tools, which will facilitate transfer of technical knowhow.

Figure 8. Simulation tools according to types of (a) developers of the simulation tools and (b) institutions that collaborated with developers/publishers of the simulation tools





03 GREEN GROWTH SIMULATION MODELS

3.1 Efficient and sustainable resource use

3.1.1 Efficient and sustainable energy

Efficient and sustainable energy refers to delivering more services or products per unit of energy used and meeting present needs by using renewable sources to ensure sustainability of energy for future use (IRENA & C2E2, 2015; Kutscher et al., 2018). The details on the mathematical models and variables for the equations for energy system are provided in Table 4 and Table 5. The flow diagrams for the models are presented in Figure A1 and Figure A2 in Appendix 3.

EE1: Energy Intensity Level of Primary Energy (MJ per GDP)

The rationale behind this indicator is to establish a link between the energy input into a country and its corresponding economic output. This indicator aims to reflect a country's efficiency in converting energy into one unit of economic output. A proxy for calculating energy intensity is getting the ratio between the national energy supplied (MJ) and the country's Gross Domestic Product (GDP). And since this is an efficiency indicator, a lower ratio is preferred since it indicates that less energy is being used to produce one unit of output. In addition, a lower ratio can be achieved through installation of efficient equipment and machines, which produce more output for the same energy input, or through energy-saving devices, which use lower energy input for the same amount of output.

The mathematical models for this indicator represent the supply side of the energy sector, covering the subsectors for fossil fuels and renewable energy. The fossil fuels include coal, petroleum, and natural gas. On the other hand, the renewable energy is classified into green renewable including solar, wind, and geothermal and other renewable energy including hydro, biomass, and nuclear. While the latter includes sources of non-fossil fuels, they were separated from the former sources of renewable energy because of their potential environmental impacts, for example, water stress from hydropower, biodiversity loss from biofuel production, and health impacts from nuclear disaster.

The mathematical models for the supply (EE1) and consumption (EE2) of energy are interlinked, building a comprehensive simulation model for the energy system. The interlinkages were created by integrating the models for trade balance such as imports and exports as well as energy transformation such as electricity and heat generation.

EE2: Share of Renewable to Total Final Energy Consumption (Percent)

This indicator is the percentage of final energy consumption derived from renewable resources. It is important to note that this indicator was calculated from the consumption side and not from the production side of the energy balance. In doing so, this indicator can reflect the actual energy used from renewable resources excluding the losses because of energy conversion and transmission. The International Energy Agency (IEA) databases do not provide detailed disaggregation of energy consumption by renewable and non-renewable energy sources. To compute the share of renewable to total final energy consumption, the percentage share of renewable on the supply side was used as proximate metrics for the consumption side. Mathematical models are available for different sectors including transport, residential, industry, and agriculture. Only the transport sector has detailed mathematical models because its data are available from the IEA databases. The detailed models for the other sectors will be included in the Phase 2 application of the Simulation Tool.

For the transport model, the transport activity demand is divided into two – freight (transportation of goods) and passenger (passenger trips) activities. The modes considered in the model include light duty vehicles, buses, inland water ways, and rail transport. The models are further disaggregated by old and new vehicle technologies, each corresponding to a fuel type such as natural gas, diesel, or petrol. The parameters such as the occupancy ratio and load factor enable running of different scenarios to compute the impact to the entire environment.

Reducing GHG emissions from transport is an important target to reach. The road to decarbonizing the transport sector is still a challenge despite the overall reductions among the other sectors in the economy. This transport model attempts to model passenger transport, specifically, the various layers that influence GHG emissions both for the current and future years. It adopted several equations from the EU-calculator transport module, which follows a bottom-up approach to compute energy consumption and GHG emissions from the transport sector using historical data (Taylor et al., 2019). Moreover, the mathematical models for transport can be linked to other indicators such as the ratio of CO_2 emissions excluding Agriculture, Forestry and Other Land Use (AFOLU) to population (GE1), ratio of non-CO_2 emissions excluding AFOLU to population (GE2), and particulate matter (PM2.5) air pollution, mean annual population -weighted exposure (EQ1).

There were few challenges in including a more comprehensive model for the transport sector. For example, the Phase 1 of the Simulation Tool lacks equations linking the transport activity demand to socio-economic drivers such as income and population and instead relies on existing values in literature to run scenarios for Hungary. The growth of transport activity demand follows a non-linear relationship with the socio-economic drivers through a logistic curve (ICCT, 2012). The regression model showing the relationships between drivers will be included in the Phase 2 of the Simulation Tool. Moreover, the Phase 1 Tool did not include the effect of new car sales and technology on energy consumption. In Phase 2, it is envisaged that the energy efficiency input variable will be computed in terms of the total amount of fuel consumed and the heating value of the fuel technology used. The replacement of energy efficiency with fuel consumed will enable the application of the tool to different countries which may vastly differ from the European Union (EU) values used for Hungary.

Other challenges in developing the transport model include:

- There was lack of available data on fuel consumption by different vehicle technology types and thus had to use energy intensity values (MJ/km) as used in the EU-calculator online tool (T1). This further limited the model in computing the new vehicles and their impact on the energy consumption values.
- The model requires a high disaggregation of activity within the transport sector especially the technology types of different modes of vehicles. However, due to complications with data, the classification of passenger cars according to sizes and commercial vehicles was not executed and this will be explored further in the Phase 2 of the model.

An illustration of implementation of the mathematical models for transport sector is presented in Chapter 4.1. Energy and transport in Hungary.

Table 4. Equations used in the mathematical models for efficient and sustainable energy

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq1	$EP_{new} = EP_{fuel} - EP_{retired}$	Energy produced refers to the difference between fossil fuel MW reduction per year and energy produced for fossil fuels.	EE1	IEA, 2020 (A222)
Eq2	$\sum EP_{fn}$	It is the summation of different fossil fuels, where "n" denotes the different fossil fuel types such as coal, petroleum, and natural gas.	EE1	IEA, 2020 (A222)
Eq3	$FES = \sum[EP_{fn} * (1 + EPR_{fn})]$	Fossil fuel energy supply is the summation of different fossil fuels multiplied by the growth rate of its energy produced.	EE1	Gu, C., Ye, X., et al., 2020 (A133)
Eq4	$EP = EP_{GRES} - RE_{new}$	Energy produced for non-fossil fuels refers to the difference between energy produced for green renewable energy sources and new renewable energy installed.	EE1	IEA, 2020 (A222)
Eq5	$\sum EP_{rn}$	It is the summation of different green renewables, where "n" denotes different green renewable types such as solar, wind, and geothermal.	EE1	IEA, 2020 (A222)
Eq6	$GRES = \sum[EP_{rn} * (1 + EPR_{rn})]$	Green renewable energy supply is the summation of different green renewables by the growth rate of its energy produced.	EE1	Gu, C., Ye, X., et al., 2020 (A133)
Eq7	$\sum EP_{on}$	It is the summation of other non-fossil fuels, where "n" denotes other non-fossil fuel types such as hydro, biomass, and nuclear.	EE1	IEA, 2020 (A222)
Eq8	$oNFES = \sum[EP_{on} * (1 + EPR_{on})]$	Other non-fossil fuel energy supply is the summation of other non-fossil fuels by the growth rate of its energy produced.	EE1	Gu, C., Ye, X., et al., 2020 (A133)
Eq9	$TES = FES + GRES + oNFES + EIE$	Total energy supply is the summation of the different energy supplies and energy import and export balance.	EE1	Gu, C., Ye, X., et al., 2020 (A133)
Eq10	$EE1 = \frac{TES}{GDP}$	EE1 is the ratio of total primary energy supply to GDP.	EE1	IEA, 2020 (A222)
Eq11	$SoR = GRES + oNFES - Nuclear$	Share of renewable is the summation of the different energy supplies and correction factor minus nuclear.	EE2	IEA, 2020 (A222)
Eq12	TR, SD, EL, OET	(Equation to be identified in Phase 2)	EE2	IEA, 2020 (A222)
Eq13	$EPG = ES_n * TR_{electricity}$	Electric power generation is the summation of the different energy supplies multiplied by the transformation rate for electricity per technology (fossil fuel, green renewable, and other non-fossil fuel).	EE1	IEA, 2020 (A222)
Eq14	$HP = ES_n * TR_{heat}$	Heat production is the summation of the different energy supplies multiplied by the transformation rate for heat per technology (fossil fuel, green renewable, and other non-fossil fuel).	EE2	IEA, 2020 (A222)
Eq15	$TET = EPG + HP + OET + EL + SD$	Total energy transformation is the summation of electric power generation, heat production, statistical differences, energy losses, and other energy transformations.	EE2	IEA, 2020 (A222)
Eq16	$FC_n = OET_n + EPG_n + HP_n$	Final consumption is the summation of electric power generation, heat production, and other energy transformations (transportation, residential, and agriculture/forestry).	EE2	IEA, 2020 (A222)
Eq17	$TFC = FC_t + FC_r + FC_a + FC_{others}$	Total final energy consumption is the summation of the different final consumptions.	EE2	IEA, 2020 (A222)
Eq18	$TES = TFC + TET$	Energy balance verification is the equal balance energy supply and energy consumption.	EE2	Wu, D. & Ning, S., 2018 (A170)
Eq19	$EE2 = \frac{SoR}{TFC}$	EE2 is the share of renewable to total final energy consumption.	EE2	IEA, 2020 (A222)
Eq20	$TTD = \alpha + \log\beta 1 * TTD_{base} * \log\beta 2 * f(population, GDP, prices\ or\ Income)$	This computes the logistic regression for transport activity demand (TTD) with the GDP, where income is one of the independent variables.	EE2	ICCT, 2012 (A223)

Table 4. Equations used in the mathematical models for efficient and sustainable energy (continued)

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq21	$TD_M = TTD * MS_M$	This computes the passenger transport activity demand for different modes of transport. The passenger transport modes used in the tool include passenger car, bus, rail, tram and metro (urban rail), and domestic aviation.	EE2	Taylor, E., Martin, B., et al., 2019 (T1) and 2050 Energy and Emissions Calculator (T54)
Eq22	$VD_{M1} = \frac{TD_M}{O_M}$	The transport demand vector vehicles are based on the occupancy of the different vehicle types.	EE2	Taylor, E., Martin, B., et al., 2019 (T1) and 2050 Energy and Emissions Calculator (T54)
Eq23	$VD_{M2} = TD_M * MS_M$	Rail transport demand is the product of total passenger transport demand by mode of transport and model share	EE2	Taylor, E., Martin, B., et al., 2019 (T1) and 2050 Energy and Emissions Calculator (T54)
Eq24	$VD_{M3} = TD_M * A_M$	Transport demand aviation is the product of the total transport demand and aviation as a percent modal share.	EE2	Taylor, E., Martin, B., et al., 2019 (T1) and 2050 Energy and Emissions Calculator (T54)
Eq25	$FD_M = TFD * MS_M$	Freight transport demand per mode is a product of the shares of different transport modes and the total freight transport demand.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq26	$FVD_{M1} = FD_M * A_M$	Freight transport demand marine/aviation is the product of the Freight transport demand per mode and the share of domestic/international transport.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq27	$FVD_{M2} = \frac{FD_M}{LF_M}$	The transport demand per vehicle type is based on the load factor.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq28	$V_{mt} = V_{mt-1} * (1 - R)$	This computes the remaining vehicles per technology to the share of vehicles remaining from the previous year after removing the scrapped vehicles.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq29	$EC_t = EE_{t-1} * V_{mt}$	Energy consumption old fleet is computed based on the energy efficiency value from the previous year and the remaining stock of vehicles in the year (t).	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq30	$V_t = \frac{(V_{mt} + V_n)}{V}$	Total amount of vehicles per technology is obtained by dividing the sum of the total amount of new vehicles per technology and remaining vehicles per technology to the total vehicles.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq31	$L_{new} = V_n * lifetime$	Lifetime new vehicles per technology is computed as a product of the lifetime (total distance travelled by the vehicle since purchase in km or years of use) and the total amount of new vehicles per technology.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq32	$L_t = \frac{[(V_{mt} * lifetime_{t-1}) + L_{new}]}{V_t}$	Average lifetime of vehicle fleet is computed by taking the product of the remaining vehicles per technology and the lifetime of new vehicles per technology and adding it to the lifetime of new vehicles per technology and dividing it by the total amount of vehicles per technology.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq33	$EC_n = EE_n * V_n$	Energy consumption new fleet is based on the product between the energy efficiency of new vehicles and the total amount of new vehicles per technology.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq34	$AC_{MT} = \frac{(EC_n * EC_t)}{V_t}$	Average energy consumption per vehicle type per technology is based on the product of the energy consumption of the old and new fleet divided by the total amount of vehicles per technology.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)

Table 4. Equations used in the mathematical models for efficient and sustainable energy (continued)

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq35	$EC_{MT1} = VD_{Mn} * V_T * AC_{MT}$	Passenger transport energy consumption per technology and fuel type is the product of the average energy consumed per vehicle, the share of the vehicle technology type, and the energy demand per mode of transport.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq36	$EC_{MT2} = FVD_{Mn} * V_T * AC_{MT}$	Freight energy consumption per technology and fuel type is computed by multiplying the transport demand per vehicle type, vehicle technology shares, and the average energy consumption per vehicle type per technology.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq37	$EC_{TF} = EC_{MTn} * Fuel_{MT}$	This computes the energy consumption per technology and fuel vector determined from the blends of different fuels such as diesel, gasoline, and natural gas.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq38	$GHG_{MT} = EC_{TF} * EF_{MTe}$	GHG emission vector per technology and mode is computed based on tier 1 method of the IPCC using emission factors and the energy consumed per mode and fuel technology.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)
Eq39	$EE2 = \frac{SUM(Biofuel, PtX, Efuel)}{SUM(Fossil\ Fuel)}$	This computes the share of renewable to total final (transportation) energy consumption.	EE2	Taylor, E., Martin, B., et al., 2019 (T1)

*Details are on Appendix 1 and Appendix 2

Table 5. Details of input variables, parameters, and scenarios for efficient and sustainable energy

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq1	EP_{fuel}	Input variable	Energy Produced for Fossil Fuel	MJ	IEA
Eq1	$EP_{retired}$	Input scenario	Fossil Fuel MW Reduction per year	MW/year	Model assumption
Eq1	EP_{new}	Output variable	Energy Produced	MJ	Simulation Tool
Eq2	$\sum EP_{fn}$	Output variable	Total of different fossil fuel energy produced (coal, petroleum & natural gas)	MJ	Simulation Tool
Eq2, Eq3	EP_{fn}	Output variable	Energy Produced for fossil fuel	MJ	Simulation Tool
Eq3	EPR_{fn}	Input variable	Fossil fuels: Growth Rate of Energy Produced (coal, petroleum & natural gas)	rate	IEA
Eq3, Eq9	FES	Output variable	Fossil Fuel Energy Supply	MJ	Simulation Tool
Eq4	EP_{GRES}	Input variable	Energy Produced for Green Renewable Energy	MJ	IEA
Eq4	RE_{new}	Input scenario	New Renewable Energy installed	MW	IEA
Eq4	EP	Output variable	Energy Produced for non-fossil fuels	MJ	Simulation Tool
Eq5	$\sum EP_{rn}$	Output variable	Total of different green renewable energy produced (solar, wind & natural gas)	MJ	Simulation Tool
Eq5, Eq6	EP_{rn}	Output variable	Energy Produced for green renewable energy	MJ	IEA
Eq6	EPR_{rn}	Input variable	Green renewable: Growth Rate of Energy Produced (solar, wind & geothermal)	rate	IEA
Eq6, Eq9, Eq11	GRES	Output variable	Green Renewable Energy Supply	MJ	Simulation Tool
Eq7	$\sum EP_{on}$	Output variable	Total of different other non-fossil fuel (hydro, biomass & nuclear)	MJ	Simulation Tool
Eq7, Eq8	EP_{on}	Output variable	Energy Produced for other non-fossil fuel	MJ	IEA
Eq8	EPR_{on}	Input variable	Other Non-Fossil Fuel: Growth Rate of Energy Produced (hydro, biomass & nuclear)	rate	IEA
Eq8, Eq9, Eq11	oNFES	Output variable	Other Non-Fossil Fuel Energy Supply	MJ	Simulation Tool
Eq9	EIE	Input variable	Energy Import and Export Balance	MJ	IEA
Eq9, Eq10	TES	Output Variable	Total Energy Supply	MJ	Simulation Tool
Eq10	GDP	Input variable	GDP PPP	$	World Bank
Eq10	EE1	Output variable	Ratio of total primal energy supply to GDP	MJ per $2011 PPP GDP	Simulation Tool
Eq11	Nuclear	Input variable	Nuclear Fuel Energy supply	MJ	IEA
Eq11	SoR	Output variable	Share of renewable	MJ	Simulation Tool
Eq12	TRC	Output variable	Transformation Rate Computation	rate	Simulation Tool (Phase 2)
Eq12, Eq15	OET	Input variable	Other Energy Transformations	MJ	IEA
Eq12, Eq15	EL	Input variable	Energy Losses	MJ	IEA
Eq12, Eq15	SD	Input variable	Statistical Differences	MJ	IEA
Eq12	TR	Input variable	Energy Transformation Rate	%	IEA
Eq13, Eq14	ES_n	Input variable	Energy Supply of fossil fuel, renewable energy & other non-fossil fuel	MJ	IEA
Eq13	$TR_{electricity}$	Input parameter	Transformation Rate for electricity per technology	rate	IEA
Eq13, Eq15	EPG	Output variable	Electric Power Generation	MW	Simulation Tool
Eq14	TR_{heat}	Input parameter	Transformation Rate for heat per technology	rate	IEA
Eq14, Eq15	HP	Output variable	Heat Production	MJ	Simulation Tool
Eq15, Eq18	TET	Output variable	Total Energy Transformation	MJ	Simulation Tool

Table 5. Details of input variables, parameters, and scenarios for efficient and sustainable energy (continued)

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq16	$\mathrm{OET_n}$	Input variable	Other Energy Transformations for transportation, residential & agriculture/ forestry	MJ	IEA
Eq16	$\mathrm{EPG_n}$	Input variable	Electric Power Generation for transportation, residential & agriculture/ forestry	MJ	IEA
Eq16	$\mathrm{HP_n}$	Input variable	Heat Production for transportation, residential & agriculture/forestry	MJ	IEA
Eq16	$\mathrm{FC_n}$	Output Variable	Final Consumption Transport	MJ	Simulation Tool
Eq17	$\mathrm{FC_t}$	Input variable	Final Consumption Transport for transportation	MJ	IEA
Eq17	$\mathrm{FC_r}$	Input variable	Final Consumption Transport for residential	MJ	IEA
Eq17	$\mathrm{FC_a}$	Input variable	Final Consumption Transport for agriculture/forestry	MJ	IEA
Eq17	$\mathrm{FC_{others}}$	Input variable	Final Consumption Transport for others	MJ	IEA
Eq17, Eq18	TFC	Output Variable	Total Final Energy Consumption	MJ	Simulation Tool
Eq19	$\mathrm{EE2}$	Output Variable	Share of renewable to total final energy consumption	%	Simulation Tool
Eq20	TTD_{base}	Output Variable	Baseline total transport demand	Bn pkm	IEA
Eq20	$\mathrm{f}(Population, GDP, Prices\ or\ Income)$	Input parameter	Independent variables for predicting Transport activity demand (log)	-	(Phase 2)
Eq20	TTD	Output variable	Total passenger transport activity demand	Billion pkm or tkm	IEA (Phase 2)
Eq21, Eq23, Eq25	MS_M	Input scenario	Modal Share	%	OECDstat, and Eurostat
Eq21, Eq22, Eq23, Eq24	TD_M	Output variable	Total Passenger transport demand by mode of transport	b pkm	Simulation Tool
Eq22	O_M	Input scenario	Occupancy rate (Bus, Passenger Car and Motorcycle)	pkm/vkm	TRACCS database
Eq22	VD_{M1}	Output variable	Transport demand vector vehicles	b pkm	Simulation Tool
Eq23	VD_{M2}	Output variable	Rail transport demand	b pkm	Simulation Tool
Eq24, Eq26	A_M	Input variable	Share of domestic/international transport	%	Eurostat
Eq24	VD_{M3}	Output variable	Transport demand aviation	b pkm	Simulation Tool
Eq25	TFD	Input scenario	Total freight transport demand	Bn tkm	Assumption (based on ERTRAC-Hungary-VISION 2030
Eq25, Eq26, Eq27	FD_M	Output Variable	Freight Transport Demand per mode	Bn tkm	Simulation Tool
Eq26	FVD_{M1}	Output variable	Freight transport demand marine/ aviation	Bn tkm	Simulation Tool
Eq27	LF_M	Input variable	Load factor	tkm/vkm	Eurostat
Eq27	FVD_{M2}	Output variable	Transport demand per vehicle type	Bn tkm	Simulation Tool
Eq28	V_{mt-1}	Input variable	Total amount of vehicles per technology in previous year	vehicles	Eurostat (Phase 2)
Eq28	R	Input variable	Renewal rate of vehicle	%	Eurostat (Phase 2)
Eq28, Eq29, Eq30, Eq32	V_{mt}	Output variable	Remaining vehicles per technology	vehicles	Simulation Tool (Phase 2)
Eq29	EE_{t-1}	Input variable	Energy efficiency of vehicles in previous year	MJ/km	Simulation Tool (Phase 2)
Eq29, Eq34	EC_t	Output Variable	Energy consumption of old fleet	MJ	Simulation Tool (Phase 2)
Eq30, Eq31, Eq33	V_n	Input variable	Total amount of new vehicles per technology	Bn veh	Eurostat (Phase 2)

Table 5. Details of input variables, parameters, and scenarios for efficient and sustainable energy (continued)

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq30	V	Input variable	Total vehicles	Bn veh	Eurostat (Phase 2)
Eq30, Eq32, Eq34	V_t	Output variable	Total amount of vehicles per technology	%	Simulation Tool (Phase 2)
Eq31	$lifetime$	Input scenario	Lifetime of new vehicles	Km	Assumption (Phase 2)
Eq32	$lifetime_{t-1}$	Input variable	Lifetime of vehicles in previous year	Km	Assumption (Phase 2)
Eq31, Eq32	L_{new}	Output variable	Lifetime new vehicles per technology	km or years	Simulation Tool (Phase 2)
Eq32	L_t	Output variable	Average lifetime of vehicle fleet per technology	Km	Simulation Tool (Phase 2)
Eq33	EE_n	Input scenario	Energy efficiency of new vehicles	MJ/km	Assumption (Phase 2)
Eq33, Eq34	EC_n	Output Variable	Energy consumption of new fleet	MJ	Simulation Tool (Phase 2)
Eq34, Eq35, Eq36	AC_{MT}	Output variable	Average energy consumption per vehicle type per technology	MJ/vkm or pkm	Simulation Tool IEA (Phase 2)
Eq35	VD_{Mn}	Output variable	Summation of different transport demands (VD_{M1}, VD_{M2}, and VD_{M3})	b pkm	Simulation Tool
Eq35, Eq36	V_T	Output variable	Vehicle technology shares	%	ACEA, 2019
Eq35	EC_{MT1}	Output Variable	Passenger Transport Energy consumption per technology & fuel type	PJ	Simulation Tool
Eq36	FVD_{Mn}	Output variable	Summation of different freight transport demand (FVD_{M1} and FVD_{M2})	Bn tkm	Simulation Tool
Eq35, Eq36	EC_{MT2}	Output Variable	Freight Energy consumption per technology & fuel type	PJ	Simulation Tool
Eq37	$Fuel_{MT}$	Input parameter	Fuel mix	%	Biofuel quota-Legal sources of Renewable Energy Sources
Eq37	EC_{MTn}	Output variable	Summation of passenger and freight energy consumption per technology & fuel type (EC_{MT1} and EC_{MT2})	PJ	Simulation Tool
Eq37, Eq38	EC_{TF}	Output variable	Energy consumption per technology & fuel vector	PJ	Simulation tool
Eq38	EF_{MTe}	Input parameter	Emission factor per fuel technology	Kg/j	IPCC, 2006
Eq38	GHG_{MT}	Output variable	Total GHG Emissions	KgCO2eq	Simulation Tool
Eq39	$\mathrm{EE2}$	Output variable	Share of renewable to total final (transportation) energy consumption	%	Simulation Tool

3.1.2 Efficient and sustainable water use

Efficient and sustainable water use refers to delivering more services or products per unit of water used, reducing environmental impact resulting from water scarcity and pollution, and improving water allocation among competing uses (UNEP, 2014b; Wang et al., 2015). The details on the mathematical models and variables for the equations for water use system are provided in Table 6 and Table 7. The flow diagram for the models is presented in Figure A3 in Appendix 3.

EW1: Water Use Efficiency (USD per m³)

The rationale behind this indicator is to provide information on the efficient water usage of the primary economic sectors and the society as well as the water losses. The results can give incentives to improve the efficient use of water resources and show which sectors fall behind.

Based on the UNSTAT methodology (UNSTATS, 2019), total water use efficiency is calculated as sum of the three sectors, namely, agriculture, industry and services, weighted according to the proportion of water used by each sector over the total use. Each sector is calculated by total water use (or withdrawal) over gross value added. However, in terms of agricultural water use efficiency, it was corrected to only include the water use from irrigation. A corrective coefficient was calculated from the proportion of irrigated land on the total arable land and permanent crops. A generic default ratio was used to define the ratio between rainfed and irrigated crop yields. Industrial water use efficiency includes sectors of mining and quarrying, manufacturing, electricity, gas, steam and air conditioning supply, and constructions. Using the International Standard Industrial Classification of All Economic Activities (ISIC) as reference, the service water use efficiency includes all the service sectors related to ISIC E and ISIC G-T. Altogether, the three sectoral efficiencies provide a measure of overall water efficiency in a country. In order to integrate the efficient and sustainable water use indicators, the modelled sectoral water withdrawals from EW2 are used as numerator in EW1.

EW2: Share of Freshwater Withdrawal to Freshwater Availability (Percent)

Indicator EW2, known as water stress or the share of freshwater withdrawal to availability (%), was modelled through equations representing the three major water use sectors, namely, agriculture, industry, and municipal as well as country-level freshwater availability.

Agricultural water withdrawal sub-model

The primary methodology used to determine the irrigation water withdrawal per country was described by the Food and Agriculture Organization (Allen et al., 1998; Frenken & Gillet, 2012). But, it was recognized that additional journal articles such as Luck et al. (2015) also used adapted versions from FAO to estimate agricultural water withdrawal, therefore, the combination of both methods was used for the GGPM Simulation Tool.

The atmosphere's evaporation power is defined by the evapotranspiration of the reference crop at a precise time and place, disregarding the characteristics of crops and soil factors (ET_0). The different characteristics like crop height, crop roughness, ground cover, reflection, and resistance to transpiration can be reflected by the crop coefficient (Kc) and give different results for ET levels. The evapotranspiration from crops that are well-fertilized, disease-free, cultivated in large fields and under the best soil water conditions, and can fully produce under a given climatic condition is considered as the evapotranspiration of crops under standard conditions (ET_c) (Allen et al., 1998).

Irrigation consumptive use is the annual depth of water needed to fulfill the deficit between what crops could consume with ample water and under rainfed conditions. It is calculated as potential evapotranspiration (ET_c) minus actual evapotranspiration (ET_a). Irrigation water requirement (IWR) is a measure of the water required for optimal crop growth including consumptive and non-consumptive purposes and is calculated from irrigation consumptive use, with an adjustment for paddy land. The 0.2 represents the additional non-consumptive water use from the depth of rice paddy irrigation (in metres), which is returned to the surface waters following harvest (Luck et al., 2015). The water requirement ratio (WRR), also referred to as irrigation efficiency, is the amount of water required by crops to meet their evapotranspiration needs, divided by the amount of water actually withdrawn to meet those needs. This ratio is less than 1 because of water leakage or other losses in the irrigation system on the way from the source to the plant (Luck et al., 2015). To develop the scenario on irrigation technology efficiency, the irrigation water withdrawal equation is adapted to include three different types of systems, namely, surface, sprinkler, and localized irrigation as well as their corresponding water use efficiencies and land area share.

Industrial water withdrawal sub-model

There is lack of data for the equations and methodology chosen to represent industrial water withdrawal. Thus, the data estimates from FAO's AQUASTAT database were used for total industrial water withdrawal for Phase 1 development. Thermoelectric power plants and manufacturing were identified to be some of the largest water users in the industry sector. Equations from Vassolo and Döll (2005) were chosen to represent these industries to estimate the aggregated industrial water use. Specifically, this method uses variables of water intensity to represent the various withdrawal amounts per type of thermoelectric technology and various manufacturing sectors. However, due to challenges in data availability, these equations have been set aside first until the Phase 2 development of the Simulation Tool. Briefly, the total annual thermoelectric power water withdrawal is calculated as the sum of the withdrawals of all the power stations as a function of annual electricity produced and station-specific water withdrawal intensity which is dependent on the cooling system of the power station. On the other hand, the country-specific total manufacturing water withdrawal is calculated by annual production volumes per manufacturing sectors and their sector-specific water intensity. The manufacturing water withdrawal also includes an adjustment factor variable. The challenges related to data availability include finding data for typical sector-specific water withdrawal intensities, which are only available for some industrialized countries, as well as a comprehensive dataset on existing power plants and their corresponding cooling systems. The inclusion of equations in Phase 2 will allow the policies scenarios focused on changing or shutting down power stations to reflect decreases in water withdrawal intensity, which may be further linked to the share of renewables (EE2) model. Scenarios of future manufacturing water use can

be generated by prescribing the development of the production volumes and including technological change factors to consider a decrease of the sectoral manufacturing water use intensities.

Municipal water withdrawal sub-model

Municipal water withdrawal was modelled based on the article by Hejazi et al. (2013). First, the municipal water withdrawal per capita was determined using a regression function of gross domestic product per capita (GDPC), the average municipal water price, and a technological advancement rate of the efficiency enhancement in domestic appliances. The coefficients for the model were estimated and calibrated by the GGPM team, with $\beta1$ and $\beta2$ coefficients being the same as Hejazi et al. (2013), while the α coefficient varies at 2.39, although still within the 95% confidence interval provided within the article. One explanation for this variation in the alpha coefficient is that Hejazi et al. (2013) has a regional spatial scale, while the aim of the Simulation Tool is at the country level. Obtaining reliable estimates for the technological advancement rate has been limited due to unavailable data at the country-level, therefore, it was assumed to be 1.0 within the model. To estimate how much water is withdrawn in total by the municipal sector, the water use per capita of a given country or region was multiplied by its population.

This sub-model also considers the impacts of municipal wastewater from urban and rural environments. A scenario is developed to allow the policymakers to treat municipal wastewater by investing in various wastewater technologies. Investment estimates and the capacity of activated-sludge and bio-membrane wastewater technologies are integrated into the model framework, which will determine the amount of treated wastewater that can be recycled into the existing non-conventional water supply. The inclusion of additional equations in Phase 2 to connect the amount of municipal water consumption to wastewater generation will create a link to both the access to basic services (AB1) and Disability Adjusted Life Years (DALY) rate (EQ2) indicators.

Freshwater Availability sub-model

Freshwater availability is defined by FAO (2003) as the "natural renewable water resources are the total amount of a country's water resources (internal and external resources), both surface water and groundwater, which is generated through the hydrological cycle." The total renewable freshwater is a summation of both internal and external renewable water resources. Due to data limitations, the external renewable water resources were not disaggregated and a total value was taken directly from the FAO's AQUASTAT database, which includes part of a country's renewable water resources that enter from upstream countries through rivers (external surface water) or aquifers (external groundwater resources). However, internal renewable water resources were further disaggregated into surface and groundwater. This is to build in a scenario into the EW 2 model, which accounts for changes in surface water availability due to climate change, to be implemented into the Simulation Tool during Phase 2. Therefore, during Phase 1, the total internal renewable freshwater was calculated as the sum of surface water and groundwater generated from endogenous precipitation minus the overlap between the two water sources.

Other issues that will need attention when developing the Phase 2 Simulation Tool are the following:

- Many global models used spatial maps and raster analysis to identify the proportion of water use per gridded area. It is assumed that removing the spatial component of these equations can lead to variations in outputs.
- There is lack of available data for some model variables specifically within the industrial sub-model and livestock water use. Therefore, those model variables are not included in the Phase 1 development of Simulation Tool.
- The freshwater availability sub-model used a very simplified version of the water balance. This is to enhance simplicity of the model in both equation complexity and data requirements. GGPM recognizes that there are other major water fluxes to contribute to natural freshwater availability from the global hydrological cycle. Thus, future plans include improving the complexity and adding other fluxes to build a more realistic freshwater availability sub-model that will also complement the climate scenarios to be embedded within the efficient and sustainable water use framework.

An illustration of implementation of the mathematical models for water use efficiency is available in Chapter 4.2. Water use in Hungary and Mexico.

Table 6. Equations used in the mathematical models for efficient and sustainable water use

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq1	$ETc = \sum (Kc_i * CI_i * ETo)$	Crop evapotranspiration is a function of a crop's growing coefficient, the percentage of cropping intensity, and reference evapotranspiration.	EW2	Frenken, K. & Gillet, V., 2012 (A224)
Eq2	$ICU = ETc - ETa$	Irrigation consumptive use is the amount of water required for irrigated crops, explained as the deficit between crop evapotranspiration and actual evapotranspiration.	EW2	Frenken, K. & Gillet, V., 2012 (A224) and Aqueduct (T2)
Eq3	$IWR = ICU * AIR + 0.2 * A_{rice}$	Irrigation water requirement is the total water required by crops over the area of irrigated land within a country. The area of paddy land is accounted for by the variables A_rice, with 0.2 representing additional non-consumptive water use from the depth of rice paddy irrigation in meters.	EW1 and EW2	Frenken, K. & Gillet, V., 2012 (A224) and Aqueduct (T2)
Eq4	$AIR_t = P_t * AIR$	Irrigation area based on technology is calculated by multiplying the total area of irrigation and the proportion of each type of irrigated area, where t represents the various types of irrigation technologies such as surface, sprinkler, and localized.	EW2	FAO, 2020 (A247)
Eq5	$IWW = \frac{IWR}{WRR}$	Irrigation water withdrawal is the estimated amount of water which will be used for irrigation purposes, factoring in that some water extracted will be lost during the distribution process to crops. This equation is the baseline equation where irrigation water withdrawal is calculated by dividing the irrigation water requirement by the water requirement ratio.	EW2	Frenken, K. & Gillet, V., 2012 (A224) and Aqueduct (T2)
Eq6	$IWW = \sum \left(\frac{ICU * AIR_t}{ETech_t}\right) + \left(\frac{0.2 * A_{rice}}{WRR}\right)$	To incorporate technology irrigation scenarios for irrigation water withdrawal, this equation is used where the irrigation water requirement is computed by dividing specific irrigation areas by their respective technology efficiency, where t represents the various types of irrigation technologies such as surface, sprinkler, and localized.	EW2	Frenken, K. & Gillet, V., 2012 (A224) and Aqueduct (T2)
Eq7	$AWU = IWW + LWU$	Total agricultural water withdrawal includes irrigation water withdrawal and livestock water withdrawal. Due to data unavailability, LWU is not included in the EW 2 model.	EW1 and EW2	Aqueduct (T2)
Eq8	$Ai = \frac{AIR}{TC}$	It is the proportion of irrigated area in total cultivated land. Total cultivated land includes both arable and permanent land.	EW1	UNSTATS, 2019 (A225)
Eq9	$Cr = \frac{1}{(1 + (\frac{Ai}{1 - Ai}) * 0.375)}$	The corrective coefficient Cr for the agricultural sector is needed to focus the indicator on the irrigated production	EW1	UNSTATS, 2019 (A225)
Eq10	$P_a = \frac{AWU}{TWW}$	It is the proportion of agricultural withdrawal to total water withdrawal.	EW1	UNSTATS, 2019 (A225)
Eq11	$WUEa = \frac{AGVA * (1 - Cr)}{AWU}$	It is for the agricultural water use efficiency as an output of gross value added and agricultural water withdrawal.	EW1	UNSTATS, 2019 (A225)

Table 6. Equations used in the mathematical models for efficient and sustainable water use (continued)

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq12	$TEW = EP * WI * CS$	It is for the thermoelectric water withdrawal as a function of the electricity produced by power plants and the water withdrawal intensity from the type of cooling system. Data are currently unavailable, therefore, equation is not included in the Phase 1 model.	EW2	Vassolo, S. & Döll, P., 2005 (A208)
Eq13	$MWW = f * VP * WI$	Manufacturing water withdrawal is dependent on the water withdrawal intensity and the annual production volume per sub-sector. F is an adjustment factor. Data are currently unavailable, therefore, equation is not included in the Phase 1 model.	EW2	Vassolo, S. & Döll, P., 2005 (A208)
Eq14	$IWU = TEW + MWW$	The data on industrial water withdrawal are currently unavailable, therefore, equation is not included in the Phase 1 model, instead the data from FAO are used.	EW1 and EW2	Vassolo, S. & Döll, P., 2005 (A208)
Eq15	$P_i = \frac{IWU}{TWW}$	It is the proportion of industrial withdrawal to total water withdrawal.	EW1	UNSTATS, 2019 (A225)
Eq16	$WUEi = \frac{IGVA}{IWU}$	Industrial water use efficiency is calculated by dividing the industrial gross value added by the industrial water withdrawal.	EW1	UNSTATS, 2019 (A225)
Eq17	$MWUD = \alpha(GDPC)^{\beta 1} * (Price)^{\beta 2} * Tech$	It is for the municipal water withdrawal per capita as a function of a country's level of GDPC, average municipal water price, and end-use technology advancement rate. Due to lack of country-level data, 'Tech' is not included in the model.	EW2	Hejazi, M., Edmonds, J., et al., 2013 (A191)
Eq18	$MWU = MWUD * Pop$	Total municipal water withdrawal is the municipal water per capita multiplied by the population.	EW1 and EW2	Hejazi, M., Edmonds, J., et al., 2013 (A191)
Eq19	$P_s = \frac{MWU}{TWW}$	It is the proportion of municipal withdrawal to total water withdrawal.	EW1	UNSTATS, 2019 (A225)
Eq20	$WUEs = \frac{SGVA}{MWU}$	This equation is for the service sector water use efficiency.	EW1	UNSTATS, 2019 (A225)
Eq21	$MWC = WSE * MWU$	Municipal water consumption is equal to the municipal water withdrawal multiplied by the water supply efficiency.	EW2 and EQ2	Hejazi, M., Edmonds, J., et al., 2013 (A191)
Eq22	$TW_i = \Sigma\,(\text{Number of Facilities} * TC_i * E_i)$	The amount of treated wastewater is dependent on the number of wastewater treatment facilities, the water treatment capacity of each technology, and the treatment efficiency. 'i' denotes the different technologies either activated sludge or bio-membrane.	EW2 and EQ2	Chawre, B., 2019 (A33)
Eq23	$Investment = \Sigma(CAPEX_i + (OPEX * 1000)_i * TW_i)$	The investment cost of wastewater technology is dependent on the initial construction cost, operational cost, and amount of treated wastewater.	EW2 and EQ2	Chawre, B., 2019 (A33)
Eq24	$IRWR = GW + SW - Overlap$	Internal renewable water resources include surface or ground water generated from endogenous precipitation within a country's boundaries.	EW2	UNSTATS, 2020 (A248)

Table 6. Equations used in the mathematical models for efficient and sustainable water use (continued)

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq25	$TRF = IRWR + ERWR$	Total renewable freshwater includes both internal and external water resources. External water resources include transboundary flow from neighboring countries.	EW2	UNSTATS, 2020 (A248)
Eq26	$TNCW = DW + TW$	Total non-conventional water includes desalinated water and wastewater than can be re-used.	EW2	FAO, 2020 (A247)
Eq27	$TFA = TRF + TNCW$	Total freshwater availability considers both renewable freshwater and non-conventional sources.	EW2	FAO, 2020 (A247)
Eq28	$TWW = AWU + IWU + MWU$	Total Water Withdrawal is the sum of agricultural water withdrawal, industrial water withdrawal, and municipal water withdrawal.	EW2	UNSTATS, 2020 (A248)
Eq29	$EW\,1 = WUEa * Pa + WUEi * Pi + WUEs * Ps$	It is the total water use efficiency for all sectors of agriculture, industry, and the service sector.	EW1	UNSTATS, 2019 (A225)
Eq30	$\text{Natural } EW\,2 = \dfrac{TWW}{(TRF - EFR) * 100}$	EW 2 water stress indicator only considers natural freshwater availability	EW2	UNSTATS, 2020 (A248)
Eq31	$EW\,2 = \dfrac{TWW}{(TRF - EFR) * 100}$	EW 2 water stress indicator includes non-conventional water sources such as desalination and treated wastewater. Comparing both EW 2 values can help provide insight on the use of non-conventional water sources in influencing country-level water stress.	EW2	UNSTATS, 2020 (A248)

Details are on Appendix 1 and Appendix 2

Table 7. Definitions of variables and parameters and sources of data for efficient and sustainable water use

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq1	Kc	Input parameter	Cropping coefficients	dimensionless	FAO
Eq1	CI	Input variable	Cropping Intensity	%	FAO
Eq1	ETo	Input variable	Reference Evapotranspiration	mm/year	FAO
Eq1, Eq2	ET_C	Output variable	Crop Evapotranspiration	mm/year	Simulation Tool
Eq2	ETa	Input variable	Actual Evapotranspiration	mm/year	USGS
Eq2, Eq3, Eq6	ICU	Output variable	Irrigation Consumptive Use	mm/year	Simulation Tool
Eq3, Eq4, Eq8	AIR	Input variable	Actual Irrigated Area	hectares	FAO AQUASTAT
Eq3, Eq6	A_{rice}	Input variable	Area of Paddy Irrigation	hectares	FAO AQUATSTAT
Eq3, Eq5	IWR	Output variable	Irrigation Water Requirement	m^3/year	FAO AQUASTAT*
Eq4, Eq6	AIR_t	Output variable	Actual Irrigated Area per type of irrigation technology	hectares	Simulation Tool
Eq4	P_t	Input scenario	Proportion of irrigated area by irrigation technology	%	Assumption
Eq5, Eq6	WRR	Input variable	Water Requirement Ratio	%	FAO
Eq5, Eq6, Eq7	IWW	Output variable	Irrigation Water Withdrawal	m^3/year	FAO AQUASTAT*
Eq6	ETech	Input parameter	Irrigation technology efficiency	%	Iwanaga et al. 2020 (A39)
Eq7	LWU	Input variable	Livestock Water Withdrawal	m^3/year	-
Eq7, Eq 10, Eq 28	AWU	Output Variable	Agricultural Water Withdrawal	m^3/year	FAO AQUASTAT*
Eq8	TC	Input variable	Total Cultivated Land	hectares	FAO AQUASTAT
Eq8, Eq9	Ai	Output variable	Proportion of Irrigated Land	dimensionless	Simulation Tool
Eq9, Eq11	Cr	Output variable	Corrective Coefficient	dimensionless	Simulation Tool
Eq10, Eq29	Pa	Input parameter	Proportion of Agricultural Water Use Efficiency	dimensionless	UNSTAT
Eq11	AGVA	Input variable	Agricultural Gross Value Added	US $ (constant 2010)	World Bank
Eq11, Eq29	WUEa	Output variable	Agricultural Water Use Efficiency	US$/ m^3	Simulation Tool
Eq12	EP	Input variable	Annual Electricity Produced by a Thermal Power Station	MWh/year	Global Power Plant Database (World Resources Institute) (Phase 2)
Eq12	CS	Input parameter	Type of Cooling System	Dimensionless	Zhai and Rubin, 2010 (Phase 2)
Eq12, Eq13	WI	Input variable	Water Withdrawal Intensity	m^3/MWh (thermoelectricity) or m^3/ton (manufacturing)	Zhai and Rubin, 2010 (Phase 2)
Eq12	TEW	Output variable	Thermoelectric Water Withdrawal	m^3/year	Simulation Tool (Phase 2)
Eq13	VP	Input variable	Annual Production Volume per Manufacturing Sector	tonnes/year	Simulation Tool (Phase 2)
Eq13, Eq14	MWW	Output variable	Manufacturing Water Withdrawal	m^3/year	Simulation Tool (Phase 2)
Eq14, Eq15, Eq16, Eq 28	IWU	Input variable	Industrial Water Withdrawal	m^3/year	FAO AQUASTAT
Eq15, Eq29	Pi	Input parameter	Proportion of Industrial Water Use Efficiency	dimensionless	UNSTAT
Eq16	IGVA	Input variable	Industrial Gross Value Added	US $ (constant 2010)	World Bank
Eq16, Eq29	WUEi	Output variable	Industrial Water Use Efficiency	US$/$m^3$	Simulation Tool
Eq17	GDPC	Input variable	Gross Domestic Production per Capita	US$/person (constant 2010)	World Bank

Table 7. Definitions of variables and parameters and sources of data for efficient and sustainable water use (continued)

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq17	Price	Input scenario	Water Price	US$/15 m^3	Assumption and International Benchmarking Network (IBNET)*
Eq17	Tech	Input parameter	Technology Rate	dimensionless	Hejazi, M., Edmonds, J., et al., 2013 (A191)
Eq17, Eq18	MWUD	Output variable	Municipal Water Withdrawal per capita	m^3/year/person	Simulation Tool
Eq18	Pop	Input variable	Population	persons	World Bank
Eq18, Eq19, Eq20, Eq21, Eq28	MWU	Output variable	Municipal Water Withdrawal	m^3/year	FAO AQUASTAT*
Eq19, Eq29	Ps	Input parameter	Proportion of Service Sector Water Use Efficiency	dimensionless	UNSTAT
Eq20	SGVA	Input variable	Service Sector Gross Value Added	US $ (constant 2010)	World Bank
Eq20, Eq29	WUEs	Output variable	Service Sector Water Use Efficiency	US$/ m^3	Simulation Tool
Eq21	WSE	Input parameter	Water Supply Efficiency	dimensionless	Hejazi, M., Edmonds, J., et al., 2013 (A191)
Eq21	MWC	Output variable	Municipal Water Consumption	m^3/year	Simulation Tool
Eq22	Facilities	Input scenario	Number of Treatment Facilities	Value	Assumption
Eq22	TC_i	Input variable	Wastewater Technology Treatment Capacity	kilotons	Ke, W., Lei, Y., et al., 2016 (A32)
Eq22	E_i	Input parameter	Wastewater Technology Sewage Efficiency	dimensionless	Ke, W., Lei, Y., et al., 2016 (A32)
Eq22, Eq23	TW	Output variable	Total Treated Wastewater	kilotons	Simulation Tool
Eq23	CAPEX	Input variable	Construction Cost	US$	Ke, W., Lei, Y., et al., 2016 (A32)
Eq23	OPEX	Input variable	Operational Cost	US$/ton	Ke, W., Lei, Y., et al., 2016 (A32)
Eq23	Investment	Output variable	Potential Investment Cost of Wastewater Technology	US$	Simulation Tool
Eq24	SW	Input variable	Surface Water	m^3/year	FAO AQUASTAT
Eq24	GW	Input variable	Ground Water	m^3/year	FAO AQUASTAT
Eq24	Overlap	Input variable	Overlap between Surface Water and Ground Water	m^3/year	FAO AQUASTAT
Eq24, Eq25	IRWR	Input variable	Internal Renewable Water Resource	m^3/year	FAO AQUASTAT
Eq25	ERWR	Input variable	External Renewable Water Resources	m^3/year	FAO AQUASTAT
Eq25, Eq27, Eq30	TRF	Input variable	Total Renewable Freshwater	m^3/year	FAO AQUASTAT
Eq26	DW	Input Variable	Desalinated Water	m^3/year	FAO AQUASTAT
Eq26	TW	Input variable	Treated Wastewater	m^3/year	FAO AQUASTAT
Eq26, Eq27	TNCW	Output variable	Total Non-conventional Water	m^3/year	Simulation Tool
Eq27, Eq31	TFA	Output variable	Total Freshwater Available	m^3/year	Simulation Tool
Eq10, Eq15, Eq19, Eq28, Eq30, Eq31	TWW	Output variable	Total Water Withdrawal	m^3/year	Simulation Tool
Eq30, Eq31	EFR	Input variable	Environmental Flow Requirement	m^3/year	FAO AQUASTAT
Eq29	EW1	Output variable	Total Water Use Efficiency	US$/$m^3$	Simulation Tool
Eq30, Eq31	EW2	Output variable	Share of Freshwater Withdrawal to Freshwater Availability	%	Simulation Tool

**data was used for model output validation*

3.1.3 Sustainable land use

Sustainable land use refers to delivering more services or products for a fixed amount of land used and without compromising many ecosystem services provided by land (Auzins et al., 2014; Smith, 2018). The details on the mathematical models and variables for the equations for land use system are provided in Table 8 and Table 9. The flow diagrams for the models are presented in Figure A4 in Appendix 3.

SL1: Soil nutrient balance (kg nitrogen per hectare)

The mathematical models for land use are based on the framework from EU Calculator Agriculture and Land-Use Module (Baudry et al., 2019). The main driver of land use change is food demand. There are 97 different food groups divided into crop- and animal-based products, based on the aggregation by FAOSTAT (FAO, 2020). The demand for each of the different food groups is calculated by taking into account human food consumption, seed, residuals, imports, exports, and non-food use losses. There are several scenarios linked to food demand that can be altered such as a reduction in food waste on the consumption or production side.

Animal-based food groups, such as milk, meat, and eggs, are aggregated accordingly and their respective animal populations are computed. This was done by dividing the total kilocalories (kcal) demand by the average animal yields and multiplying it with the ratio of production to total animals. To compute the animal feed demand, the total animal population was multiplied by a feed conversion factor estimated by Alexander et al. (2016). The food demand model was calibrated with the 2017 data, and if needed, a correction variable was used. This total animal feed demand minus the animal feed from grasslands and forage was added to the food demand to compute the total demand for each food group. The change in animal-based food products will not only influence the animal-based food groups, but also the crop-based food groups due to a change in the respective feed requirement. Also, the animal groups play important roles to compute the emission from enteric processes and manure that are linked to indicator GE3.

From the total crop-based food demands, the total cropland demand was computed by dividing it by the total crop yields for 2017. However, some minor differences occurred as the food groups calculated did not exactly match the crop types in FAOSTAT. Thus, an additional parameter was used to correct this. With the total cropland demand, the change in land use was calculated by comparing it to the previous year. If the cropland area increased, it was assumed that this caused a decrease in the inactive or fallow land area. A reforestation scenario set by the user determines the share of inactive lands to be converted to forests. Both the fallow land and forest area were then computed by adding their respective changes to the land use of the previous year. The changes in crop- and forest area can then be multiplied with the emission factors from the IPCC to compute the emission from land use change. The inputs from the changes in land use were also used to compute the share of forest area to total land area (BE2) and aboveground biomass (BE3).

The nutrient sub-model is based on Tan et al. (2005) using the data from FAO (2020). The change in the nutrient balance is based on the total nitrogen inputs from manure, fertilizer, biological fixation, and atmospheric composition, as well as nitrogen outputs from crop production. For each of the animal groups used earlier, the total manure production was computed using a vector of manure yields. From total manure production, the fraction of manure applied to croplands was calculated. In the current version of the simulation tool, the fertilizer use per hectare, biological fixation, and atmospheric composition are direct inputs in the model and assumed constant over the years. To compute the nitrogen outputs from crops, total crop production was multiplied with the crop nutrient concentrations. These nutrient concentrations per kg of yields were calculated by dividing the total nutrient output by the total crop output from FAO in the baseline year and assumed constant. The change in the nutrient balance can be linked to the change in the nutrient budget (SL1). The emissions from fertilizer were also calculated using an emission factor.

An illustration of implementation of the mathematical models for nutrient balance is presented in Chapter 4.2. Land use.

Table 8. Equations used in the mathematical models for sustainable land use

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq1	$\mathrm{KKR_i} = (\frac{\mathrm{FDKC2017_i}}{\mathrm{FDKG2017_i}/365})$	This computes the kcal/kg ratio of each crop using the total food demand in kg and the food demand in kcal in the baseline year, for each food group i.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq2	$\mathrm{FWP2017_i} = \frac{\mathrm{FLO2017_i} * \mathrm{KKR_i} * \frac{1000000}{365}}{\mathrm{P}}$	This computes food waste in the baseline year by taking the vector of food waste in tons per year and converting it to kcal/cap/day for each food group i.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq3	$\mathrm{FW_i} = \mathrm{FWP2017_i} * \mathrm{FWPP_i}$	This computes the food waste by taking the producer food waste in the baseline year multiplied by a parameter indicating producer food waste reduction policy for each food group i.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq4	$\mathrm{TCDi} = \mathrm{P} * \mathrm{FDKC2017_i} + \mathrm{FW_i} - \mathrm{FWCR_i})$	The total calorie demand per food group is the total population times the daily calorie demand per person, plus the food waste per person on the production side minus consumer food waste reduction in kcal/day.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)

Table 8. Equations used in the mathematical models for sustainable land use (continued)

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq5	$OF_i = SD_i + NFD_i + PD_i + RD_i + SV_i$	Other food demand is the sum of the demand for seed, non-foodstuffs, processed foods, residuals, and stock variation for each food group i.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq6	$SSR_i = \frac{100 * FP_i}{FP_i - FE_i + FI_i}$	The self-sufficiency ratio indicates the ratio of food production exported. It is calculated by the total production divided by the production minus exports plus imports in the baseline year for each food group i.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq7	$FD_i = \frac{\left(\frac{TCD_i * SSR_i}{100}\right) * 365}{KKR_i}$	The total domestic food demand in tons is the total daily calorie demand times the self-sufficiency ratio divided by the kcal/kg ratio.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq8	$ANP_i = \frac{FD_{i,animal} * 1000000}{AY_{2017i}}$	The total production animal is calculated by dividing the animal-based food produced with the animal yields in the baseline year.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq9	$TAFD_i = \frac{FCR_i * AY2017_i * ANP_i}{1000000}$	The total animal feed demand is a feed-conversion ratio multiplied by the total production animals and animal yields.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129) and Alexander P., Brown, C., et al., 2016 (A226)
Eq10	$PTTA_i = \frac{TAH2017_i}{ANP2017_i}$	The production-to-total-animal ratio is calculated using the total animals divided over the production animals for the baseline year for each animal group i.	SL1 & GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq11	$TA_i = (ANP_i * PTTA_i) * CPTA_i$	The total animal population is the production animals multiplied by the production-to-total animal ratio and a correction parameter.	SL1 & GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq12	$MY_i = \frac{TMP2017i}{ANP2017_i}$	The manure yields are calculated by dividing the total manure production with the total animals in the baseline year for each animal group i.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq13	$TM_i = TA_i * MY_i$	The total manure production is the total animals multiplied with manure yields for each animal group i.	SL1 & GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq14	$MM_{ASi} = \frac{TMAS2017_i}{TMP2017i}$	The % of total manure applied to the soil is the total manure applied to the soil divided by total manure production in the baseline year	SL1 & GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq15	$MAS_i = TM_i * MM_{ASi}$	The vector manure applied to soil is the total manure production multiplied with the share of manure application to soils for each manure producing animal group i.	SL1 & GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq16	$FeedD = \frac{TAFD_i}{CRfd}$	Total crop-feed demand is the total animal feed demand divided by the crop-forage feed ratio, which indicates the distribution of feed from pasture and from crops.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq17	$FM_i = \frac{FDi_{2017}}{\sum FDi_{2017}}$	The feed mix is the distribution of animal feed for different crop types. It is calculated by taking the feed demand for crop I divided by the total feed demand for the baseline year.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq18	$AFD_i = FM_i * FeedD$	The total animal feed is the total feed demand multiplied by the feed mix.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq19	$FDTi_{total} = \frac{SSR_i}{100} * (OF_i + AFD_i) + FD_i$	The vector total food demand is the self-sufficiency ratio, which indicated the import-export ratio for each crop, multiplied by the total animal feed demand plus other demand. Secondly, the vector of total domestic food production is added.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)

Table 8. Equations used in the mathematical models for sustainable land use (continued)

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq20	$FDTagr_i = \sum_{i=1}^{13} FDTi_{total}$	Total crop demand is the sum of all crop-based food products.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq21	$CNY2017_i = \frac{CO2017i}{(CNO2017i * 1000)}$	The vector of crop nitrogen yield is calculated using the crop output divided by the crop nitrogen concentrations in for 2017.	SL1 & GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq22	$OUT_C = \sum(FDTagr_i * CNY2017_i) * 1000$	Total crop nitrogen output is crop production multiplied with the crop nitrogen yields.	SL1	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq23	$TCropDi = \frac{FDTi_{total} * 100000}{CY_i}$	This calculates the total cropland demand for each crop.	SL1 & GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq24	$chCL = \sum TCropDi - (CL_{t-1} + CL_{perm})$	This calculates the change in cropland based on the calculated cropland demand and the cropland area in the previous year excluding the permanent crops.	SL1 & GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq25	$ILstock_t = ILstock_{t-1} - chCL$	The inactive land is affected by the change in cropland area. If the total cropland increases, the inactive land available for reforestation decreases. If the cropland area decreases, the total inactive land increases.	SL1, BE2, BE3, GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq26	$RF_{land} = \frac{R_{rate}}{100} * ILstock_t$	The reforested land is calculated by multiplying a reforestation rate with the total inactive/fallow agricultural land area.	SL1, BE2, BE3, GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq27	$ILstock_{t+1} = ILstock_t - RF_{land}$	The new inactive/fallow land area in the next year is the inactive/fallow land area from the previous year minus the newly reforested land.	SL1, BE2, BE3, GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq28	$FLstock_{t+1} = FL_{stock_t} + RF_{land}$	New forest area is the forest area of the previous year plus the newly reforested area.	SL1, BE2, BE3, GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq29	$chFL = FLstock_t - FLstock_{t+1}$	The change in forest area is the forest area of the new year minus the forest area of the previous year.	SL1, BE2, BE3, GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq30	$CLstock_t = \sum TCropDi + CL_{perm} - chFL$	The total cropland area is the sum of the total cropland demand multiplied with a correction parameter, permanent crops are added and the share of the inactive agricultural land that is converted to forest subtracted.	SL1 & GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq31	$\Delta C = 0.5 * \left(-C + \sqrt{\frac{C^2 - 4 * \epsilon_p * C * \Delta F_{subsidy}}{P_c}}\right)$	This allows inclusion of scenarios for fertilizer subsidy.	SL1	Vivid Economics, 2017 (A227)
Eq32	$FU = \frac{FU2017}{TCD2017}$	The fertilizer use per hectare is the total fertilizer use in the baseline year divided by the total crop demand in the same year.	SL1 & GE3	Baudry, G., Mwabonje, O., et al., 2019 (T129)
Eq33	$IN_F = CLstock_t * FU + \Delta C$	The nitrogen application on the total cropland is calculated by multiplying the total cropland area with the fertilizer use per hectare.	SL1 & GE3	FAOSTAT, n.d.(a) (A228)
Eq34	$NB = \frac{\sum MAS_i}{1000} + IN_F + BF_{2017} + AD_{2017} - OUT_C$	The nutrient balance is computed by taking the nitrogen inputs and subtracting them with the nitrogen outputs.	SL1	Tan, Z., Lal, R., et al., 2005 (A209)

**Details are on Appendix 1 and Appendix 2*

Table 9. Definitions of variables and parameters and sources of data for sustainable land use

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq1	$FDKG2017_i$	Input variable	Vector of KG food demand per food group	kg/capita/yr	FAOSTAT
Eq1, Eq4	$FDKC2017_i$	Input variable	Vector of KCAL food demand per food group	Kcal/capita/day	FAOSTAT
Eq1, Eq2, Eq7	KKR_i	Output variable	Vector kcal/kg ratio for 2017	Kcal/kg	Simulation Tool
Eq2	$FLO2017_i$	Input variable	Vector food waste 2017	x1000t	FAOSTAT
Eq2, Eq4	P	Input scenario	Population	heads	Assumption
Eq2, Eq3	$FWP2017_i$	output variable	Vector food waste production 2017	Kcal/capita/day	FAOSTAT
Eq3	$FWPP_i$	Input scenario	Vector food waste reduction policy	%	Assumption
Eq3, Eq4	FW_i	Input variable	Vector food losses production	Kcal/capita/day	Simulation Tool
Eq4	$FWCR_i$	Input scenario	Vector food waste reduction	Kcal/capita/day	Simulation Tool
Eq4, Eq7	$TCDi$	Output variable	Total calorie demand per food group	Kcal/day	Simulation Tool
Eq5	SD_i	Input variable	Vector seed demand (2017)	x1000 t	FAOSTAT
Eq5	NFD_i	Input variable	Vector non-food demand (2017)	x1000 t	FAOSTAT
Eq5	PD_i	Input variable	Vector processed food demand (2017)	x1000 t	FAOSTAT
Eq5	RD_i	Input variable	Vector residual demand (2017)	x1000 t	FAOSTAT
Eq5	SV_i	Input variable	Vector stock variation	x1000 t	FAOSTAT
Eq5, Eq19	OF_i	Output variable	Other food demand (2017)	x1000 t	Simulation Tool
Eq6	FP_i	Input variable	Vector food production (2017)	x1000 t	FAOSTAT
Eq6	FI_i	Input variable	Vector food imports (2017)	x1000 t	FAOSTAT
Eq6	FE_i	Input variable	Vector food exports (2017)	x1000 t	FAOSTAT
Eq6, Eq7, Eq19	SSR_i	Output variable	Self-sufficiency ratio	ratio	Simulation Tool
Eq7	$TCDi$	Output variable	Total calorie demand per food group	kcal/day	Simulation Tool
Eq7, Eq8, Eq19	FD_i	Output variable	Vector total domestic food production	x1000 t	Simulation Tool
Eq8, Eq9	$AY2017_i$	Input variable	Vector of animal yields	Kg/animal	FAOSTAT
Eq8, Eq11	ANP_i	Output variable	Vector animals needed for production	heads	Simulation Tool
Eq9	FCR_i	Input variable	feed conversion ratio	kg DM feed/ kg EW	Alexander et al., 2016
Eq9, Eq16	$TAFD_i$	Output variable	Vector total animal feed demand	x1000 t	Simulation Tool
Eq10	$TAH2017_i$	Input variable	Vector total animals (2017)	Heads	FAOSTAT
Eq10, Eq12	$ANP2017_i$	Input variable	Vector total production animals (2017)	heads	FAOSTAT
Eq10, Eq11	$PTTA_i$	Output variable	Production-to-total animal ratio	heads	Simulation Tool
Eq11	$CPTAi$	Input variable	Correction animal population	-	Calibration
Eq11, Eq13	TA_i	Output variable	Vector total animal population corrected	No. of heads	Simulation Tool
Eq12, Eq14	$TMP2017i$	Input variable	Vector total manure production 2017	Kg N	FAOSTAT
Eq12, Eq13	MY_i	Output variable	Vector manure yields	Kg N / animal	Simulation Tool
Eq13, Eq15	TM_i	Output variable	Vector total manure produced	Kg N	Simulation Tool

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Table 9. Definitions of variables and parameters and sources of data for sustainable land use (continued)

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq14	$TMAS2017_i$	Input variable	Total manure applied to soil 2017 (vector)	Kg N	FAOSTAT
Eq14, Eq15	MM_{ASi}	Output variable	The % of total manure that is applied to the soil	%	Simulation Tool
Eq15, Eq34	MAS_i	Output variable	Vector of animal manure application to soils	x1000 t N	Simulation Tool
Eq16	$CRfd$	Input variable	Crop-forage feed ratio (using 2017 calibration)	ratio	Calibration
Eq16, Eq18	$FeedD$	Output variable	Total crop feed demand	x1000 t	Simulation Tool
Eq17	FDi_{2017}	Input variable	Animal feed demand	x1000 t	FAOSTAT
Eq17, Eq18	FM_i	Output variable	Feed mix fraction	fraction	Simulation Tool
Eq18, Eq19	AFD_i	Output variable	Vector total animal feed demand	x1000 t	Simulation Tool
Eq19, Eq20	$FDTi_{total}$	Output variable	Vector total food demand	x1000 t	Simulation Tool
Eq20, Eq22	$FDTagr_i$	Output variable	Total crop demand	x1000 t	Simulation Tool
Eq21	$CO2017i$	Input variable	Total crop output 2017	x1000 t	FAOSTAT
Eq21	$CNO2017i$	Input variable	Total crop nitrogen output 2017	t	FAOSTAT
Eq21, Eq22	$CNY2017_i$	Output variable	Vector crop nitrogen yield	N/kg	Simulation Tool
Eq23, Eq34	OUT_C	Output variable	Crop nitrogen output	t N	Simulation Tool
Eq23	CY_i	Input variable	Vector crop yields	hg/ha	FAOSTAT
Eq23, Eq24, Eq30	$TCropDi$	Output variable	Vector total cropland demand	ha	Simulation Tool
Eq24, Eq30	CL_{perm}	Input variable	Permanent cropland	x1000 ha	FAOSTAT
Eq24	CL_{t-1}	Output variable	Area dedicator to cropland in previous year	x1000 ha	Simulation Tool
Eq24, Eq25	$chCL$	Output variable	Change in cropland demand	x 1000ha	Simulation Tool
Eq25, Eq26, Eq27	$ILstock_t$	Output variable	Inactive/fallow land stock at time t	x 1000ha	Simulation Tool
Eq26	R_{rate}	Input scenario	Reforestation rate	%	Assumption
Eq26, Eq27, Eq28	RF_{land}	Output variable	Reforestation of land	x 1000ha	Simulation Tool
Eq27	$ILstock_{t+1}$	Output variable	Inactive/fallow land stock at time t+1	x 1000ha	Simulation Tool
Eq28, Eq29	$FLstock_t$	Output variable	Forest land stock at time t	x 1000ha	Simulation Tool
Eq29, Eq30	$chFL$	Output variable	Change in forest land	x 1000ha	Simulation Tool
Eq30, Eq33	$CLstock_t$	Output variable	Total cropland	x1000 ha	Simulation Tool
Eq31	ϵ_P	Input variable	Price elasticity	-	Abdoulaye & Sanders, 2005; David, 1976; Langyintuo et al., 2003 (Phase 2)
Eq31	$F_{subsidy}$	Input scenario	Fertilizer subsidy	USD	Assumption (Phase 2)
Eq31	P_c	Input variable	Fertilizer price	USD/nutrient	FAOSTAT (Phase 2)
Eq31, Eq33	C	Output variable	Fertilizer consumption	tons	Simulation Tool (Phase 2)
Eq32	$FU2017$	Input variable	Total fertilizer use 2017	T n	FAOSTAT
Eq32	$TCD2017$	Input variable	Total cropland demand 2017	x1000 ha	FAOSTAT

Table 9. Definitions of variables and parameters and sources of data for sustainable land use (continued)

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq32, Eq33	FU	Output variable	Fertilizer use	Kg/ha	Simulation Tool
Eq33, Eq34	$\mathrm{IN_F}$	Output variable	Nitrogen application to cropland	x1000 t N	Simulation Tool
Eq34	$\mathrm{AD_{2017}}$	Input variable	Atmospheric nitrogen deposition	x1000 t N	FAOSTAT
Eq34	$\mathrm{BF_{2017}}$	Input variable	Biological nitrogen fixation	x1000 t N	FAOSTAT
Eq34	NB	Output variable	Nutrient balance	x1000 t N	Simulation Tool

3.1.4 Material use efficiency

Material use efficiency refers to delivering more services or products per unit of raw material used and reducing material demand through increased recycling, longer-lasting products, and component re-use, among others (Allwood et al., 2011; Lifset & Eckelman, 2013). The details on the mathematical models and variables for the equations for material use system are provided in Table 10 and Table 11. The flow diagram for the models is presented in Figure A5 in Appendix 3.

ME1: Domestic Material Consumption per GDP (Tons/US$)

Domestic material consumption is defined as the sum of all the materials that are directly utilized by the economy in addressing the needs for goods and services within and even outside of a country (Wiedmann et al., 2015). It is calculated by adding the total domestic extraction and imports minus exports. Within the Simulation Tool, the current framework disaggregated these variables into the four major material categories, namely, biomass, fossil fuels, metals, and non-metallic minerals.

Due to domestic material consumption being predominately measured through accounting methodologies such as material flow accounting and input-output analysis, the Simulation Tool used the estimated ME1 output to extend the material use efficiency model and provide information on sectoral waste generation, potential job generation, and resource efficiency. For instance, the inclusion of the Resource Efficiency Simulation Tool (REST) methodology by UN ESCAP (2019) was implemented in the Simulation Tool to help connect resource efficiency to domestic material consumption. Although, this framework does not take account the full range of co-benefits offered by resource-efficiency and is another component that could be integrated into the simulation tool in later phases.

The amount of resources saved was estimated by a user defined percentage change in resource efficiency with the ME1 output. To convert the resources saved into a monetary value, it required finding the comparable cost per unit of material resources. If country specific prices are not available in all cases, then the latest global market prices for all major traded non-fuel and fuel commodities produced were used combined with their world export weights. To give a broad idea on the job generation potential of resource efficiency improvement, monetary savings were converted into job equivalents. Then, the job equivalents for a country were calculated using the mean yearly wages for the country/region/sub-region. The calculation of job equivalents assumed the conversion of all resources saved into employment generation and this may not be the case in reality. However, the number of job equivalents provides an upper envelope of the job creation potential of resource efficiency improvements. Depending on the prevailing wages, these job equivalents vary from country to sub-regions (UN ESCAP, 2019).

To link waste generation and provide another linkage to the green growth, the material sub-model from Dafermos et al. (2017) was used. It uses a material balance to identify the amount of waste generated from demolished and discarded material goods, which provides insight into wastes generated from construction as well as household consumption. Waste generated is calculated as the difference between the discarded socio-economic stock and the recycled socio-economic stock. The discarded socio-economic stock equates to the contents of the materials from devalued capital goods as well as the end-of-life durable consumption goods multiplied by ME1 to convert the units from US$ to tonnes. On the other hand, the recycled socio-economic stock is determined by the recycling rate and discarded socio-economic stock. As these equations are based on mass-balance principles, the GGPM team plans to extend this framework to include the waste from biomass and fossil fuels as well as the incorporation of other sectors such as the manufacturing, which is also involved in the accumulation of physical capital. By including biomass and non-durable consumption goods, this would also allow linkages to the indicator, EQ 3: municipal solid waste generation.

ME2: Material Footprint per Capita (Tons per capita)

Due to limitations in data and models for material footprint, an ordinary-least squares regression equation was used to explain material footprint per capita. The domestic material consumption was identified as a suitable explanatory variable used to predict material footprint. The final output of ME2 was calculated by dividing the predicted material footprint value by the population of a specified country. Regression analysis will still be conducted to identify the suitable coefficients to predict material footprint from domestic material consumption in each individual country. This model could further be expanded to include additional variables within a country that could also contribute to its material footprint.

Table 10. Equations used in the mathematical models for material use efficiency

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq1	$\mathrm{DMC_i} = (\mathrm{DE_i} + \mathrm{I_i}) - \mathrm{E_i}$	Domestic material consumption includes domestic extraction plus imports minus exports. 'i' denotes the material type such as biomass, fossil fuels, metals, and non-metallic minerals. The sum of all groups estimates total domestic material consumption.	ME1, ME2	UNSTATS, 2018b (A246)
Eq2	$\mathrm{MF} = \alpha + \beta 1 * \mathrm{DMC}$	It is the regression for estimating total material footprint from total domestic material consumption.	ME2	Regression Analysis
Eq3	$\mathrm{ME\ 1} = \dfrac{\mathrm{DMC}}{\mathrm{GDP}}$	This computes the total domestic material consumption (kg) per US$ GDP.	ME1	UNSTATS, 2018b (A246)
Eq4	$\mathrm{ME\ 2} = \dfrac{\mathrm{MF}}{\mathrm{Population}}$	Material footprint per capita is calculated by total material footprint divided a country's population.	ME2	UNSTATS, 2018a (A229)
Eq5	$\mathrm{RS} = (\mathrm{MEI} * \mathrm{ME\ 1}) * \mathrm{GDP}$	It is the amount of resources saved from % change in material efficiency.	ME1	UN ESCAP (T39)
Eq6	$\mathrm{MS_i} = \dfrac{\mathrm{DMC_i}}{\sum \mathrm{DMCi}}$	It is for the share of material consumption type in total domestic material consumption, where 'i' denotes the material type such as biomass, fossil fuels, metals, and non-metallic minerals.	ME1	UN ESCAP (T39)
Eq7	$\mathrm{CM_i} = \mathrm{EX_i} + \mathrm{AP_i}$	The cost of each material is calculated by multiplying the average of the latest commodity market prices by their relative export weights. Each commodity is assigned to a material group.	ME1	UN ESCAP (T39)
Eq8	$\mathrm{PM} = \Sigma(\mathrm{CM_i} * \mathrm{MS_i})$	The total price of materials is estimated by the sum of the proportion of each material group in domestic material consumption multiplied by the material cost.	ME1	UN ESCAP (T39)
Eq9	$\mathrm{TMS} = \mathrm{PM} * \mathrm{RS}$	Total monetary savings is the sum of price of each material multiplied by the resources saved.	ME1	UN ESCAP (T39)
Eq10	$\mathrm{JE} = \dfrac{\mathrm{TMS}}{\mathrm{AW}}$	Potential job equivalents from the % change in material efficiency is the total monetary savings divided by the annual average wage rate.	ME1, GJ1	UN ESCAP (T39)
Eq11	$\mathrm{DSES} = \mathrm{ME\ 1} * (\mathrm{RC} * \mathrm{PCS} + \mathrm{PDCG} * \mathrm{DCGS})$	Discarded socio-economic is comprised of the depreciation of capital stock and the depreciated durable and semi-durable consumption goods stock. To convert these monetary values into tonnes, it is multiplied by ME 1, which is also known as material intensity.	ME1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq12	$\mathrm{RSES} = \mathrm{DSES} * \mathrm{RR}$	Recycled socio-economic stock is the portion of discarded socio-economic stock multiplied by the recycling ratio.	ME1, EQ3	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq13	$\mathrm{Waste} = \mathrm{DSES} - \mathrm{RSES}$	Waste includes the sectoral waste from construction and demolition and discarded durable and semi-durable household goods. It is calculated as the difference between total discarded socio-economic stock and recycled socio-economic stock.	ME1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)

Details are on Appendix 1 and Appendix 2

Table 11. Definitions of variables and parameters and sources of data for material use efficiency

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq1	DE_i	Input variable	Vector of type of materials (biomass, fossil fuels, metal ores and non-metallic minerals) in domestic extraction.	tons	IRP Material Flows Database
Eq1	I_i	Input variable	Vector of type of materials in imports	tons	IRP Material Flows Database
Eq1	E_i	Input variable	Vector of type of materials in exports	tons	IRP Material Flows Database
Eq1, Eq2, Eq3, Eq5, Eq6	DMC_i	Output variable	Vector of type of materials in domestic material consumption	tons	Simulation Tool
Eq2	RM	Input variable	Vector of Regression Coefficients	Dimensionless	Regression Analysis
Eq2	MF	Output variable	Material Footprint	Tons	Simulation Tool
Eq3, Eq5	GDP	Input variable	Gross Domestic Product	$US (constant price)	World Bank and IRP Material Flows Database
Eq3, Eq5, Eq11	ME1	Output variable	Total Domestic Material Consumption per unit of GDP	DMC (kg) per GDP	Simulation Tool
Eq4	Pop	Input variable	Population	Persons	World Bank
Eq4	ME2	Output variable	Material Footprint per capita	Tons per person	Simulation Tool
Eq5	MI	Input scenario	Material Efficiency Improvement	%	Assumption
Eq5, Eq9	RS	Output variable	Resources Saved	Tons	Simulation Tool
Eq6, Eq8	MS_i	Output variable	Vector of the Share of Materials in Total Domestic Material Consumption	%	Simulation Tool
Eq7	AP	Input variable	Vector of Latest Average Market Prices of Commodities	$	International Monetary Fund (IMF)
Eq7	EX	Input variable	Vector of Export Weights to Total Commodities	%	International Monetary Fund (IMF)
Eq7, Eq8	CM	Output variable	Vector of Cost per unit of Materials	$	Simulation Tool
Eq8, Eq9	PM	Output variable	Total Price per unit of Materials	$	Simulation Tool
Eq9, Eq10	TMS	Output variable	Total Monetary Savings	$	Simulation Tool
Eq10	AW	Input variable	Annual Average Wage	$	OECD
Eq10	JE	Output variable	Job Equivalents	Persons	Simulation Tool
Eq11	PCS	Input variable	Total Physical Capital Stock (GFCF Investment)	$	OECD
Eq11	DCGS	Input variable	Durable Consumption Good Stock	$	OECD (National Accounts)
Eq11	RC	Input parameter	Rate of Capital Depreciation	%	Penn World Tables
Eq11	PDCG	Input parameter	Proportion of Durable Consumption Goods Discarded per year	%	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq11, Eq12, Eq13	DSES	Output variable	Discarded Socio-Economic Stock	tons	Simulation Tool
Eq12	RR	Input scenario	Recycling Ratio	%	Assumption
Eq12, Eq13	RSES	Output variable	Recycled Socio-Economic Stock	tons	Simulation Tool
Eq13	Waste	Output variable	Total Waste Generated	tons	Simulation Tool

3.2 Natural capital protection

3.2.1 Environmental quality

Environmental quality refers to properties and characteristics of the environment which may affect the health of human beings and other organisms, including air, water and noise pollution, access to open space, and visual impacts of buildings (EEA, 2015, 2017). The details on the mathematical models and variables for the equations for environmental quality are provided in Table 12 and Table 13. The flow diagrams for the models are presented in Figure A2 for the PM.25 emissions (link to transport sector) and Figure A6 for the DALY rate in Appendix 3.

EQ1: PM2.5 air pollution, mean annual population-weighted exposure (Micrograms per m³)

This indicator has no mathematical models of its own because it is an output variable for the transport sector. It is thus interlinked to other mathematical models in the energy system. The emission factor from the IPCC was used to link air pollution (EQ1) to the transport model in share to renewable (EE2).

EQ2: DALY rate due to unsafe water sources (DALY lost per 100,000 persons)

The equations used in the EQ2 model were drawn from two frameworks for DALY calculations. The first framework is proposed by the World Health Organization (WHO) for the calculation of DALY rates with respect to different diseases such as diarrhea, cholera, and malaria. It calculates the population attributable fraction of a particular disease, which is the proportion of incidents in the population that are attributable to the risk factor. The second framework presents an agent-based model to simulate pollution discharge into water bodies (Deng et al., 2018). The total pollution from agricultural and industrial sources are considered in this framework, with a detailed focus on pollution from various sources within these sectors as well. Due to inadequacy of data, however, the entire model could was not fully included and only the equation that links the DALY rate to the dosage of pollution in water was actually considered. Other equations that calculate total nitrogen or phosphorous pollution are difficult to implement, especially in developing countries with limited data. For the Phase 2 application, this indicator can be linked to the access to safely managed water and sanitation system (AB1).

EQ3: Municipal solid waste (MSW) generation per capita (Tons per year per capita)

There are no available mathematical models for MSW and the lack of time-series data for this indicator did not allow the development of regression models. The mathematical models for the material use system and land use system through food waste can be linked to MSW. But these will be part of the Phase 2 application when data can be collected from the national agencies.

Table 12. Equations used in the mathematical models for environmental quality

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq1	$TN_{crops} = \Sigma F_j * NC_j$	Total nitrogen discharged into the water by crop planting is the summation of the amount of the jth fertilizer and nitrogen content of the jth fertilizer.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq2	$TN_{livestock} = \Sigma AQ_n * NC_n$ or $TN_{livestock} = AQ_{watershed} * K_2$	Total nitrogen discharged into the water by livestock and poultry breeding is the summation of the amount of the nth category poultry or livestock multiplied by nitrogen excretion of the nth category poultry or livestock. It can be also calculated by multiplying the amount of poultry or livestock at the watershed with the nitrogen emission factor during the livestock breeding.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq3	$TN_{life} = Pop * Protein * NC_p * K_3$	Total nitrogen discharged into the water by life is calculated by multiplying the permanent resident population in the basin with annual protein consumption per capita, nitrogen content of the protein, and the non-consumed protein factor in wastewater.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq4	$TN_{farms} = TN_{crops} * W_{crops1} + TN_{livestock} * W_{livestock1} + TN_{jife} * W_{life1}$	Total nitrogen content discharged into water by agricultural household agents is calculated by the summation of different nitrogen content discharged in the water multiplied by its respective nitrogen losses rates.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq5	$TN_{factories} = NC_w * X_e$	Total nitrogen content discharged into water by factory agents is calculated by multiplying the nitrogen content of wastewater discharged by factories with waste water.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq6	$TN_{total} = TN_{farms} + TN_{factories}$	Total nitrogen content discharged into water is the summation of nitrogen content discharge into water of agricultural household agents and factory agents.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)

Table 12. Equations used in the mathematical models for environmental quality (continued)

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq7	$COD_{livestock} = \Sigma AQ_n * CODC_n$ or $COD_{livestock} = AQ_{watershed} * K_6$	Total COD discharged into the water during livestock and poultry breeding is the summation of the amount of nth category poultry or livestock multiplied by the content of COD in the nth category poultry or livestock. Another calculation is by multiplying the emission factor of COD during livestock breeding with the amount of poultry or livestock at the watershed.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq8	$COD_{life} = Pop * K_7$	Total COD content discharged from life can be calculated by multiplying permanent resident population in the basin with emission factor of COD during the life of each person.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq9	$COD_{factories} = CODC_w * X_e$	Total COD content discharged from factory agents is calculated by multiplying the COD content of wastewater discharged by factories by wastewater.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq10	$COD_{total} = COD_{livestock} * W_{livestock3} + COD_{life} * W_{life3} + COD_{factories}$	Total COD discharged into the water is the summation of COD content discharged from livestock and life multiplied by its COD loss rates plus the COD content discharged from factory agents.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq11	$TP_{crops} = \Sigma F_j * PC_j$	Total phosphorus content discharged into the water during crop planting is the summation of the amount of the jth fertilizer multiplied by the phosphorus content of the jth fertilizer.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq12	$TP_{life} = Pop * K_5$	Total phosphorus content discharged into water during life is calculated by multiplying the permanent resident population in the basin with the emission factor of phosphorus during life per capita.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq13	$TP_{livestock} = \Sigma AQ_n * PC_n$ or $TP_{livestock} = AQ_{watershed} * K_4$	Total phosphorus content discharged into water during livestock and poultry breeding is the summation of the amount of nth category poultry or livestock multiplied by phosphorus content of the nth category poultry or livestock. It can be also be calculated by multiplying the amount of poultry or livestock at the watershed with phosphorus emission factor during livestock breeding.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq14	$TP_{farms} = TP_{crops} * W_{crops2} + TP_{livestock} * W_{livestock2} + TP_{life} * W_{life2}$	Total phosphorus content discharged into water from agricultural household agents can be calculated by multiplying the summation of different phosphorus content discharge with its respective phosphorus loss rates.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq15	$TP_{factories} = PC_w * X_e$	Total phosphorus content discharged into water from factory agents can be calculated by multiplying the phosphorus content in wastewater discharged by factories with waste water.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq16	$TP_{total} = TP_{farms} + TP_{factories}$	Total phosphorus discharged into water is the summation of the phosphorus discharged by agricultural household agents and factory agents.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)
Eq17	$PAF = \frac{\Sigma pj(RRj - 1)}{\Sigma pj(RRj - 1) + 1}$	The population attributable fraction depends on the risk associated with exposure at a level and the proportion of a population exposed at that level.	EQ2	Cui, F., Zhang, L., et al., 2016 (A249)
Eq18	$PAF = 1 - \pi(1 - PAFr)$	It is the burden attributable to a cluster of risk factors.	EQ2	Cui, F., Zhang, L., et al., 2016 (A249)
Eq19	$AB = PAF * B$	Burden of disease attributable to unsafe water sources is calculated by multiplying the population exposed to unsafe water with the disease burden of diarrhea.	EQ2	Cui, F., Zhang, L., et al., 2016 (A249)
Eq20	$EQ2 = \Sigma DALY = \Sigma Cdi * Dose$	DALY rate is calculated as the damage to life caused by the ith pollutant in a water source. Dose is the amount of pollutant in the water.	EQ2	Deng, C., Wang, H., et al., 2018 (A138)

Source of data will be identified when implementing the models in Phase 2 Simulation Tool

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Table 13. Definitions of variables and parameters and sources of data for environmental quality

Eq. No.	Acronym	Type	Definition	Unit	Sources of data*
Eq1	NC_j	Input parameter	Nitrogen content of jth fertilizer	%	-
Eq1, Eq11	F_j	Input variable	Amount of jth fertilizer	kg	-
Eq1, Eq4	TN_{crops}	Output variable	Total nitrogen discharged through crop planting	kg	Simulation Tool (Phase 2)
Eq2, Eq7, Eq13	AQ_n	Input variable	Amount of the nth category poultry or livestock	Number of cattle/ poultry	-
Eq2	NC_n	Input variable	Nitrogen excretion of the nth category of poultry or livestock	kg	-
Eq2, Eq7, Eq13	$AQ_{watershed}$	Input parameter	Amount of poultry or livestock at the watershed.	Number of cattle/ poultry	-
Eq2	K_2	Input parameter	Nitrogen emission factor during livestock breeding	kg/(capita * year)	-
Eq2, Eq4	$TN_{livestock}$	Output variable	Total nitrogen discharged through livestock and poultry breeding	kg	Simulation Tool (Phase 2)
Eq3	NC_p	Input variable	Nitrogen content of the protein	kg	-
Eq3, Eq8, Eq12	Pop	Input parameter	Permanent resident population in the basin	Number of people	-
Eq3	Protein	Input parameter	Annual protein consumption per capita	kg	-
Eq3	K_3	Input parameter	Non-consumed protein factor in wastewater	-	-
Eq3, Eq4	TN_{life}	Output variable	Total nitrogen discharged during life	kg	Simulation Tool (Phase 2)
Eq4	W_{crops1}	Input parameter	Nitrogen discharge rates during crop planting	Rate	-
Eq4	$W_{livestock1}$	Input parameter	Nitrogen discharge rates during livestock and poultry breeding	Rate	-
Eq4	W_{life1}	Input parameter	Nitrogen discharge rates during life	Rate	-
Eq4, Eq5	TN_{farms}	Output variable	Total Nitrogen Discharged by agricultural household agents	kg	Simulation Tool (Phase 2)
Eq5	NC_w	Input variable	Nitrogen content of wastewater discharged from factories	kg	-
Eq5, Eq9, Eq15	X_e	Input variable	Waste water	-	-
Eq5, Eq6	$TN_{factories}$	Output variable	Total Nitrogen Discharged by factory agents	kg	Simulation Tool (Phase 2)
Eq6	TN_{total}	Output variable	Total nitrogen content discharged in water	kg	Simulation Tool (Phase 2)
Eq7	$CODC_n$	Input variable	Content of COD in the nth category of poultry or livestock	kg	-
Eq7	K_6	Input parameter	Emission factor of COD during livestock breeding	kg/(capita * year)	-
Eq7, Eq10	$COD_{livestock}$	Output variable	Total COD discharged through livestock and poultry breeding	kg	Simulation Tool (Phase 2)
Eq8	K_7	Input parameter	Emission factor of COD during the life of each person	-	-
Eq8, Eq9	COD_{life}	Output variable	Total COD discharged during life	kg	Simulation Tool (Phase 2)
Eq9	$CODC_w$	Input parameter	Chemical Oxygen Demand from factories	mg/L	-
Eq9, Eq10	$COD_{factories}$	Output variable	Total COD discharged by factory agents	kg	Simulation Tool (Phase 2)
Eq10	$W_{livestock3}$	Input parameter	COD discharge rate during livestock and poultry breeding	Rate	-
Eq10	W_{life3}	Input parameter	COD discharge rate during life	Rate	-

Table 13. Definitions of variables and parameters and sources of data for environmental quality (continued)

Eq. No.	Acronym	Type	Definition	Unit	Sources of data*
Eq10	COD_{total}	Output variable	Total COD discharged into water	kg	Simulation Tool (Phase 2)
Eq11	PC_j	Input parameter	Phosphorus content of the jth fertilizer	%	-
Eq11, Eq14	TP_{crops}	Output variable	Total phosphorus content discharged during crop planting	kg	Simulation Tool (Phase 2)
Eq12	K_5	Input parameter	Emission factor of phosphorous during life per capita	-	-
Eq12, Eq14	TP_{life}	Output variable	Total phosphorus discharged during life	kg	Simulation Tool (Phase 2)
Eq13	K_4	Input parameter	Phosphorus emission factor during livestock breeding	kg/ (capita * year)	-
Eq13	PC_n	Input variable	Phosphorus content of the nth category of poultry or livestock	kg	-
Eq13, Eq14	$TP_{livestock}$	Output variable	Total phosphorus discharged through livestock and poultry breeding	kg	Simulation Tool (Phase 2)
Eq14	W_{crops2}	Input parameter	Phosphorus loss rates of crop planting	Rate	-
Eq14	$W_{livestock2}$	Input parameter	Phosphorus loss rates of livestock/poultry breeding	Rate	-
Eq14	W_{life2}	Input parameter	Phosphorus loss rates during life	Rate	-
Eq14, Eq16	TP_{farms}	Output variable	Total Phosphorus discharged by agricultural household agents	kg	Simulation Tool (Phase 2)
Eq15	PC_w	Input variable	Phosphorus content in wastewater discharged by factories	kg	-
Eq15, Eq16	$TP_{factories}$	Output variable	Total Phosphorus discharged by factory agents	kg	Simulation Tool (Phase 2)
Eq16	TP_{total}	Output variable	Total phosphorus content discharged into water	kg	Simulation Tool (Phase 2)
Eq17	RR	Input variable	Relative risk associated at the exposure level	dimensionless	WHO
Eq17	pj	Input variable	Proportion of population exposed at different risk levels	%	WHO
Eq18	Π	Input parameter	Number of risk factors	dimensionless	National data and WHO
Eq17, Eq18, Eq19	PAF	Output variable	Population attributable fraction	dimensionless	Calculated from other variables
Eq19	B	Input parameter	Total burden of disease	Years of life lost	WHO
Eq19	AB	Output variable	Burden of disease attributable to each risk factor	Years of life lost	WHO
Eq20	Cdi	Input variable	Damage to life caused by the ith pollutant	Years of life lost	National data
Eq20	Dose	Input variable	Amount of ith pollutant in the water	Concentration (g/L)	National data
Eq20	EQ2	Output variable	DALY rate due to unsafe water sources	DALY lost per 100 persons	Simulation Tool (Phase 2)

**Source of data will be identified when implementing the models in Phase 2 Simulation Tool*

3.2.2 GHG emissions reduction

Greenhouse gas emissions reduction refers to the reduction and removal of CO_2 and non-CO_2 emissions from the atmosphere in order to address climate change (IPCC, 2013; Symon, 2013). The details on the mathematical models and variables for the equations for GHG emissions system are provided in Table 14 and Table 15. The flow diagrams for the models are presented as interlinkages to other models, including Figure A2 for transport sector and Figure A7 for GHG emissions reduction in Appendix 3.

GE1: Ratio of CO_2 emissions to population, including AFOLU (Tons per capita)

The different dynamic systems for energy and material use are linked to this indicator, hence it does not have its own mathematical models. The interlinkages were implemented through the use of emission factors from the IPCC database. This is illustrated in the transport model for the case study in Hungary in Chapter 4.1. Energy and transport.

GE2: Ratio of non-CO_2 emissions to population, excluding AFOLU (CO_2eq tons per capita)

Similar to CO_2 emissions, this indicator does not have its own mathematical models because it is linked to the energy and material use systems, including those related to industry and waste sectors. Due to lack of online data to implement the mathematical models for industry and waste, there are no integration models available yet for this indicator. Thus, the interlinkages will also be implemented using the emission factors from the IPCC database.

GE3: Ratio of non-CO_2 emissions in agriculture to population (CO_2eq tons per capita)

The mathematical models for this indicator were from the food-demand computations included in the land use. The CH_4 emissions from enteric fermentation in ruminants, CH_4 and N_2O emissions from manure, and N_2O emissions from fertilizer use are among the most important factors that determine agricultural GHG emissions (Smith et al., 2014). The livestock emissions are based on two part: emissions from manure and enteric emissions. Using an emission factor database such as IPCC (2006), both CO_2 and non-CO_2 emissions can be calculated. The database from FAO (2020) already includes such emission factors for various animals and types of manure processing. The total animal population is a vector containing cattle, pigs, poultry, sheep, goats, and other animals. The total manure production per animal was calculated using the data on total manure production from FAOSTAT (FAO, 2020). Manure is assumed to be either applied to the soil, left on the pasture, or treated. For each type, an emission factor and weight conversion ratio were used to estimate the respective N_2O emissions. For treated manure, the total CH_4 emissions were also calculated. Likewise, emission factors are used to calculate the enteric emissions from ruminants.

The interlinkages of the land use systems to the GE3 indicator were implemented through the ratio of non-CO_2 emissions in agriculture to population, which is represented by the sum of the manure, enteric, and fertilizer emissions in carbon dioxide equivalent (CO_2eq). There are some other emissions added from burning, rice cultivation, or organic soils cultivation (FAO, 2020). The resulting total emissions were divided by the total population. The results of the mathematical models implementation for this indicator in the Simulation Tool are illustrated in Chapter 4.3. Land use in Hungary and Uganda.

Table 14. Equations used in the mathematical models for GHG emissions reduction

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq1	$EF_F = \frac{FE2017 * 1000}{FU2017 * WC_{N2O}}$	The emission factor for fertilizer application is calculated by dividing the total N_2O emissions from fertilizers by the fertilizer use in the baseline year, corrected for molecular weight.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq2	$F_{N2O} = \frac{IN_F * WC_{N2O} * EF_F}{1000}$	The N_2O emissions from fertilizer use are calculated by multiplying the fertilizer input with a molecular weight conversion and the emission factor for fertilizer application.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq3	$FE_{CO2eq} = F_{N2O} * GWP_{N2O}$	Emissions from fertilizer in CO_2 equivalents are the N_2O emissions multiplied with the global warming potential for N_2O.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq4	$MMAS_i = \frac{TM\_AS2017_i}{TMP2017_i}$	The fraction of manure applied to soils in the baseline year is calculated by taking the total manure applied to soils divided by the total manure production in the same year.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq5	$MAS_i = TM_i * MMAS_i$	The manure applied to soils is calculated by multiplying the total manure production with the fraction applied to soils in the baseline year.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq6	$EFAS_i = \frac{EAS2017_i * 1000000}{TM\_AS2017_i * WC_{N2O}}$	The emission factors N_2O applied to soils are calculated by taking the total emissions from manure applied to soils divided by the total manure production converted to the right molecular weight in the baseline year for each animal group i.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)

Table 14. Equations used in the mathematical models for GHG emissions reduction (continued)

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq7	$EAS_i = \frac{EFAS_i * MAS_i * WC_{N2O}}{1000000}$	The N_2O emissions from manure applied to soils are calculated by multiplying the emission factors with the total manure applied to soils and a molecular weight conversion.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq8	$TMA_{CO2eq} = \sum EAS_i * GWP_{N2O}$	Emissions from manure applied to soils in CO_2 equivalents are the N_2O emissions multiplied with the global warming potential for N_2O.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq9	$MMLP_i = \frac{TM\_LP2017_i}{TMP2017_i}$	The fraction of manure left on pasture in the baseline year is calculated by taking the total manure left on the pasture divided by the total manure production in the same year.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq10	$MLP_i = TM_i * MMLP_i$	The manure left on pasture is calculated by multiplying the total manure production with the fraction of manure left on the pasture in the baseline year.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq11	$EFL_i = \frac{EL2017_i * 1000000}{TM\_LP2017_i * WC_{N2O}}$	The emission factors N_2O left on pasture are calculated by taking the total emissions from manure left on pasture divided by the total manure production converted to the right molecular weight in the baseline year for each animal group i.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq12	$EL_i = \frac{EFL_i * MLP_i * WC_{N2O}}{1000000}$	The N_2O emissions from manure left on pasture are calculated by multiplying the emission factors with the total manure left on pasture and a molecular weight conversion.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq13	$TMP_{CO2eq} = \sum EL_i * GWP_{N2O}$	The emissions from manure left on pasture in CO_2 equivalents are the N_2O emissions multiplied with the global warming potential for N_2O.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq14	$EFCH4T_i = \frac{ECH4T2017_i * 1000000}{TAH2017_i}$	The CH_4 emission factors for manure management are calculated by dividing the dividing the total CH_4 emissions in the baseline year for each animal group i.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq15	$ETCH4_i = \frac{EFCH4T_i * TA_i}{1000000}$	CH_4 emissions from manure management are calculated by multiplying the respective emission factors with the total animal population for each animal group i.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq16	$EF\_EE_i = \frac{EECH4_i * 1000000}{TAH2017_i}$	The emission factors for enteric fermentation are calculated by dividing the total CH_4 emissions by the animal population in the baseline year for each animal group i.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq17	$EE_{CH4} = TA_i * EF\_EE_i$	The enteric CH_4 emissions from the animal population are the total animals multiplied by the enteric fermentation emission factor for each animal group i.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq18	$TEE_{CO2eq} = \frac{\sum EE_{CH4} * GWP_{CH4}}{WC_{CH_4}}$	The emissions from enteric fermentation in CO_2 equivalents are calculated by multiplying the total CH_4 emissions by the global warming potential and dividing it by a parameter to convert it to the right molecular weight.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq19	$MMT_i = \frac{TMT2017_i}{TMP2017i}$	This calculates the fraction of manure managed relative to total manure production using the baseline year.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq20	$MT_i = TM_i * MMT_i$	The total managed manure production is calculated by multiplying the fraction of manure managed in the baseline year and the manure production.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq21	$EFT_i = \frac{ET2017_i * 1000000}{TMT2017_i}$	This calculates the N_2O emission factors for manure management by dividing the total N_2O emissions by the total manure managed.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq22	$ET_i = \frac{EFT_i * MT_i * WC_{N2O}}{1000000}$	The N_2O emissions from manure management are calculated by multiplying an emission factor with the total manure managed and a molecular weight conversion.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq23	$TMT_{CO2eq} = \sum ET_i * GWP_{N2O} + \sum ETCH4_i * GWP_{CH4}$	This converts N_2O and CH_4 emissions from manure management to CO_2 equivalents by multiplying it with their respective global warming potential for N_2O.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)
Eq24	$GE3 = \left[\frac{\sum OE_i + TEE_{CO2eq} + TMT_{CO2eq} + TMP_{CO2eq} + TMA_{CO2eq} + FE_{CO2eq}}{P * 1000}\right]$	This sums up all the non-CO_2 emissions stemming from agriculture relative to the population. This includes emissions from manure, enteric processes, fertilizer application, and LUC.	GE3	Li, X., Wallerand, A., et al., 2019 (T130) and FAOSTAT, n.d.(b) (A230)

Details are on Appendix 1 and Appendix 2

Table 15. Definitions of variables and parameters and sources of data for GHG emissions reduction

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq1	$FE2017$	Input variable	Fertilizer N_2O emissions 2017	gg N_2O	FAOSTAT
Eq1	$FU2017$	Input variable	Total fertilizer use in 2017	t	FAOSTAT
Eq1, Eq2	EF_F	Output variable	Emission factor N_2O emissions from fertilizer	kg N_2O-N/kg N	Simulation Tool
Eq1, Eq2, Eq6, Eq7, Eq11, Eq12, Eq22	WC_{N2O}	Variable	Conversion factor N_2O-N to N_2O	-	IPCC
Eq2	IN_F	Output variable	Fertilizer input (see Table 9)	Kg N	Simulation Tool
Eq2, Eq3	F_{N2O}	Output variable	N_2O emissions from fertilizer use	gg N_2O	Simulation Tool
Eq3, Eq8, Eq13, Eq23	GWP_{N2O}	Variable	Global warming potential N_2O relative to CO_2	-	FAOSTAT
Eq3, Eq24	FE_{CO2eq}	Output variable	CO_2eq emissions from fertilizer	gg CO_2eq	Simulation Tool
Eq4, Eq6,	TM_AS2017_i	Input variable	Vector total manure applied to soils 2017	Kg N	FAOSTAT
Eq4, Eq19,	$TMP2017i$	Input variable	Vector total manure production in 2017	Kg N	FAOSTAT
Eq4, Eq5	$MMAS_i$	Output variable	Fraction manure applied to soils	%	Simulation Tool
Eq5, Eq10, Eq20	TM_i	Output variable	Vector total manure produced per animal group (see Table 9)	Kg N	FAOSTAT
Eq5, Eq7	MAS_i	Output variable	Vector manure applied to soils	Kg N	Simulation Tool
Eq6	$EAS2017_i$	Output variable	N_2O emissions from manure applied to soils in 2017	gg N_2O	Simulation Tool
Eq7	$EFAS_i$	Output variable	Vector Emission factors N_2O applied to soils	Kg N_2O-N/kg N	Simulation Tool
Eq7, Eq8	EAS_i	Output variable	N_2O emissions from manure applied to soils	gg N_2O	Simulation Tool
Eq8, Eq24	TMA_{CO2eq}	Output variable	CO_2eq emissions from manure applied to soils	gg CO_2eq	Simulation Tool
Eq9, Eq11	TM_LP2017_i	Input variable	Vector total manure left on pasture 2017	Kg N	FAOSTAT
Eq9, Eq10	$MMLP_i$	Output variable	Fraction manure left on pasture	%	Simulation Tool
Eq10, Eq12	MLP_i	Output variable	Vector manure left on pasture	Kg N	Simulation Tool
Eq11	$EL2017_i$	Output variable	N_2O emissions from manure left on pasture in 2017	gg N_2O	Simulation Tool
Eq11, Eq12	EFL_i	Output variable	Vector Emission factors N_2O left on pasture	Kg N_2O-N/kg N	Simulation Tool
Eq12, Eq13	EL_i	Output variable	N_2O emissions from manure left on pasture	gg N_2O	Simulation Tool
Eq13, Eq24	TMP_{CO2eq}	Output variable	CO_2eq emissions from manure left on pasture	gg CO_2eq	Simulation Tool
Eq14	$ECH4T2017_i$	Input variable	CH_4 emissions manure management 2017 (vector)	gg CH_4	FAOSTAT
Eq14, Eq16	$TAH2017_i$	Input variable	Vector total animals (2017)	Heads	FAOSTAT
Eq14	$EFCH4T_i$	Output variable	Vector Emission factors CH_4 from manure management	kg CH_4/head	Simulation Tool
Eq15, Eq17	TA_i	Output variable	Vector total animal population corrected (see Table 9)	Heads	Simulation Tool
Eq15, Eq23	$ETCH4_i$	Output variable	CH_4 emissions from manure management	gg CH_4	Simulation Tool
Eq16	$EECH4_i$	Input variable	Vector enteric CH_4 emissions 2017	gg CH_4	FAOSTAT
Eq16, Eq17	EF_EE_i	Output variable	Emission factor enteric CH_4 emissions	Kg CH4 / head	Simulation Tool
Eq17, Eq18	EE_{CH4}	Output variable	Vector enteric emissions CH_4	gg CH_4	Simulation Tool
Eq18	WC_{CH_4}	Variable	Conversion factor CH_4-C to CH_4	-	IPCC
Eq18, Eq23	GWP_{CH4}	Variable	Global warming potential CH_4 relative to CO_2	-	FAOSTAT

Table 15. Definitions of variables and parameters and sources of data for GHG emissions reduction (continued)

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq18, Eq24	TEE_{CO2eq}	Output variable	CO_2eq emissions from enteric fermentation	gg CO_2eq	Simulation Tool
Eq19, Eq21	$TMT2017_i$	Input variable	Total manure management 2017	Kg N	FAOSTAT
Eq19, Eq20	MMT_i	Output variable	Fraction of manure managed relative to total manure production	%	Simulation Tool
Eq20, Eq22	MT_i	Output variable	Total manure managed	Kg N	Simulation Tool
Eq21	$ET2017_i$	Input variable	N_2O emissions manure management 2017 (vector)	gg N_2O	FAOSTAT
Eq21, Eq22	EFT_i	Output variable	Vector Emission factors N_2O from manure management	-	Simulation Tool
Eq22, Eq23	ET_i	Output variable	N_2O emissions from manure management	gg N_2O	Simulation Tool
Eq23, Eq24	TMT_{CO2eq}	Output variable	CO_2eq emissions from manure management	gg CO_2eq	Simulation Tool
Eq24	OE_i	Input variable	The sum of other emissions not included (i.e., biomass burning, crop residues, rice cultivation and cultivation organic soils)	gg CO_2eq	FAOSTAT
Eq24	P	Input variable	Population	Heads	FAOSTAT

3.2.3 Biodiversity and ecosystem protection

Biodiversity and ecosystem protection refers to the protection of species, habitats, and ecosystems as well as the services they provide, with protected areas as an important measure to achieve biodiversity conservation (IPBES, 2018; UNEP-WCMC & IUCN, 2016). The details on the mathematical models and variables for the equations for biodiversity and ecosystem are provided in Table 16 and Table 17. The flow diagrams for the models are presented as interlinkages to other models, particularly in Figure A4 for land use in Appendix 3.

BE1: Average proportion of key biodiversity areas (KBA) covered by protected areas (Percent)

This indicator is an average of key biodiversity in four areas – terrestrial, freshwater, marine, and mountain. Based on the UNSTATS metadata (2020a, 2020b), each indicator in these areas was calculated using an overlay analysis of different spatial maps on protected areas, which were collected from World Database on Protected Areas (UNSTATS, 2020a), and key biodiversity protected areas (KBAs), which were collected from World Database of KBAs. Moreover, the database of Global Administrative Areas was used as basis for classifying terrestrial KBAs (UNSTATS, 2020b). Due to unavailability of spatial maps for the drivers of change for this indicator, no mathematical models are available in the Phase 1 application of the Simulation Tool. The spatial dynamics will be included in the Phase 2 application.

BE2: Share of forest area to total land area (Percent)

This indicator is linked with the land use system and does not have its own mathematical models. In the land use model, the change in forest area was computed based on the changes in cropland and reforestation policy. The share of forest area to total land area (BE2) was computed from the changes in cropland and by setting a reforestation rate. By changing certain variables such as population, food losses, or food composition, it will be possible to construct several scenarios and simulate land use changes. The use of the Simulation Tool to measure the impacts of reforestation on non-CO_2 emissions is illustrated in Chapter 4.3. Land use in Hungary and Uganda.

BE3: Above-ground biomass stock in forest (Tons per hectare)

Like indicator BE2, the above ground (forest) biomass (BE3) does not have its own mathematical models. It is also linked to the land use system and calculated using the data on the natural increment rate of forest growth. The user can set a harvest rate and climate smart forestry policies, which affect the change in the forest growing stock per m³. With a conversion parameter, the change in above-ground biomass in forests was computed.

Table 16. Equations used in the mathematical models for biodiversity and ecosystem protection

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq35	$BE2 = 100 * \frac{FLstock_{t+1}}{TLA}$	This computes the share of forest area to total land area, using the new forest land area computed in the sustainable land use module (Table 9).	BE2	Price, J. & Forstenhaeusler, N., 2019 (T131) and FAOSTAT, n.d.(c) (A231)
Eq36	$FBI = CSF + NFI$	Forest biomass increment is the sum of natural forest increments and climate smart forestry policies.	BE3	Price, J. & Forstenhaeusler, N., 2019 (T131)
Eq37	$TF = FBI * \frac{HR}{100}$	The total forest felling is calculated as a fraction of the natural increment set by the user.	BE3	Price, J. & Forstenhaeusler, N., 2019 (T131)
Eq38	$NCFB = FBI - TF$	This computes the net change forest biomass.	BE3	Price, J. & Forstenhaeusler, N., 2019 (T131)
Eq39	$BE3 = NCFB * FB\_conv$	This computes the net change in forest biomass in tons per hectare.	BE3	Marklund, L. & Schoene, D., 2006 (A232)

Note: Equation numbers started at 35 since the biodiversity and ecosystem protection is linked with the sustainable land use model (Table 8)
**Details are in Appendix 1 and Appendix 2*

Table 17. Definitions of variables and parameters and sources of data for biodiversity and ecosystem protection

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq35	$FLstock_{t+1}$	Output variable	New forest stock (see Table 9)	1000 ha	Simulation Tool
Eq35	TLA	Input variable	Total land area	1000 ha	FAOSTAT
Eq35	$BE2$	Output variable	Share of forest area to total land area	%	Simulation Tool
Eq36	NFI	Input variable	Net natural forest increment rate	m³/ha	FAO, 2020 and ForestEurope
Eq36	CSF	Input scenario	Climate smart forestry practices	m³/ha	Assumption
Eq36, Eq37, Eq38	FBI	Output variable	Forest biomass increment	m³/ha	Simulation Tool
Eq37	HR	Input scenario	Harvest rate	%	FAO, 2020 and ForestEurope
Eq37, Eq38	TF	Output variable	Total fellings	m³/ha	FAO, 2020 and ForestEurope
Eq38, Eq39	$NCFB$	Output variable	net change forest biomass	m³/ha	Simulation Tool
Eq39	FB_conv	Input variable	Conversion factor m³ to t/ha		Marklund & Schoene, 2006
Eq39	$BE3$	Output variable	Net change forest biomass	t/ha	Simulation Tool

3.2.4 Cultural and social value

Cultural and social value refers to the societal value given to natural capital due to its importance to communities and their local culture which encourages sustainable use and protection of natural resources (da Rocha et al., 2017; Small et al., 2017) The details on the mathematical models and variables for the equations for cultural and social value system are provided in Table 18 and Table 19. The flow diagram for the models is presented in Figure A8 in Appendix 3.

CV1: Red list index (Index)

The mathematical models for this indicator are based on a regression analysis. But due to lack of available online data, the regression analysis cannot be implemented in the Phase 1 application of the Simulation Tool. These models will be interlinked with the indicators on KBAs (BE1) and share of terrestrial and marine protected areas (CV3), which are not yet implemented in the Phase 1 Simulation Tool due to lack of spatial data.

CV2: Tourism and recreation in coastal and marine areas (Score)

This indicator, which was developed as part of the Ocean Health Index (OHI), measures the overall country scores for coastal and marine areas. The mathematical models were adopted from the equation of the OHI documentation (OHI, 2013). The equations primarily used employment data, which are currently not available online. The mathematical models for this indicator will thus be implemented in the Phase 2 of the Simulation Tool. Possible scenarios for this indicator could be based on the sustainability factor of countries, which is based on the sustainability in the fisheries sector.

CV3: Share of terrestrial and marine protected areas to total territorial areas (Percent)

The mathematical models for this indicator are linked to the biodiversity system, which is not implemented in the Phase 1 Simulation Tool due to lack of spatial data. This indicator will thus be part of the Phase 2 application of the Simulation Tool.

Table 18. Equations used in the mathematical models for cultural and social value

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq1	$W_{c(t,s)} = f(\Delta h_s, PA_s, P_s)$	Weights given to threatened species for time (t) and species (s) is a function of habitat change, protected area, and policy scenario for the protected area where species (s) resides.	CV1	Costelloe, B., Collen, B., et al., 2016 (A233)
Eq2	$CV1 = RLI_t = 1 - \left(\frac{\sum_s W_{c(t,s)}}{W_{EX} N}\right)$	Red list index is the difference between 1 and the sum of weights given to threatened species for time (t) and species (s) divided by the product of the number of species and weights assigned to extinct species.	CV1	Costelloe, B., Collen, B., et al., 2016 (A233)
Eq3	$E_t = \frac{E_{WTTC}}{L_t - (L_t * U_t)}$	Tourism and employment proportion is calculated by dividing the number of employment in sectors directly relevant to travel and tourism with the difference between the total labor force and unemployed labor force.	CV2	OHI, 2013 (A234)
Eq4	$CV2 = X_{TR} = E_t * S_t$	Tourism and recreation in coastal and marine areas are calculated by multiplying sustainability measure with tourism and employment proportion.	CV2	OHI, 2013 (A234)

Details are on Appendix 1 and Appendix 2

Table 19. Definitions of variables and parameters and sources of data for cultural and social value

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq1	Δh_s	Input variable	Habitat change for species (s)	ha	Possingham et al. 2000
Eq1	PA_s	Input variable	Protected area for species (s)	ha	IUCN database
Eq1	P_s	Input scenario	Protected area where species (s) resides	Δ%	Costelloe et al. 2016 (A233)
Eq1	$W_{c(t,s)}$	Output variable	Weights given to threatened species for time (t) and species (s)	-	Simulation Tool (Phase 2)
Eq2	W_{EX}	Input variable	Weight assigned to extinct species (=5)	-	Costelloe et al. 2016 (A233)
Eq2	N	Input variable	Number of species	-	Costelloe et al. 2016 (A233)
Eq2	$RLI_t/CV1$	Output variable	Red list index for year t	Index	Simulation Tool (Phase 2)
Eq3	E_{WTTC}	Input variable	Employees in sectors directly relevant to travel and tourism	Number of employees ('000)	UNWTO
Eq3	L_t	Input variable	Total labor force	Number of employees	World Bank
Eq3	U_t	Input variable	Unemployment	%	World Bank
Eq3	E_t	Output variable	Tourism and employment proportion	%	Simulation Tool (Phase 2)
Eq4	S_t	Input scenario	Sustainability measure		tourism competitiveness index (TTCI), World Economic Forum
Eq4	$CV2/X_{TR}$	Output variable	Tourism and recreation in coastal and marine areas	Score	Simulation Tool (Phase 2)

3.3 Green economic opportunities

3.3.1 Green investment

Green investment refers to public and private investment that promotes, in a direct or indirect manner, sustainable resource use, including material, water, energy, and land, and natural capital protection such as environmental protection and climate action, advancing sustainable development and green growth (Eyraud et al., 2011; Obradović, 2019).

GV1: Adjusted net savings, including particulate emission damage (Percent GNI)

No appropriate mathematical model was identified for green investment. However, a monetary value for total green investment was considered within the model for green employment (see Chapter 3.3.3 Green employment), although this is not linked to the metric of adjusted net savings, which is currently used as the primary measurement within the Green Growth Index. This indicator is only a proxy variable in the Index, so this was not linked to the other mathematical models for the targets systems in green economic opportunities. Further developments for Phase 2 will include the incorporation of another investment indicator in the mathematical models for green economic opportunities, including trade, employment, and innovation (Figure A9 in Appendix 3)

3.3.2 Green trade

Green trade refers to the competitiveness of a country to produce and export environmental goods that can contribute to environmental protection, climate action, green growth, and sustainable development (European Parliament, 2019; PAGE, 2017). The details on the mathematical models and variables for the equations for green trade system are provided in Table 20 and Table 21. The flow diagram for the models, which are interlinked to other models for green economic opportunities, is presented in Figure A8 in Appendix 3.

GN1: Share of export of environmental goods (OECD and APEC class.) to total export (Percent)

The green trade framework was adapted from the United Nations Industrial Development Organization's (UNIDO) Green Industrial Performance (GIP) Index methodology (de Alba & Todorov, 2018). This method utilizes the mapping of a green product list to databases such as UN COMTRADE and industrial statistics database (INDSTAT) to determine the share of green exports in manufacturing as well as other indicators such as green employment and green manufacture value added. Therefore, a major foundation of this framework is the identification of green products. De Alba and Todorov (2018) identified sources such as the World Bank (WB), OECD, Asia-Pacific Economic Cooperation (APEC), and US Department of Commerce which have various classifications of environmental goods. The GIP has a final list categorized into five categories of green products and services, namely, resource conservation, environmental assessment, energy conservation, renewable energy, and pollution control. Once a green product list has been determined, the product codes were converted to a harmonized system used in the UN COMTRADE database. By mapping COMTRADE with the green product list, the share of green exports in total manufacturing exports, corresponding to the GT1: green trade, was calculated. Additionally, a similar workflow was used to identify the share of green employment, however, the INDSTAT database was instead used to map green products. To allow various simulations and linkages to other green growth indicators, one possibility is to adjust the number of goods in each green product list category. This strategy is being considered through consultation with UNIDO to further identify the challenges and applicability of the Simulation Tool. The complexity of this framework is in the data collection, mapping, and green product categorization and not in terms of model equations. Thus, only the calculation of the green trade indicator is in the tables below.

Table 20. Equations used in the mathematical models for green trade

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source
Eq 18	$GE = GP * Exports$	Green manufactured exports are calculated by mapping the green product list with COMTRADE export data.	GT1	de Alba, J. & Todorov, V., 2018 (A235)
Eq19	$GT1 = \frac{GE}{Exports}$	This computes the share of green exports to total exports in manufacturing.	GT1 and GJ1	de Alba, J. & Todorov, V., 2018 (A235)

Table 21. Definitions of variables and parameters and sources of data for green trade

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq 18	GP	Input variable	Green Product List		World Bank, OECD, APEC
Eq18, Eq 19	$Exports$	Input variable	Total exports in total manufacturing	US$	UNCOMTRADE
Eq18, Eq 19	GE	Output variable	Green manufactured exports	US$	Simulation Tool (Phase 2)
Eq19	$GT1$	Output variable	Share of green exports in total manufacturing exports.	%	Simulation Tool (Phase 2)

3.3.3 Green employment

Green employment refers to employment created and sustained by economic activities that are more environmentally sustainable; contribute to protecting the environment and reduce people's environmental footprint; and offer decent working conditions (ILO, 2015; UNEP et al., 2008). The details on the mathematical models and variables for the equations for green employment system are provided in Table 22 and Table 23. The flow diagram for the models, which are interlinked to other models for green economic opportunities, is presented in Figure A9 in Appendix 3.

GJ1: Share of green employment in total manufacturing employment (Percent)

The framework for the mathematical models for the green employment was adapted from two different methodologies: a stock-flow-fund model from Dafermos et al. (2017, 2018) and the GIP Index (de Alba & Todorov, 2018).

The structure of the model is dynamic, involving many flows and feedbacks that allow the stock components of the model to adjust over a simulated time horizon. The model of the financial system of Dafermos et al. (2017) was specifically adapted to incorporate the impact of green investment on contributing towards the transition to a low-carbon economy. This will allow the linkage of other Green Growth Index categories such as the material use efficiency, efficient and sustainable energy, and GHG emissions to be integrated together and provide greater insight to users on how various policy scenarios have compounding effects to other indicators. The equations of the model are not complex, representing only simple algebraic expressions for changes in the stock variables over time or the use of proportions/percentages to express the share of different variables. This version of the model does not include a government body or central bank, thereby not considering the influence of green bonds as another important financial mechanism. An additional article was released by Dafermos et al. (2018) which already includes government bonds. For simplicity, the GGPM team decided to first exclude this new iteration and additional components of this model, however, will aim to further adapt and integrate more financial mechanisms in Phase 2 A short description of the green employment framework is provided below, it should be noted that the equations may change subject to model validation and data availability.

Starting with economic output, this stock is dependent on total investment and household consumption. The amount of economic output was a main variable in determining the amount of total firm profits, along with employment (wage rate and number of employees) and the impact of interest rates and loans. A portion of the firm's profits (i.e., retained profits) was then used for investment into conventional and green capital. In this model, green capital results in increased recycling rates, improved ecological efficiency, and increased share of renewables. The amount of green investment provided by firms is first dependent on the total desired amount of investment (including conventional investment), which was affected by the proportion of climate damages (with 0 representing no climate damages and 1 representing full damages). The desired amount of investment influenced the amount of new loans, thereby changing the green loans and green investment stock. Additionally, the share of desired green investment was estimated using coefficients representing the divergence between conventional and green interest rates, costs associated with each type of capital as well as consideration into climate damages. This determines the green proportion of retained profits which also influences the green investment stock.

The amount of green investment changes the green capital stock, which is also dependent on the rate of capital depreciation and previous green capital stock levels. The ratio of green capital to total capital calculates the share of green capital. As the share of green capital increases, both energy and material efficiency (at diminishing rates) also increase. In terms of energy efficiency, one positive effect would be the increase in the share of renewable energy to total energy, therefore, creating demand of renewable jobs. An estimation of renewable jobs was calculated using employment multipliers from Garrett-Peltier (2017), providing a link to indicator of green employment. However, as this only considers renewables, the GGPM team will still explore the possibility to integrate the estimation of renewable jobs with the output from GIP, through changing the green product list categories (see Chapter 3.3.2 Green Trade for further explanation).

Table 22. Equations used in the mathematical models for green employment

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq1	$I^D = [(\alpha_0 + \alpha_1 r_{-1} + \alpha_2 u_{-1} - \alpha_3 g_{\varepsilon-1}) K_{-1} + \delta K_{-1}](1 - D_{T-1})$	Desired total investment is adjusted for the damage effect of climate change and equals to net investment plus the depreciated capital. Net investment is a positive function of the rate of retained profits (r), the rate of capacity utilization (u), and the growth rate of energy intensity (g).	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq2	$I_G^D = \beta I^D$	Desired green investment is calculated by the share of green investment in total investment multiplied by the total desired investment.	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq3	$NL_G^D = I_G^D - \beta RP + rep L_{G-1} - \delta K_{G-1}$	Desired new green loans is a function of desired green investment, the share of green retained profits, the repayment of green loans. and depreciated green capital	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq4	$L_G = L_{G-1} + (1 - CR_G) NL_G^D - rep L_{G-1}$	Green loans are estimated from the amount of existing green loans plus the credit rationing of new desired green loans minus the repayment of green loans.	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)

Table 22. Equations used in the mathematical models for green employment (continued)

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq5	$I_G = \beta RP + (L_G - L_{G-1}) + \delta K_{G-1}$	Total green investment is equal to the share of green retained profits plus total green loans and the depreciated green capital.	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq6	$I = I_G + I_C$	Total investment is the sum of total green investment and total conventional investment	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq7	$Y = C + I$	Economic output is the sum of household consumption and total investment.	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq8	$TP = Y - wN - int_c L_{c-1} - int_G L_{G-1} - \delta K_{-1}$	Total firm profit is computed from variables of economic output, labour, loans, interest rates, and capital.	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq9	$RP = S_f TP_{-1}$	Firm's retained profits is calculated by multiplying total firm profit by the firm's retention rate.	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq10	$K_G = K_{G-1} + I_G - \delta K_{G-1}$	Total green capital is equal to the green capital of the previous year plus current green investment and minus the depreciation of green capital.	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq11	$K = K_C + K_G$	Total capital is the sum of total conventional and total green capital.	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq12	$\kappa = \frac{K_G}{K}$	This computes the share of green capital to total capital.	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq13	$\theta = (1 + \frac{1}{\pi\left(\frac{K_{G-1}}{K_{C-1}}\right)})^{-1}$	Share of renewable energy in total energy is dependent on the amount of green capital to conventional capital.	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219)
Eq14	$REjobs = \theta * \varphi$	Renewable energy jobs is calculated by the share of renewable energy multiplied by a renewable employment multiplier.	GJ1	Dafermos, Y., Nikolaidi, M., et al., 2017 (A219) and Garrett-Peltier, H. 2017 (A221)
Eq15	$GEM = GT\,1 * Employment$	Green employment in manufacturing is calculated by mapping the share of green exports to the number of employees in INDSTAT.	GJ1 and GT1	de Alba, J. & Todorov, V., 2018 (A235)
Eq16	$GJ\,1 = \frac{GEM}{Employment}$	Share of green employment in manufacturing is calculated by the green employment divided by total employment in manufacturing.	GJ1	de Alba, J. & Todorov, V., 2018 (A235)

**Details are on Appendix 1 and Appendix 2*

Table 23. Definitions of variables and parameters and sources of data for green employment

Eq. No.	Acronym	Type	Definition	Unit	Sources of data*
Eq1	α_0	Input parameter	Sensitivity of desired investment rate to the rate of retained profits	dimensionless	-
Eq1	α_1	Input parameter	Sensitivity of desired investment rate to the rate of capacity utilization	dimensionless	-
Eq1	α_2	Input parameter	Sensitivity of desired investment rate to the growth rate of energy intensity	dimensionless	-
Eq1	r	Input variable	Rate of retained profits	dimensionless	-
Eq1	u	Input variable	Rate of capacity utilization	dimensionless	-
Eq1	g_ε	Input parameter	Growth rate of energy intensity	dimensionless	-
Eq1	D_T	Input parameter	Total proportional damage caused by global warming	dimensionless	-
Eq1, Eq3, Eq5, Eq10	δ	Input parameter	Depreciation rate of green capital	dimensionless	-
Eq1, Eq2	I^D	Output variable	Desired total investment	US $	Simulation Tool (Phase 2)
Eq2, Eq3, Eq5	β	Input parameter	Share of desired green investment in total investment	dimensionless	-
Eq2, Eq3	I_G^D	Output variable	Desired green investment	US $	Simulation Tool (Phase 2)
Eq3, Eq4	NL_G^D	Output variable	Desired new amount of green loans	US $	Simulation Tool (Phase 2)
Eq3, Eq4	rep	Input parameter	Loan repayment ratio	dimensionless	-
Eq3, Eq5, Eq10, Eq11, Eq12, Eq13	K_G	Output variable	Green capital	US $	Simulation Tool (Phase 2)
Eq4	CR_G	Input variable	Degree of credit rationing for green loans	dimensionless	-
Eq4, Eq5, Eq8	L_G	Output variable	Green loans	US $	Simulation Tool (Phase 2)
Eq5, Eq6, Eq10	I_G	Output variable	Green investment	US $	Simulation Tool (Phase 2)
Eq6	I_C	Input variable	Conventional investment	US $	-
Eq7	C	Input variable	Household consumption	US $	-
Eq7	I	Input variable	Total investment	US $	-
Eq7	Y	Output variable	Economic output	US $	Simulation Tool (Phase 2)
Eq8	TP	Output variable	Total firm profit	US $	Simulation Tool (Phase 2)
Eq8	W	Input variable	Wage rate	US $/persons	-
Eq8	N	Input variable	Number of employees	persons	-
Eq8	int_c	Input variable	Interest rate on conventional loans	dimensionless	-
Eq8	int_G	Input variable	Interest rate on green loans	dimensionless	-
Eq8	L_c	Input variable	Conventional loans	US $	-
Eq3, Eq5, Eq9	RP	Output variable	Retained profits	US $	Simulation Tool (Phase 2)
Eq9	S_f	Input parameter	Firm's retention rate	dimensionless	-
Eq11, Eq13	K_C	Output variable	Conventional capital	US $	Simulation Tool (Phase 2)
Eq1, Eq8, Eq11, Eq12	K	Output variable	Total capital	US $	Simulation Tool (Phase 2)

Table 23. Definitions of variables and parameters and sources of data for green employment (continued)

Eq. No.	Acronym	Type	Definition	Unit	Sources of data*
Eq12	κ	Output variable	Ratio of green capital to total capital	dimensionless	Simulation Tool (Phase 2)
Eq13, Eq14	θ	Output variable	Share of renewable energy in total energy	dimensionless	Simulation Tool (Phase 2)
Eq13	π	Input parameter	Parameter to link the green capital-conventional capital ratio with the share of renewable energy	dimensionless	-
Eq14	φ	Input variable	Renewable employment multiplier	Total full time employee jobs per $1 million	Garrett-Peltier, H. 2017 (A221)
Eq14	REjobs	Output variable	Amount of renewable energy jobs	persons	Simulation Tool (Phase 2)
Eq15	GT 1	Input variable	Share of green exports in total manufacturing exports	%	de Alba, J. & Todorov, V., 2018 (A235)
Eq15, Eq16	Employment	Input variable	Total employment in manufacturing	Number of employees	INDSTAT
Eq15, Eq16	GEM	Output variable	Green employment in Manufacturing	Number of employees	Simulation Tool (Phase 2)
Eq16	GJ 1	Output variable	Share of green employment in total manufacturing employment	%	Simulation Tool (Phase 2)

**Source of data will be identified when implementing the models in Phase 2 Simulation Tool*

3.3.4 Green innovation

Green innovation refers to product, process, and service innovations such as energy-saving, pollution-prevention, waste recycling, green product designs, or corporate environmental management that yields environmental benefits (Gao et al., 2018; Schiederig et al., 2011). The details on the mathematical models and variables for the equations for green innovation system are provided in Table 24 and Table 25. The flow diagram for the models, which are interlinked to other models for green economic opportunities, is presented in Figure A9 in Appendix 3.

The conceptual framework for green innovation used a regression equation from the variables identified in the journal article of Guo et al. (2018). The article assessed various drivers including environmental policies and research and development funding to influence the number of green patents, which is used as a proxy for green innovation. The validation of regression equations and data availability is required prior to further integrating these equations into the green economic opportunities model framework. It was intended to link a proportion of the amount of green investment calculated within the green employment (GJ1) model (see Chapter 3.3.3 Green employment) to research and development (R&D). As this R&D variable was included in the regression equation for green innovation, this allowed scenario linkages from the GJ1 model to impact the output of GN1.

Table 24. Equations used in the mathematical models for green innovation

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq17	$\ln(\text{product}_{it}) = \alpha + \beta_1 \text{enr}_{it} + \beta_2 \ln(\text{gov1}_{it}) + \beta_3 \ln(\text{gov2}_{it}) + \text{control}_{it} + \varepsilon_{it}$	It is the regression model for environmental regulation and government R&D funding on green product innovation.	GN1	Guo, L., Qu, Y., et al., 2018 (A218)

**Details are on Appendix 1 and Appendix 2*

Table 25. Definitions of variables and parameters and sources of data for green innovation

Eq. No.	Acronym	Type	Definition	Unit	Sources of data*
Eq17	product	Output variable	Green Product Innovation		Simulation Tool (Phase 2)
Eq17	enr	Input variable	Environmental Regulation Intensity		-
Eq17	gov1	Input variable	Government Direct Subsidy Intensity		-
Eq 17	gov2	Input variable	Tax preference intensity		-
Eq17	control	Input variable	Control Variables		-
Eq17	ε_{it}	Input variable	Residual term		Regression Analysis (Phase 2)

**Source of data will be identified when implementing the models in Phase 2 Simulation Tool*

3.4 Social inclusion

3.4.1 Access to basic services and resources

Access to basic services refers to the general availability of services such as telecommunications, financial, water and sanitation, and energy services, to people regardless of income and location, and which requires an effective governance at multiple scales due to the local nature of these services (OECD & WB, 2006; UCLG, 2014). The details on the mathematical models and variables for the equations for basic services and resources are provided in Table 26 and Table 27. The flow diagrams for the models are presented in Figure A10 in Appendix 3. Interlinkages between these models will be built in Phase 2 application of the Simulation Tool.

AB1: Population with access to safely managed water and sanitation (Percent)

The Joint Monitoring Programme (UNICEF & WHO, 2019) provides a detailed description of the methodology used to determine access to water and sanitation. The population with access to improved water and sanitation was calculated in a three-step process. The population with access to improved water is a sum of the population with piped water and unpiped water. Similarly, improved sanitation can be in the form of sewage connections, septic tanks or latrines. Finally, the indicator percentage of population with access to improved water and sanitation (AB1) was calculated as the mean of the population with access to improved water and those with access to improved sanitation. Additionally, the rate of open defecation was predicted using a linear regression model that indicates the rate of change in open defecation when access to any of the other means of sanitation (sewage connections, septic tanks, or latrines) increases. The percentage of the population with unimproved water was similarly predicted via a linear regression model that predicts change based on the increase in access to piped and non-piped water.

AB2: Population with access to electricity and clean fuels/technology (Percent)

The indicator AB2 was modelled based on the WB framework for energy access (Bhatia & Angelou, 2015). Energy access is based on five tiers through which residential demand can be determined. The total residential demand was calculated by multiplying the proportion of households at each tier with the electricity consumption at each tier. The total electricity consumed is the sum of electricity consumed at each tier. Household electricity consumption is a simple average of electricity consumed in three key areas: cooking, heating, and electricity for lighting. The five tiers of electricity consumption are based on types of appliances and the electricity consumed by each appliance within the tier, with tier 5 indicating maximum access and tier 0 indicating no access to electricity. A similar framework exists for tiers of energy consumption.

AB3: Fixed Internet broadband and mobile cellular subscriptions (Number per 100 people)

For this indicator, a regression analysis was done to find variables for a more comprehensive model for the Phase 2 of the Simulation Tool. Lin and Wu (2013) and Gulati and Yates (2012) factors that affect fixed internet broadband subscriptions. The data were obtained from the databases of WB, International Telecommunication Union (ITU), and United Nations Development Programme (UNDP). Following their approach, the use of panel regression showed that the independent variables such as GDP per capita, mean years of schooling, lagged fixed broadband subscriptions, and an income-level dummy variable were statistically significant. In other words, these are the factors that might have an effect on fixed internet broadband subscriptions. However, some data for the variables used in the regression equation deviated from the variables in the journal articles due to poor data quality (low country/year coverage, missing data, inaccessible data). For the mobile cellular subscriptions, the variables that were statistically significant include the fixed internet broadband subscriptions, network coverage, expected years of schooling, and e-participation index. On the other hand, the independent variables omitted due to statistical insignificance for both the regression analyses include government effectiveness, regulatory quality, urbanization, level of literacy, and percentage of the population using the internet. Possible scenarios regarding the impacts of e-participation can be explored in the future.

Table 26. Equations used in the mathematical models for access to basic services and resources

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq1	$OD = \alpha + \beta1 * L + \beta2 * ST + \beta3 * SC$	It is the linear regression model to predict the rate of open defecation.	AB1	Regression Analysis
Eq2	$U = \alpha + \beta1 * NP + \beta2 * P$	It is the linear regression model to predict the percentage of population with unimproved water.	AB1	Regression Analysis
Eq3	$IS = L + SC + ST$	Population with access to improved sanitation is the summation of population with access to septic tanks, latrines, and sewer connections.	AB1	UNICEF & WHO, 2019 (A236)
Eq4	$IW = P + NP$	Population with access to improved water is a summation of piped and non-piped water sources.	AB1	UNICEF & WHO, 2019 (A236)
Eq5	$AB1 = \frac{(IW + IS)}{2}$	Population with access to improved water and sanitation is the average between population with access to improved water and sanitation.	AB1	UNSTATS, 2017 (A237)
Eq6	$RED = Pk * ki$	Residential electricity demand for a tier is calculated by multiplying the proportion of households at each tier with the amount of electricity consumed at each tier.	AB2	Bhatia, M. & Angelou, N., 2015 (A238)
Eq7	$REC = \Sigma(20 * Pk * k)$	Total residential electricity consumed is the summation of proportion of households multiplied with 20 and with tiers of electricity consumption.	AB2	Bhatia, M. & Angelou, N., 2015 (A238)
Eq8	$I_{household} = Avg(I_{Electricity} + I_{cooking})$	Household energy consumption is the average of the energy consumed from electricity use and cooking fuels.	AB2	Bhatia, M. & Angelou, N., 2015 (A238)
Eq9	$FXB = \alpha + \beta1 * INC + \beta2 * GDPC + \beta3 * FXBt - 1 + \beta4 * MYS$	It is the linear regression model to predict Fixed Internet broadband.	AB3	Lin, M. and Wu, F., 2013 (A239) and Gulati, J. and Yates, D., 2012 (A240)
Eq10	$MBS = \alpha + \beta1 * FXB + \beta2 * NC + \beta3 * EYS + \beta4 * EP$	It is the linear regression model to predict mobile cellular subscriptions.	AB3	Regression Analysis

**Details are on Appendix 1 and Appendix 2*

Table 27. Definitions of variables and parameters and sources of data for access to basic services and resources

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq1, Eq3	L	Input Variable	Population with access to Latrines	%	JMP
Eq1, Eq3	SC	Input Variable	Population with access to sewage connections	%	JMP
Eq1, Eq3	ST	Input Variable	Population with access to septic tanks	%	JMP
Eq1	OD	Output Variable	Population practicing open defecation	%	JMP
Eq2, Eq4	P	Input Variable	Population with access to piped water	%	JMP
Eq2, Eq4	NP	Input Variable	Population with access to non-piped water	%	JMP
Eq2	U	Output Variable	Population with unimproved water connections	%	JMP
Eq3	IS	Output Variable	Population with access to improved sanitation	%	JMP
Eq4	IW	Output Variable	Population with access to improved water sources	%	JMP
Eq5	$AB1$	Output Variable	Population with access to safely managed water and sanitation	%	Simulation Tool (Phase 2)
Eq6, Eq7	Pk	Input variable	Proportion of population at each tier	Ratio	World Bank
Eq6	ki	Input variable	Desired tier of access	kilowatt	World Bank
Eq6,	RED	Output Variable	Residential electricity demand	kilowatt	World Bank and IEA
Eq7	k	Input variable	Tiers of electric consumption	kilowatt	World Bank and IEA
Eq7	REC	Output Variable	Residential electricity consumed	kilowatt	World Bank and IEA
Eq8	$I_{electricity}$	Input variable	Energy consumed from electricity use	kilowatt	World Bank and IEA
Eq8	$I_{cooking}$	Input variable	Energy consumed from cooking fuels	kilowatt	World Bank and IEA
Eq8	$I_{household}$	Output Variable	Energy consumed by a household	kilowatt	World Bank and IEA
Eq9	INC	Input parameter	Income level (dummy)	-	UNSTATS
Eq9	$GDPC$	Input parameter	Gross Domestic Product per Capita	USD per capita (2017 constant)	World Bank
Eq9	FXB_{t-1}	Input parameter	(Lagged) Fixed broadband subscriptions per 100 inhabitants	Subscriptions per 100 inhabitants	ITU
Eq9	MYS	Input parameter	Mean years of schooling	Years	UNDP
Eq9, Eq10	FXB	Output variable and Input parameter	Fixed broadband subscriptions per 100 inhabitants	Subscriptions per 100 inhabitants	ITU
Eq10	NC	Input parameter	Percentage of the population covered by a mobile cellular network	%	ITU
Eq10	EYS	Input parameter	Expected years of schooling	Years	UNDP
Eq10	EP	Input parameter	e-Participation index	Score	World Bank
Eq10	MBS	Output variable	Mobile cellular subscriptions per 100 inhabitants	Subscriptions per 100 inhabitants	ITU

3.4.2 Gender balance

Gender balance refers to equality based on gender in terms of rights, resources, opportunities, and protection, and the ability to use them to make strategic choices and decision. Women's social and economic empowerment at work, home, and communities increases inclusive growth and reduces poverty (UN Women, 2018; UNICEF, 2011). The details on the mathematical models and variables for the equations for gender balance are provided in Table 28 and Table 29. The flow diagrams for the models are presented in Figure A11 in Appendix 3.

GB1: Proportion of women with seats in national parliaments (Percent)

The mathematical models for this indicator were constructed using a linear regression model with the number of women with seats in national parliaments as the dependent variable and indicator variables of female education, political quotas, incentives for voting and equal voting rights for men and women. These were based on the data and descriptions from the OECD Social Institutions and Gender Index. Goetz (2003) found a link between female education and women's political participation. Also, Bhavnani (2009) indicated that political quotas increase the number of women elected to national parliaments, even after quotas have been removed.

GB2: Gender ratio of account at a financial institution or mobile-money-service provider (Ratio)

The mathematical models for this indicator were constructed using the framework provided by the Global Financial Inclusion (Global Findex) database. Specifically, the number of females with bank accounts depends linearly on equal laws for opening bank accounts for both men and women. Similarly, the number of females with mobile money subscriptions is dependent on the AB3 indicator category: access to broadband services and mobile connectivity. The GB2 indicator is a simple ratio of the number of women with accounts in financial institutions to the corresponding metric for men.

GB3: Getting paid, covering laws and regulations for equal gender pay (Score)

The mathematical models for this indicator were adopted from the framework provided by the World Bank Group's Women, Business, and Law Report (2019). Laws and regulations for equality in gender pay is a scored indicator divided into four categories, namely, equal wages for men and women, equality in types of jobs, equality in industries, and equal opportunities for night time work. Additionally, each category was also predicted using a linear regression model. Equal wages is dependent on economic output of a country (GDP), the Human Development Index (HDI), and fertility rates of women in the country. Fertility rates are strongly linked with rates of female education. Similarly, equality in industries is linked with laws against employment discrimination, which can be traced back to the GB1 indicator or number of women representatives in parliament.

Table 28. Equations used in the mathematical models for gender balance

Eq. No.	Equations	Purpose (brief explanation what relationship and/ or output is being measured in the equations)	Relevant indicator	Source
Eq1	$GB1 = \alpha + \beta1 * FE + \beta2 * VR + \beta3 * PQ + \beta4 * I$	It is the linear regression model for proportion of seats held by women in national parliament.	GB1	OECD SIGI data (A241)
Eq2	$FBA = \alpha + \beta1 * LB + Y_i$	The number of females with bank accounts depends on laws for equal opening of bank accounts.	GB2	Global Findex database (A242)
Eq3	$FMM = \alpha + \beta1 * AB3 + Y_i$	It is the linear regression model for the number of females with mobile money subscriptions.	GB2	Global Findex database (A242)
Eq4	$FFI = \frac{(FBA + FMM)}{2}$	Females with accounts in financial institutions is the average of female with bank account and females with mobile money accounts.	GB2	Global Findex database (A242)
Eq5	$GB2 = \frac{FFI}{MFI}$	GB2 is the share of female to male in financial institutions.	GB2	Global Findex database (A242)
Eq6	$L_{it} = \alpha + \beta1 * GB1 + Y_i$	It is the linear regression for laws preventing employment discrimination.	GB3	Data from OECD (A243)
Eq7	$EI_{it} = \alpha + \beta1 * L_{it} + Y_i$	It is the linear regression model for Equality in types of industries.	GB3	World Bank data (A244)
Eq8	$EJ_{it} = \alpha + \beta1 * L_{it} + Y_i$	It is the linear regression model for Equality in types of jobs.	GB3	World Bank data (A244)
Eq9	$F_{it} = \alpha + \beta1 * FE + Y_i$	It is the linear regression model for Fertility rates.	GB3	Data from OECD (A243)
Eq10	$EW_{it} = \alpha + \beta1 * EG_{it} + \beta2 * F_{it} + \beta3 * HDI_{it} + Y_i$	It is the linear regression model for Equal wages (men and women).	GB3	Generated from World Bank data (A244)
Eq11	$GB3 = EW + NW + EJ + EI$	GB3 is a summation of scores from equality in types of industries, types of jobs permitted, equal wages for men and women, and night-time work, with 25 to each indicator.	GB3	World Bank Group, 2019 (A245)

Table 29. Definitions of variables and parameters and sources of data for gender balance

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq1, Eq9	FE	Input scenario	Female education	%	OECD SIGI database
Eq1	VR	Input scenario	Equal Voting rights	Yes/No	OECD SIGI database
Eq1	PQ	Input scenario	Political quotas	Yes/No	OECD SIGI database
Eq1	I	Input scenario	Incentives to include women on candidates lists in national elections	Yes/No	OECD SIGI database
Eq1	GB1	Output variable	Proportion of seats held by women in national parliaments	%	Simulation Tool (Phase 2)
Eq2	LB	Input scenario	Laws for opening bank accounts	-	Global Findex database
Eq2, Eq3	Y	Dummies	Country dummies in the regression	-	UNSTATS database
Eq2, Eq4	FBA	Output variable	Number of females with bank accounts	Number of females	Global Findex database
Eq3	AB3	Input variable	Fixed internet broadband and mobile cellular subscriptions (from AB3)	Number per 100 people	ITU
Eq3, Eq4	FMM	Output variable (from AB3)	Number of females with mobile money subscriptions	Number of females	Global Findex database
Eq4, Eq5	FFI	Output variable	Females with accounts in financial institutions and mobile	Number of females	Global Findex database
Eq5	MFI	Input variable	Number of men with accounts in financial institutions	Number of men	Global Findex database
Eq5	GB2	Output variable	Gender ratio of account at a financial institution or mobile-money-service provider	Ratio	Simulation Tool (Phase 2)
Eq6, Eq7, Eq8, Eq9, Eq10	Y	Dummies	Country dummies in the regression	-	UNSTATS database
Eq6	L	Output variable	Laws against employment discrimination	Yes/No	OECD SIGI database
Eq7	EI	Output variable	Equality in industries	Score out of 25	Women, Business and Law database
Eq8, Eq11	EJ	Output variable	Equality in types of jobs permitted	Score out of 25	Women, Business and Law database
Eq9	F	Output variable	Fertility rate	Number of children	OECD
Eq10	EG	Input parameter	Economic output (GDP)	USD	World Bank
Eq10	HDI	Input parameter	Level of economic development	Index	UNDP HDI database
Eq10,Eq11	EW	Output variable	Equal wages to men and women	Score out of 25	Women, Business and Law database
Eq11	NW	Input variable	Night-time work	Score out of 25	Women, Business and Law database
Eq11	GB3	Output variable	Getting paid, covering laws and regulations for equal gender pay	Score	Simulation Tool (Phase 2)

3.4.3 Social equity

Social equity refers to a fair and equitable public and social policy, giving equal opportunities to all by a fair allocation of and access to resources that take into account social inequalities. Addressing and embedding equity issues in the design of a policy will lead to sustainable economic growth over the long term (Clench-Aas & Holte, 2018; OECD, 2018). The details on the mathematical models and variables for the equations for social equity are provided in Table 30 and Table 31. The flow diagrams for the models are presented in Figure A12 for share of youth in NEET and Figure A10 for ratio of urban-rural access to basic services in Appendix 3.

SE1: Inequality in income based on Palma ratio (Ratio)

As compared to other income inequality indices (e.g., Gini, Atkinson), Palma ratio is relatively a new measure and has not been used to assess social issues in mathematical models. Models that are available to simulate welfare distributional impacts are linked to redistributive effects of taxes (e.g., Jara & Varela, 2017; Wright et al., 2016). These models are using survey data, which are not available for the Phase 1 application of the Green Growth Simulation Model. Moreover, the Phase 2 development of the Tool will only aim to use data that can be collected from government agencies. Although methods from these studies can be adapted for the Simulation Tool, details on the models are not available from available publications. Modelers will be requested to collaborate with the GGPM Team in the Phase 2 development of the Simulation Model. An alternative method for building model for Palma ratio will be to develop a regression model using the framework of the Organisation for Economic Co-operation and Development (OECD, 2012), which suggests that income inequality in a nation is dependent on socioeconomic issues such as equitable taxation policies and education programs, the reach of education, and active labor market reforms. This will require finding appropriate indicators and data that will represent these issues in the regression model.

SE2: Ratio of urban-rural access to basic services, i.e. electricity (Ratio)

This indicator is linked to the access to basic services system so it does not have its own mathematical model. Its application will be made in the Phase 2 Simulation Tool where demographic scenarios will be included.

SE3: Share of youth (aged 15-24 years) not in education, employment, or training (NEET) (Percent)

The mathematical models for this indicator were also developed using a regression analysis, which helped to identify factors that affect the share of youth not in employment, education or training (NEET). The data were obtained from the WB database. Based on the regression results, the independent variables such as GDP per capita, proportion of 15-24 year-old enrolled in vocational education, and school life expectancy of tertiary education were statistically significant, which mean that these might be the variables that affect youth NEET share. The independent variables that were omitted due to its statistical insignificance include R&D expenditures, number of illiterate youth (15-24), and participation rate of youth and adults in formal and non-formal education and training in the previous 12 months.

Table 30. Equations used in the mathematical models for social equity

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source
Eq1	$\mathrm{SE3} = \alpha + \beta 1 * \mathrm{GDPC} + \beta 2 * \mathrm{SLE} + \beta 3 * \mathrm{VOC}$	It is the linear regression model to predict youth not in employment, education, or training.	SE3	Regression Analysis
Eq11	$\mathrm{SE2} = \alpha + \beta 1 * \mathrm{QWS} + \beta 2 * \mathrm{URs}$	It is the linear regression model to predict the ratio of urban-rural access to basic services.	SE2	Regression Analysis

Note: SE2 starts at equation number 11 since it is linked with access to basic services and resources model (Table 26)

Table 31. Definitions of variables and parameters and sources of data for social equity

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq1	GDPC	Input parameter	Gross Domestic Product per Capita	USD per capita (2017 constant)	World Bank
Eq1	SLE	Input parameter	School life expectancy, tertiary	Years	World Bank
Eq1	VOC	Input parameter	Proportion of 15-24 year-olds enrolled in vocational education	%	World Bank
Eq1	SE3	Output variable	Share of youth not in education, employment or training	%	World Bank
Eq11	QWS	Output variable	Quality of Water Services	-	Simulation Tool (Phase 2)
Eq11	URs	Output variable	Urban/Rural services	Ratio	Simulation Tool (Phase 2)
Eq11	SE2	Output variable	Ratio of urban-rural access to basic services, i.e. electricity	Ratio	Simulation Tool (Phase 2)

3.4.4 Social Protection

Social protection refers to programs designed to provide benefits to ensure income security and access to social services, contributing to social equity and inclusive society and reducing poverty and exposure to risks (ESCWA, 2015; UNRISD, 2010). The details on the mathematical models and variables for the equations for social protection are provided in Table 32 and Table 33. The flow diagram for the models on population living in slums is presented in Figure A13 in Appendix 3. The flow diagram for other indicators will be built and interlinked to other models in the Phase 2 application of the Simulation Tool.

SP1: Proportion of population above statutory pensionable age receiving a pension (Percent)

So far, there is no mathematical model identified for this indicator and a regression model was not identified due to lack of data. This indicator is a proxy variable in the Green Growth Index and an alternative green growth indicator will be reviewed next year to facilitate the development of mathematical models for social welfare system.

SP2: Universal health coverage (UHC) service coverage index (Index)

There is also no mathematical model identified for this indicator. However, the different indicators used to compute the UHC Index can be used as a basis for regression analysis to develop mathematical models for this indicator. However, there were no sufficient data to run a regression analysis, so it will be implemented in the Phase 2 Simulation Tool.

SP3: Proportion of the urban population living in slums (Percent)

The mathematical models for this indicator were adopted from the pilot version of the Simulation Tool, which was developed by the Vivid Economics (2017). These models were constructed as an average of households without access to improved water sources or sanitation facilities and those without adequate living space in urban areas. The change in number of informal settlements depends on the tenure register and the maximum possible increase in slum populations. According to Shoko and Smit (2013) study in South Africa, the maximum number of informal settlements in a particular area can be obtained by dividing the area of the region by a factor of 16. Finally, the total land area occupied by formal private settlements is the total land area minus the area occupied by formal public houses and slums. Consequently, if the land area occupied by formal private settlements is known, then it is possible to calculate the area taken up by slums.

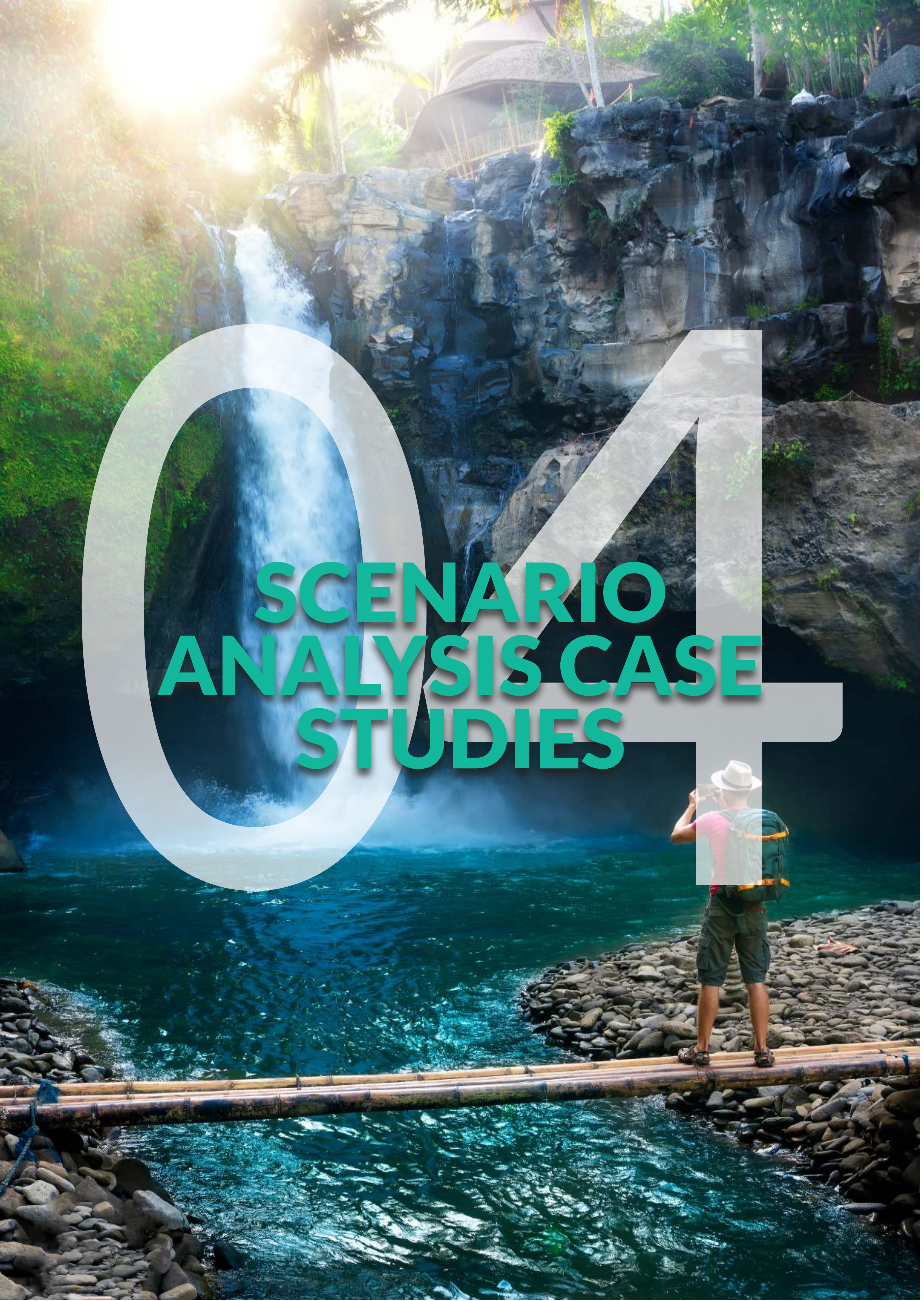
Table 32. Equations used in the mathematical models for social protection

Eq. No.	Equations	Purpose (brief explanation what relationship and/or output is being measured in the equations)	Relevant indicator	Source*
Eq1	$\mathrm{Max\ LIS(x)} = \frac{\mathrm{Area}}{16}$	Maximum land area for informal settlements is calculated by dividing the area of a region with a factor of 16.	SP3	Vivid Economics, 2017 (A227)
Eq2	$\mathrm{LFP(x)} = \mathrm{L(x)} - \mathrm{LFS(x)} - \mathrm{LIS(x)}$	The number of formal private settlements is the difference among total land area with formal public houses and informal settlements (slums).	SP3	Vivid Economics, 2017 (A227)
Eq3	$\mathrm{SP3} = \mathrm{Avg(PW, PS)}$	SP3 is an average of population without access to safely managed water and sanitation..	SP3	Vivid Economics, 2017 (A227)

**From methodology of the pilot version of the Simulation Tool*

Table 33. Definitions of variables and parameters and sources of data for social protection

Eq. No.	Acronym	Type	Definition	Unit	Sources of data
Eq1	LIS	Output variable	Land area for informal settlements	Km^2	National data
Eq2	LFP	Input scenario	Land area for formal private settlements	Km^2	National data
Eq2	LFS	Input scenario	Land area for public formalized housing	Km^2	National data
Eq3	PW	Input variable (from AB1)	Percentage of population without access to safely managed water	%	AB1
Eq3	PS	Input variable (from AB1)	Percentage of population without access to safely managed sanitation	%	AB1
Eq3	SP3	Output variable	Proportion of urban population living in slums	%	Simulation Tool (Phase 2)



04 SCENARIO ANALYSIS CASE STUDIES

The policy relevance of the Simulation Tool lies on the application of policy and investment scenarios that address governments' planning and decision making. For this reason, the Phase 2 application of the Tool will involve strong collaboration with policymakers and local experts to create scenarios that they need for specific purpose, for example, assessing GHG emissions reduction for NDCs or LEDS, co-benefits of green deal plans, etc.

The Phase 1 Simulation Tool can include scenarios for specific sectors, example of which are as follows:

- Energy and Transport – increasing electric vehicle, using efficient transport technology
- Water – implementing water pricing policies, improving irrigation technology efficiency
- Agriculture – reducing production losses and fertilizer use
- Forestry – increasing reforestation or reducing deforestation, applying climate smart forestry policies
- Waste – increasing recycling rate, reducing food waste

For Phase 2, the Simulation Tool will also include economic (e.g., GDP), demographics (e.g., population), and climate (e.g., temperature) scenarios.

In this chapter, the results from the selected scenarios for energy, transport, land, and water sectors are presented to illustrate the application of Phase 1 Simulation Tool. The case study countries include Hungary, Uganda, and Mexico. The Phase 2 of the Simulation Tool is planned to be applied for Hungary and Uganda next year, which justified the development of Phase 1 Tool for these countries for practical reasons. The availability of online data for Uganda is, however, very limited, which prevented scenario analyses for many green growth indicators. To allow cross-country comparisons, Mexico, another GGGI member Country, was included as additional case study country. For energy and transport, however, there were no sufficient data to apply the Phase 1 Simulation Tool for Mexico.

4.1. Energy and transport in Hungary

The energy model incorporated a sub-model on the transport sector which will allow the policymakers to investigate the impacts of passenger transport on the share of renewable energy (EE2, Table 4), CO_2 emissions (GE1, Table 14), and PM2.5 emissions (EQ1, Table 12). For the Phase 1 application of this model, three sets of scenarios were developed for Hungary. The first set of scenarios, which was applied to determine the impacts on the share of renewable to energy consumption and CO_2 emissions reduction, includes BAU scenario, 25% increase in share of electrical vehicle activity (SC1), and 50% increase in share of electric vehicle activity (SC2). The second set of scenarios, which was also applied to both share of renewable energy and CO_2 emissions, includes BAU, 5% increase in vehicle energy efficiency (SC1), and 15% increase in vehicle energy efficiency (SC2). The third set of scenarios, which assesses the impacts on PM2.5 emissions, includes BAU and decrease in passenger and freight vehicles by 10% (SC1) and 20% (SC2) by 2050. For Uganda and Mexico, there were no sufficient online data on transport mode and vehicle technology characteristics to run these scenario analyses.

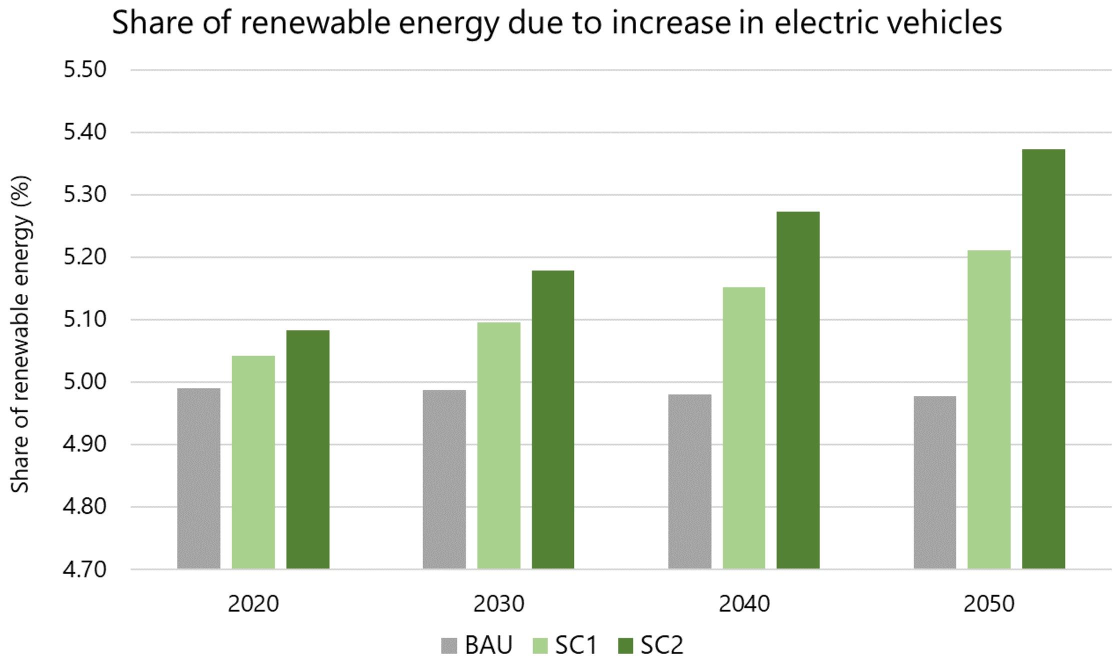
The assumptions for these scenarios are as follows:

- To run the BAU scenario, most of the variables in the model remained constant except the projections for activity demand for both freight and passenger transport as adapted from Capros et al. (2013). The Phase 1 analysis used energy efficiency values for vehicle technologies from Taylor et al. 2019 (T1) to compute the energy consumption for 2017 (baseline year). Under this scenario, the model used the biofuel blending rate of 4.9% to determine the share of biofuels used in the fuel consumed in the transport sector. Similarly, the share of renewables in the electricity consumed was used in addition to the blending rate to compute the share of renewables in the energy consumed in the sector.
- The fuel blending rate and electricity from the renewables rate were held constant up to 2050 in both the vehicle energy efficiency and electric vehicle scenarios.
- For the vehicle energy efficiency scenario, the vehicle energy consumption variable was reduced by either 5% or 15% per year to 2050. All other variables were held constant.
- For the electric vehicle activity scenario, the technology shares of passenger car vehicles were changed to equate to either a 25% or 50% increase by 2050. All other variables were held constant.

4.1.1 Changes in renewable energy consumption from transport sector

Figure 9 shows an increase in the share of renewables in the energy consumed in the transport sector for both scenarios. A 50% increase in share of electric vehicle activity (SC2) causes a significant increase in the share of renewables at 5.37% by 2050, a boost from the 4.97% compared to the BAU scenario. The increment is attributed to the decrease in the use of vehicles powered by diesel or gasoline alone. An increase in the number of electric passenger cars in use is critical to achieving the target on the share of renewables in the energy consumption mix in the transport sector. An option for electricity to power passenger cars does not cause competition to food security while ensuring the reliability in the supply as compared to the biofuels. A transition to electric cars with zero emission and other low carbon vehicles is among the many ways Hungary can meet its set target for achieving SDG7. However, it is important to note that a policy on the increase in the vehicle passenger cars should be followed with an increase in the use of renewable energy sources to generate the power consumed.

Figure 9. Changes in share of renewable energy due to increase in electric vehicles in Hungary, 2020-2050

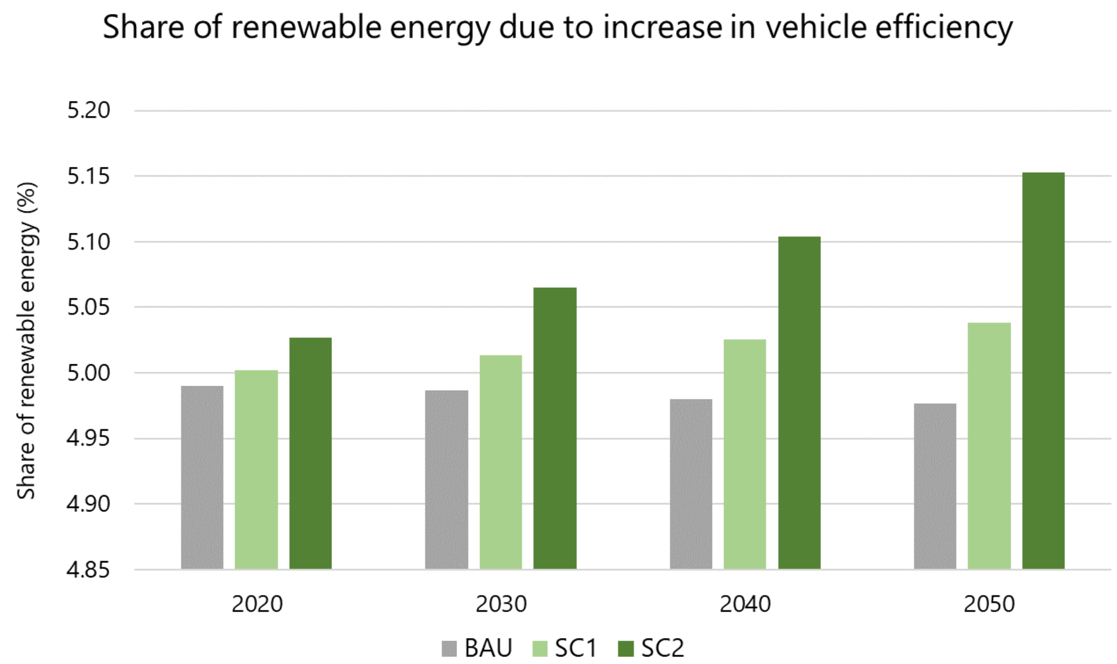


Note: Baseline year is 2017. Scenarios include BAU, 25% increase in share of electrical vehicle activity (SC1), and 50% increase in share of electric vehicle activity (SC2).

Figure 10 shows the impact of improving vehicle energy efficiency on the share of renewables in passenger and freight vehicles in the transport sector in Hungary. Scenarios represent either a 5% (SC1) or a 15% (SC2) improvement in vehicle energy efficiency. Both scenarios show an increasing trend in the share of renewables over time, with a greater improvement observed under SC2 with the share of renewable energy increasing to 5.2% by 2050. For SC1, incremental improvements are observed as the share of renewables only increases by 0.74% between 2020 to 2050.

Although, when considering the overall change in the share of renewable energy, neither scenario improves share of renewables by more than 1%. This may suggest that efficiency improvements on their own are not enough to significantly change the share of renewable energy consumption. Hence, one consideration would be to include an improvement in vehicle energy efficiency in conjunction with an additional energy policy (e.g., increase in electric vehicles) to result in a greater improvement of the renewable energy share within the transport sector in Hungary.

Figure 10. Changes in share of renewable energy due to increase in vehicle efficiency in Hungary, 2020-2050

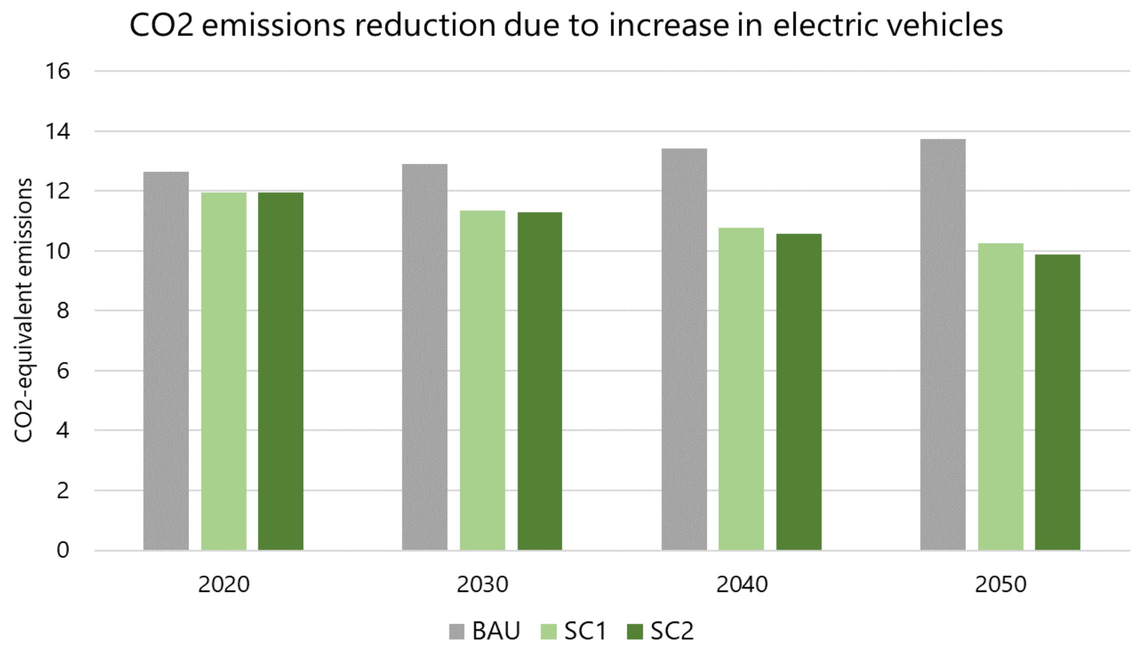


Note: Baseline year is 2017. Scenarios include BAU, 5% increase in vehicle energy efficiency (SC1) and 15% increase in vehicle energy efficiency (SC2).

4.1.2 Changes in CO_2 emissions reduction from the transport sector

The use of electric passenger cars has positive impact on the environment because of zero emissions from full electric-based and reduced emissions from hybrid electric vehicles. Electric vehicles have lower emissions as compared to the 100% Internal combustion cars. Figure 11 shows a decreasing trend in the CO_2 emissions by 2050 for both scenarios SC1 and SC2. The continuous decrease in the CO_2 emissions is attributed to the increase in the percent share of electric vehicles in SC1 and SC2 from the BAU scenario. An increase in the share of electric cars to 50% (SC2) by 2050, reduces the CO_2 emissions equivalents from 13.73 in the BAU to 9.89. However, there is no significant difference between the CO_2 emissions reduction in SC1 and SC2 scenarios through 2050. This may indicate that solely targeting passenger electric vehicles may not be sufficient to reduce CO_2 emissions for the transport sector in Hungary and policies should aim to increase the share of electric vehicles in other modes of transport or incorporate additional low carbon measures such as increasing the percentage of biofuel blends and the use of public transport. However, electrification of the vehicles remains one of the most important pathways to decarbonization because of the combined benefits such as increasing the share of renewables and maintaining a considerable decrease in the CO_2 emissions by 2050.

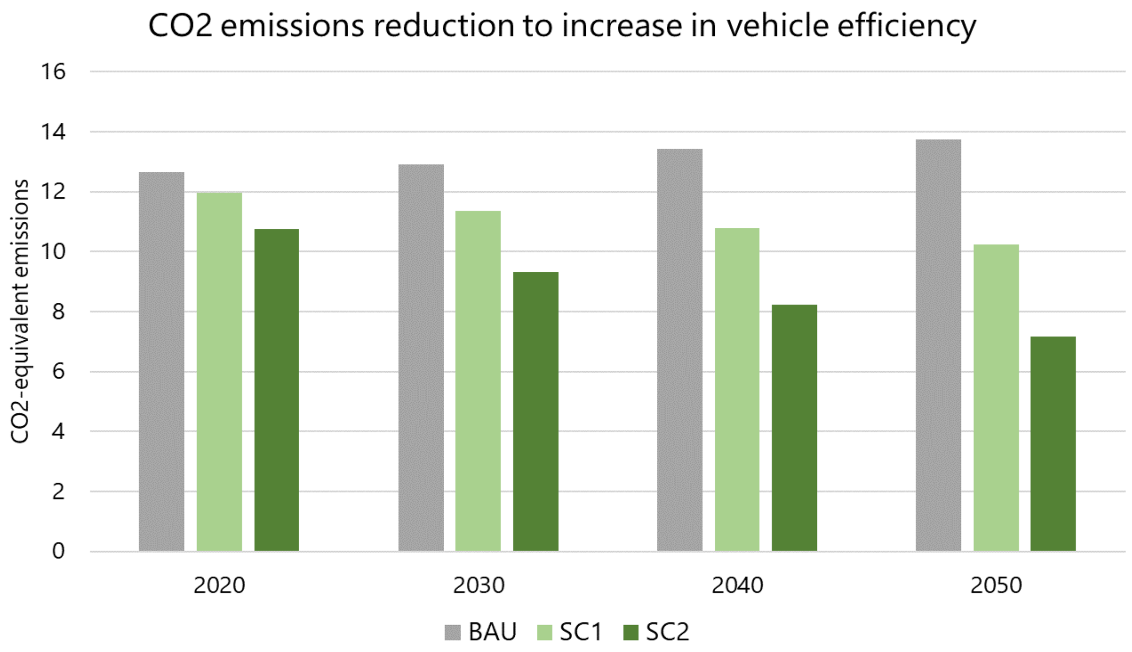
Figure 11. Changes in CO_2 emissions reduction due to increase in electric vehicles in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios include BAU, 25% increase in share of electrical vehicle activity (SC1), and 50% increase in share of electric vehicle activity (SC2).

The decrease in the energy consumed per passenger km or ton km due to improvements in the vehicle energy efficiency will help Hungary to reduce CO_2 emissions over time (Figure 12). Increasing the efficiency of vehicles can reduce the amount of fuel consumed over a distance, thus reducing the amount of emissions released into the atmosphere (Atabani et al., 2011). A higher reduction in CO_2 is observed under a 15% increase in vehicle energy efficiency (SC2), with a decrease in CO_2 emission equivalents from 12.5 to 9.89 by 2050. Increments in the energy efficiency of vehicles through to 2050 result in close to 40% CO_2 emissions savings from the BAU scenario. Both SC1 and SC2 scenarios indicate that CO_2 emissions are reduced at a diminishing rate over time, indicating that there is a threshold level between vehicle energy efficiency improvement and CO_2 emission reduction that should be considered during policy decision making processes.

Figure 12. Changes in CO_2 emissions reduction due to increase in vehicle efficiency in Hungary, 2020-2050

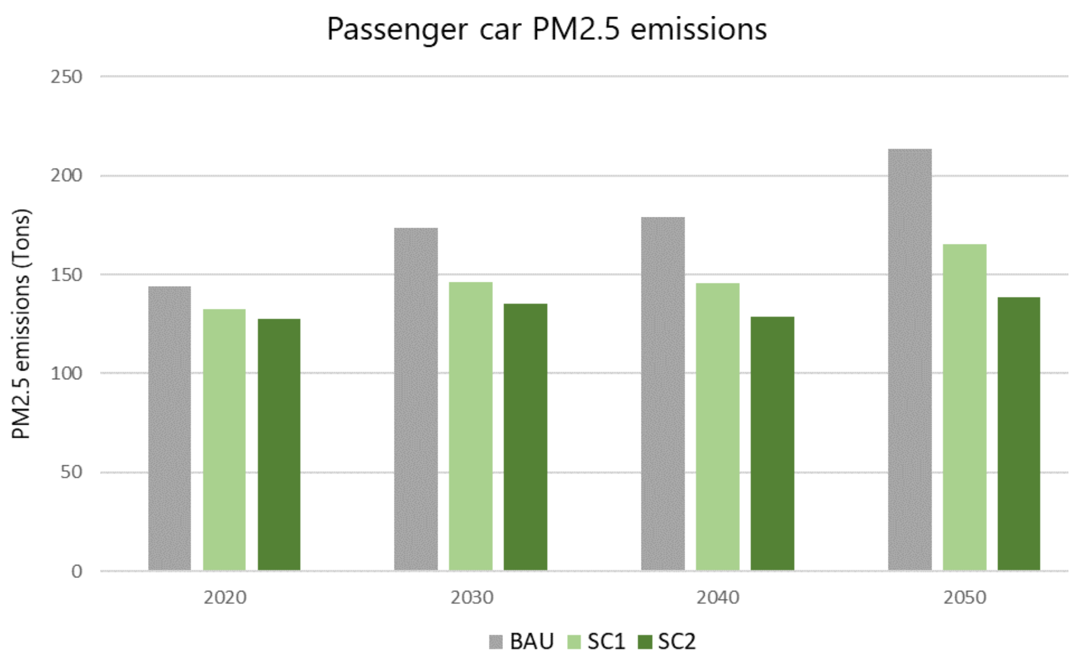


Note: Baseline year is 2017. Scenarios include BAU, 5% increase in vehicle energy efficiency (SC1) and 15% increase in vehicle energy efficiency (SC2).

4.1.3 Changes in PM2.5 air pollution due to tyre and brake wear of passenger and freight vehicles

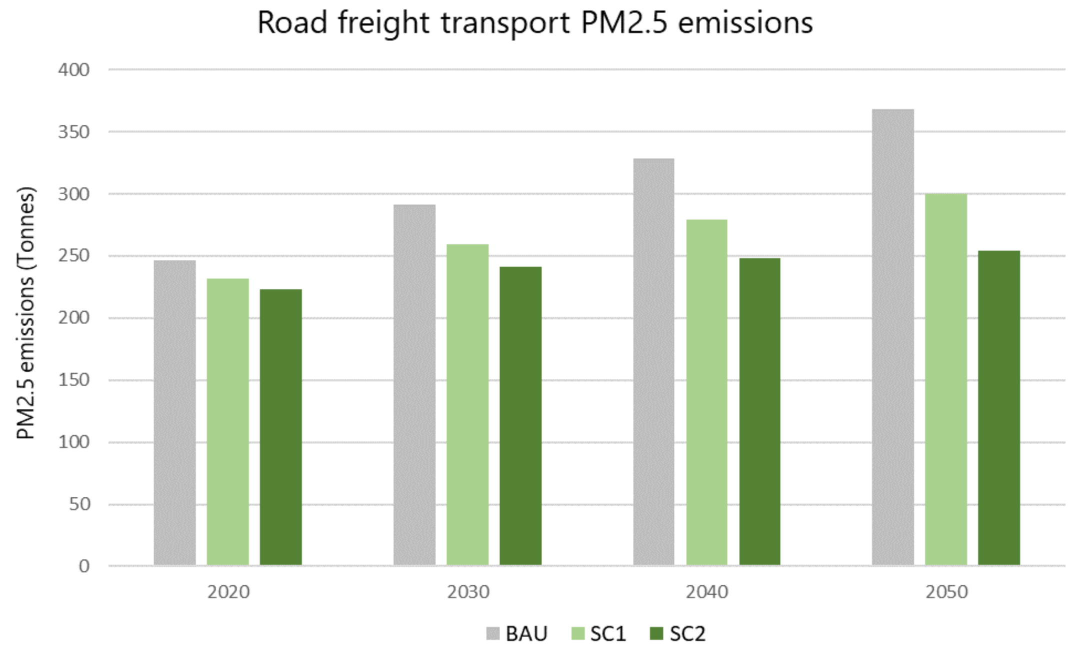
From the total vehicle kilometres travelled, the total PM2.5 air pollution (EQ1) from tyre and brake wear was computed for both passenger and freight vehicles. In the BAU, the share of passenger vehicles increases by 8% and freight heavy-duty vehicles by 4.65%. As the demand in vehicles kilometres travelled is expected to increase in Hungary, the PM2.5 emissions from tyre and break wear is also expected to increase for both passenger and freight transport vehicles in the BAU scenario. This increase can be partially mitigated by decreasing passenger and road freight vehicles. If policies will be implemented to reduce passenger vehicles by 10% (SC1) and 20% (SC2) by 2050, PM2.5 emissions will be reduced relative to BAU over time (Figure 13). Using the same scenarios, similar trend will be expected for road freight vehicles but with slightly higher reduction in emissions than passenger vehicles particularly in 2050 (Figure 14).

Figure 13. Changes in PM2.5 emissions from tyre and brake wear of passenger vehicles in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios are BAU and decrease in passenger and freight vehicles by 10% (SC1) and 20% (SC2) by 2050.

Figure 14. Changes in PM2.5 emissions from tyre and brake wear of freight vehicles in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios are BAU and decrease in passenger and freight vehicles by 10% (SC1) and 20% (SC2) by 2050.

4.2. Water use in Hungary and Mexico

Phase 1 Simulation Tool for water use models was applied for Hungary and Mexico to understand the impact of water management policies on the indicators of water use efficiency (EW1, Table 6) and the share of freshwater withdrawal to available freshwater (EW2, Table 6). The policies for improving water use in agricultural and municipal sectors include implementing water price tariff and adapting more water efficient irrigation technologies. Based on these, three sets of scenarios were developed and applied to assess their impacts on water use efficiency (EW1) and share of freshwater withdrawal to available freshwater resources (EW2). The first set of scenarios for the municipal water sector deals with changing the percentage increase in water price per year from 2017 baseline values –BAU which assumes no price change, a 5% increase in water price per year or low price scenario (SC1), and a 20% increase in water price per year or high price scenario (SC2). The second set of scenarios for the irrigation technologies aims to show the impacts of increasing the proportion of localized (or drip) irrigated area – BAU which assumes efficient technologies are not used, a 10% increase in the use of water efficient irrigation technologies or low technology ambition (SC1), and a 30% increase in the use of water efficient irrigation technologies or high technology ambition (SC2) relative to the base year values. The third set of scenarios is the combination of the first and second sets of scenarios.

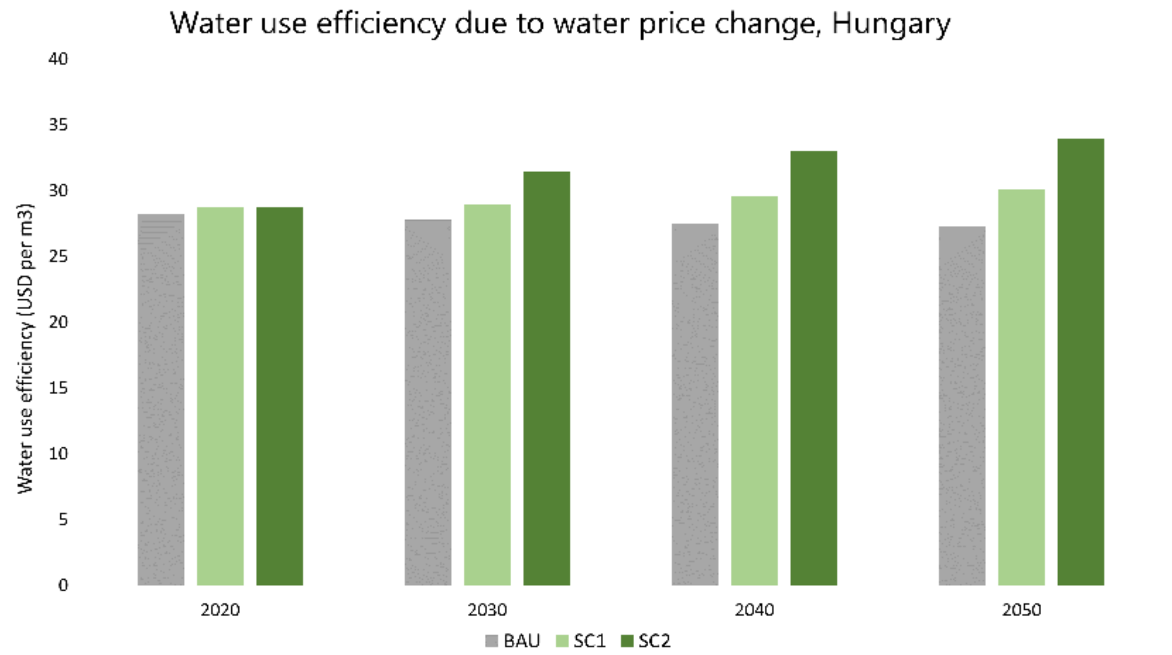
The two main assumptions for these scenarios are as follows:

- For scenarios involving changes in water price, socio-economic projections for GDP per capita and population were incorporated. These were baseline projections from the OECD up to 2050. This source was chosen due to the availability of data for both countries as well as to keep consistency between the population and GDP per capita projections. All other input variables within the water use model were held constant over time.
- For scenarios involving changes in irrigation technology efficiency, all other variables except for the input scenario variable (proportions of irrigation area via technology) were held constant over time. To identify suitable baseline proportions for each irrigated area, the most recent data from FAO AQUASTAT were used.

4.2.1 Changes in water use efficiency due to increase in water price and improved irrigation technology

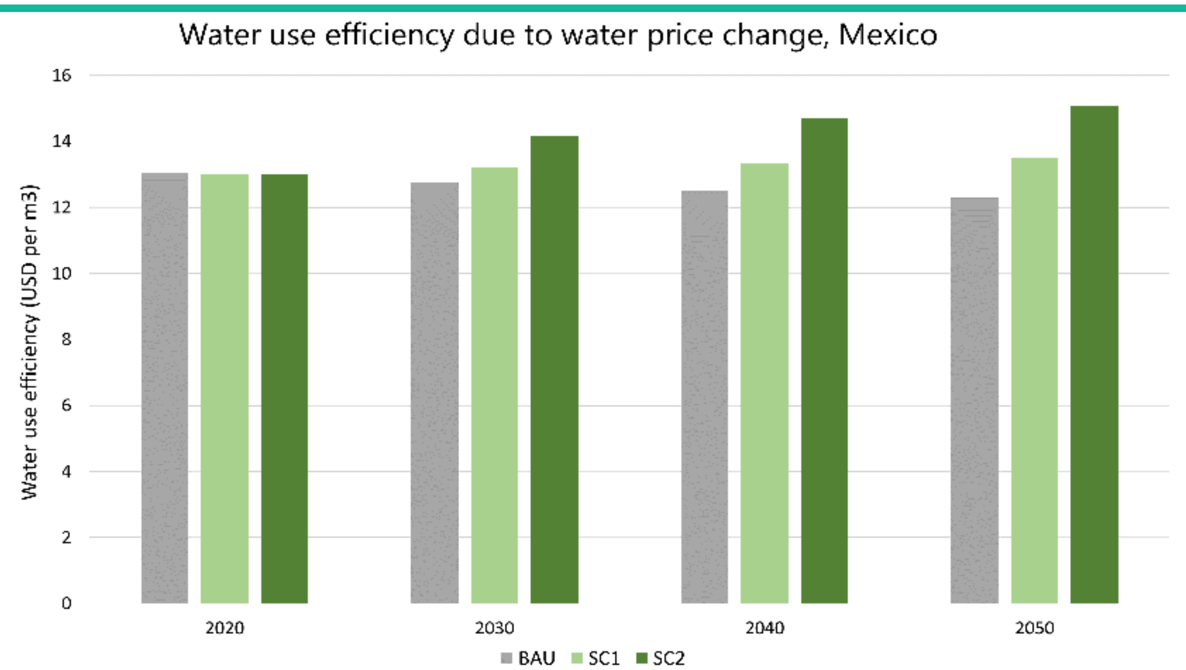
Figure 15a and b show the impacts of changing the water prices between 2020 and 2050 on the water use efficiency (EW1) for Hungary and Mexico. Both countries show a similar pattern in improving this indicator over time under high water price scenario (SC2), with Hungary having the largest increase from \$29.95 in 2020 to \$34.5 USD per m^3 in 2050 (Figure 15a). While under low water price scenario (SC1), each country still shows a positive progression towards their water use efficiency targets, however, these are only small changes such as a dollar increase. By 2050, both countries will have a decrease in water use efficiency if baseline municipal water prices are held constant. One interpretation of this result is that people may become more inefficient in water usage without a price mechanism to influence their water consumption behavior, as the municipal sector represents both household and additional service industries water usages. This is equally relevant in the agricultural sector, where the availability of solar photovoltaics to pump groundwater will encourage unsustainable use if pumped water remains cheap or, in many cases, free of charge.

Figure 15a. Changes in water use efficiency from increase in water price in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios include BAU, 5% increase in water price or low water price scenario (SC1), and 20% increase in water price or high price scenario (SC2).

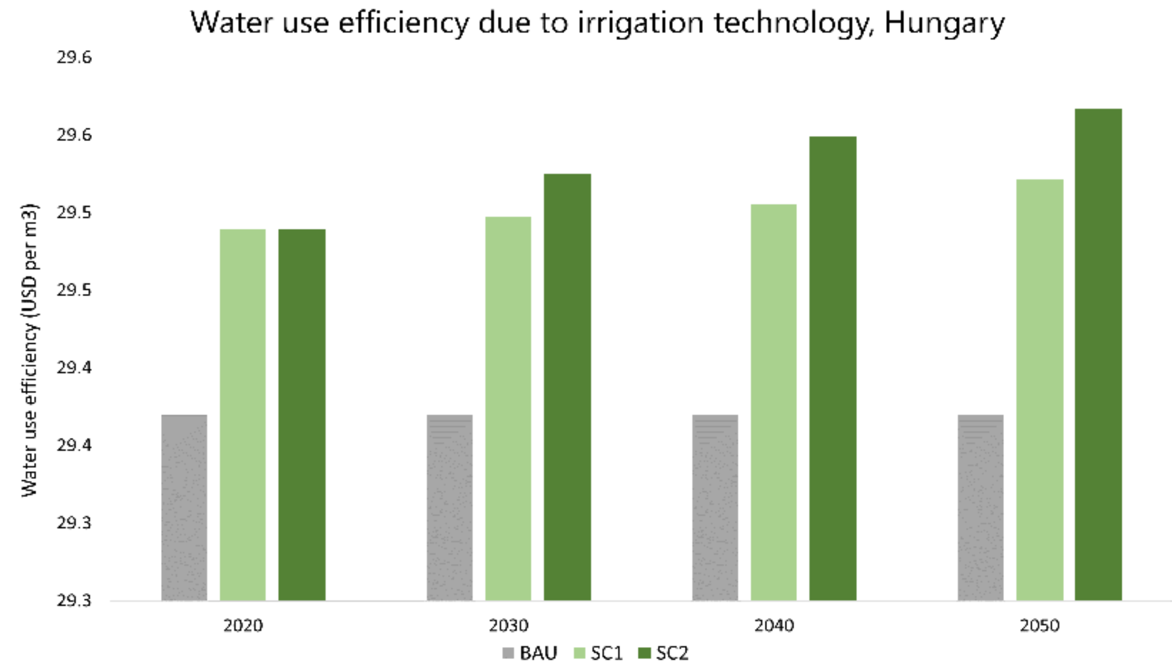
Figure 15b. Changes in water use efficiency from increase in water price in Mexico, 2020-2050



Note: Baseline year is 2017. Scenarios include BAU, 5% increase in water price or low water price scenario (SC1), and 20% increase in water price or high price scenario (SC2).

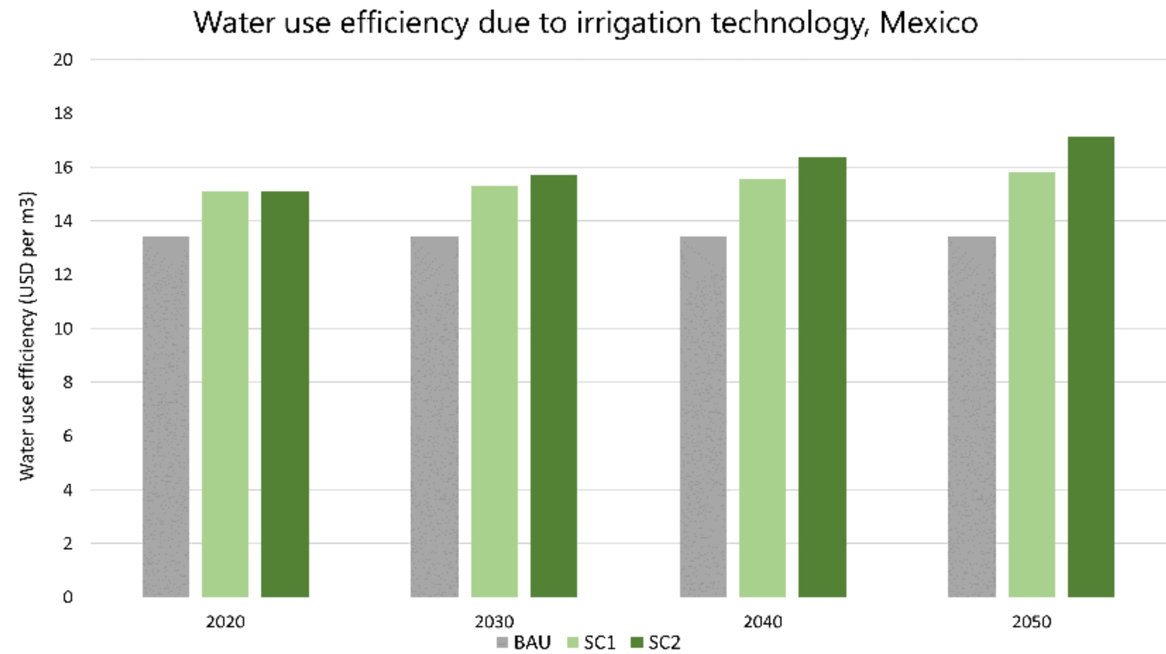
Figure 16a and b show the impacts of implementing various irrigation technology scenarios on water use efficiency. Both Hungary and Mexico show improvements in water use efficiency by increasing the area of land with more efficient irrigation technologies. High technology ambition scenario (SC2) results in the highest change in water use efficiency, although even under this type of scenario, Hungary's values only improve by $0.05 USD. For example, water use efficiency improves from $29.49 in 2020 to $29.56 USD per m^3 in 2050 (Figure 16a). This suggests that irrigation is not a major water use in Hungary and their policies that solely target agriculture will not significantly influence the country's overall performance in water use efficiency score. Comparatively, the influence of an irrigation policy on water use efficiency in Mexico is more pronounced, with a high technology ambition scenario (SC2) resulting in a new water use efficiency of $17 USD per m^3 (Figure 16b), thereby increasing by $2 USD from the 2017 baseline year value.

Figure 16a. Changes in water use efficiency from improved irrigation technology in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios include BAU, 10% increase in localized irrigation area or low technology ambition (SC1), and 30% increase in localized irrigation area or high technology ambition (SC2).

Figure 16b. Changes in water use efficiency from improved irrigation technology in Mexico, 2020-2050

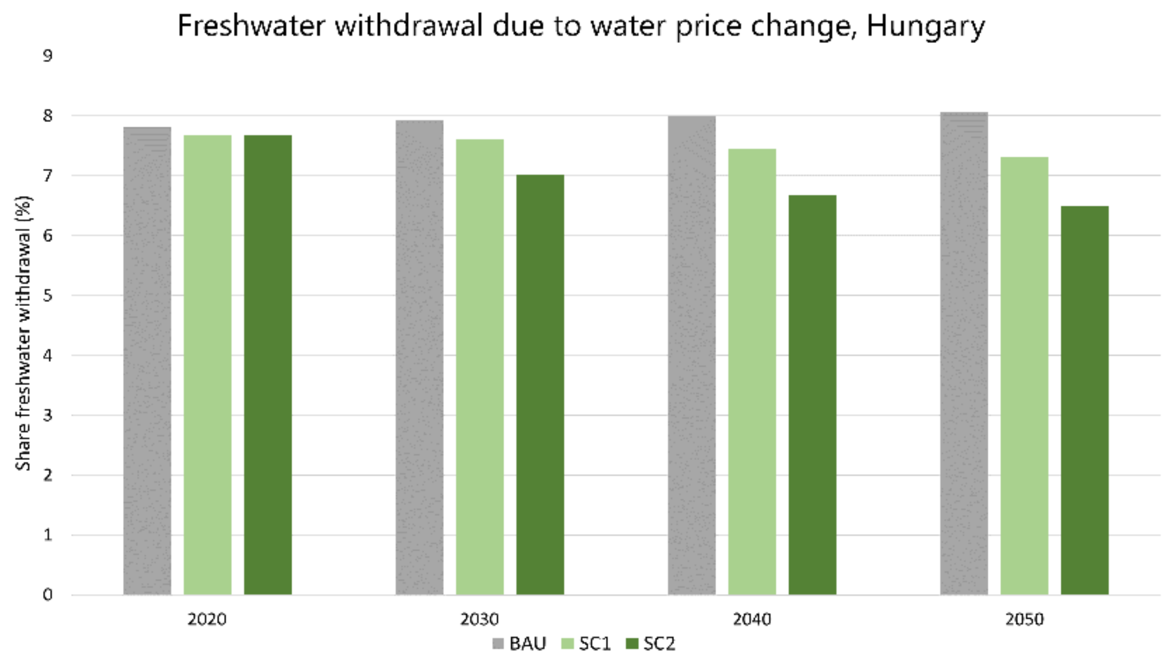


Note: Baseline year is 2017. Scenarios include BAU, 10% increase in localized irrigation area or low technology ambition (SC1), and 30% increase in localized irrigation area or high technology ambition (SC2).

4.2.2 Changes in freshwater withdrawal due to increase in water price and improved irrigation technology

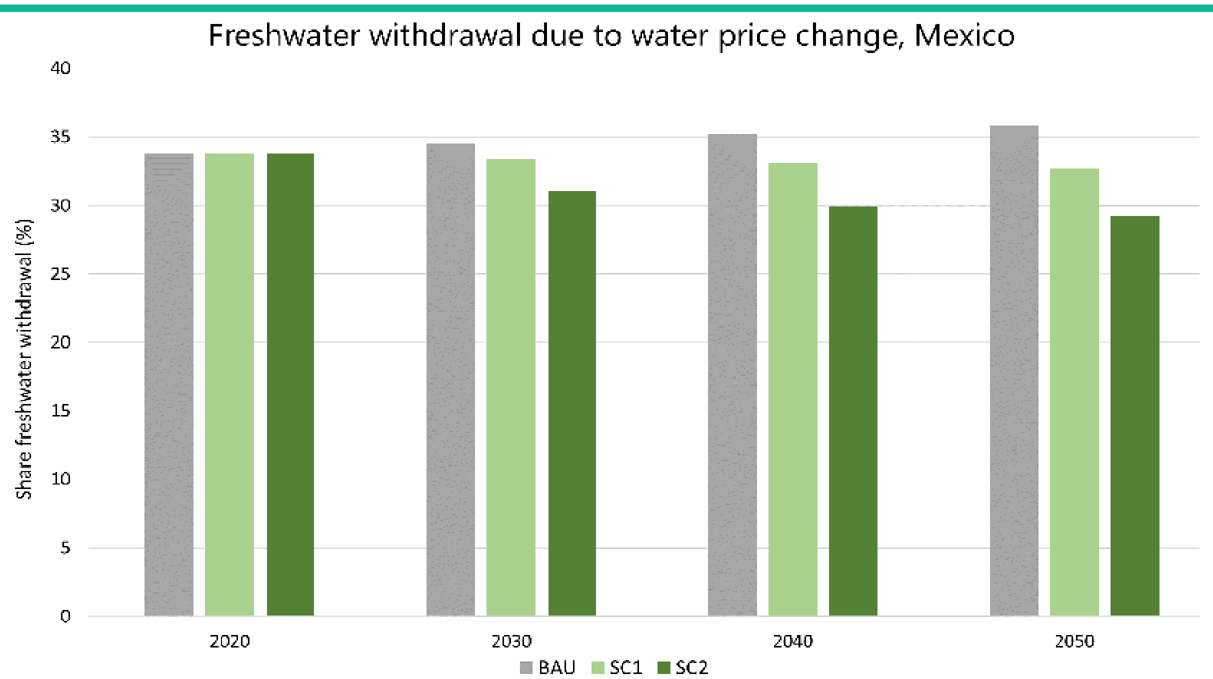
Using the same sets of scenarios, this section discusses the impacts of implementing sectoral water policies to the share of freshwater withdrawal to available freshwater resources (EW2). The influence of a water price policy was observed under high water price scenario (SC2) for both countries, with Hungary progressing its performance on this indicator by reducing its share of freshwater withdrawal from 7.5% to 6.9% (Figure 17a) and Mexico from 33% to 29% (Figure 17b) from 2020 to 2050. Although minimal to no significant improvements in water stress are observed under the low water price scenario (SC1) for either country. The BAU scenario shows that water stress from freshwater withdrawal will slightly increase in both countries over the simulated period. This is a similar trend that was observed with decreasing water use efficiency (EW1) also under the BAU scenario.

Figure 17a. Changes in freshwater withdrawal from increase in water price in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios include BAU, 5% increase in water price or low water price scenario (SC1), and 20% increase in water price or high price scenario (SC2).

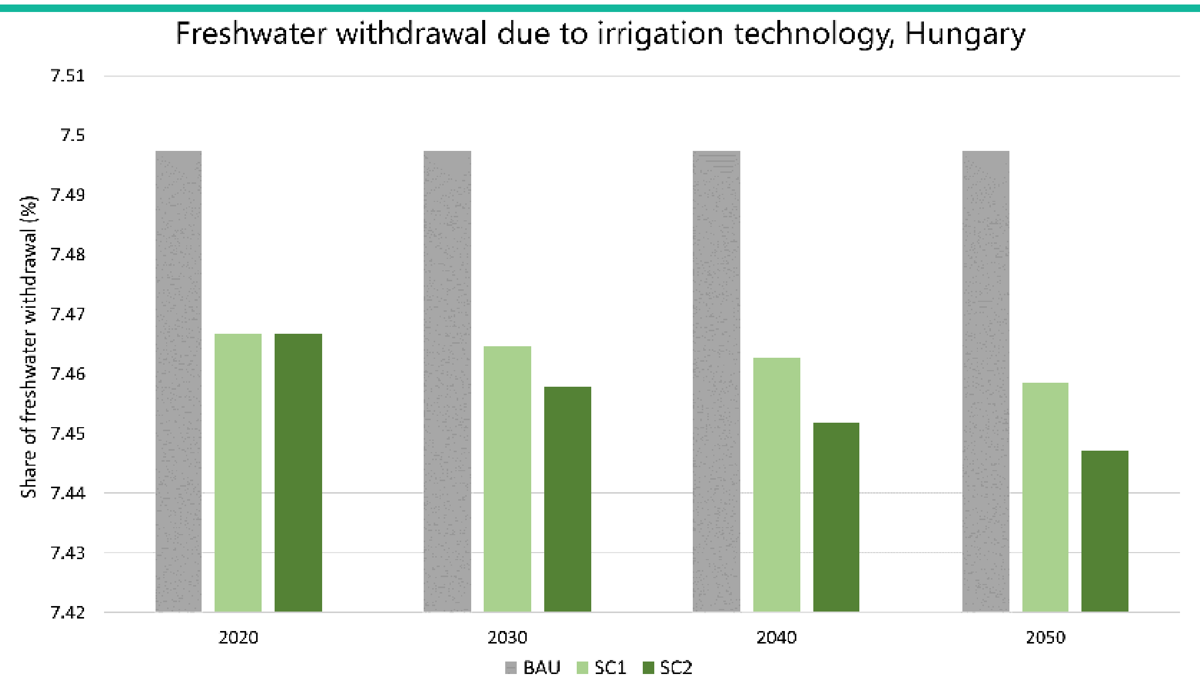
Figure 17b. Changes in freshwater withdrawal from increase in water price in Mexico, 2020-2050



Note: Baseline year is 2017. Scenarios include BAU, 5% increase in water price or low water price scenario (SC1), and 20% increase in water price or high price scenario (SC2).

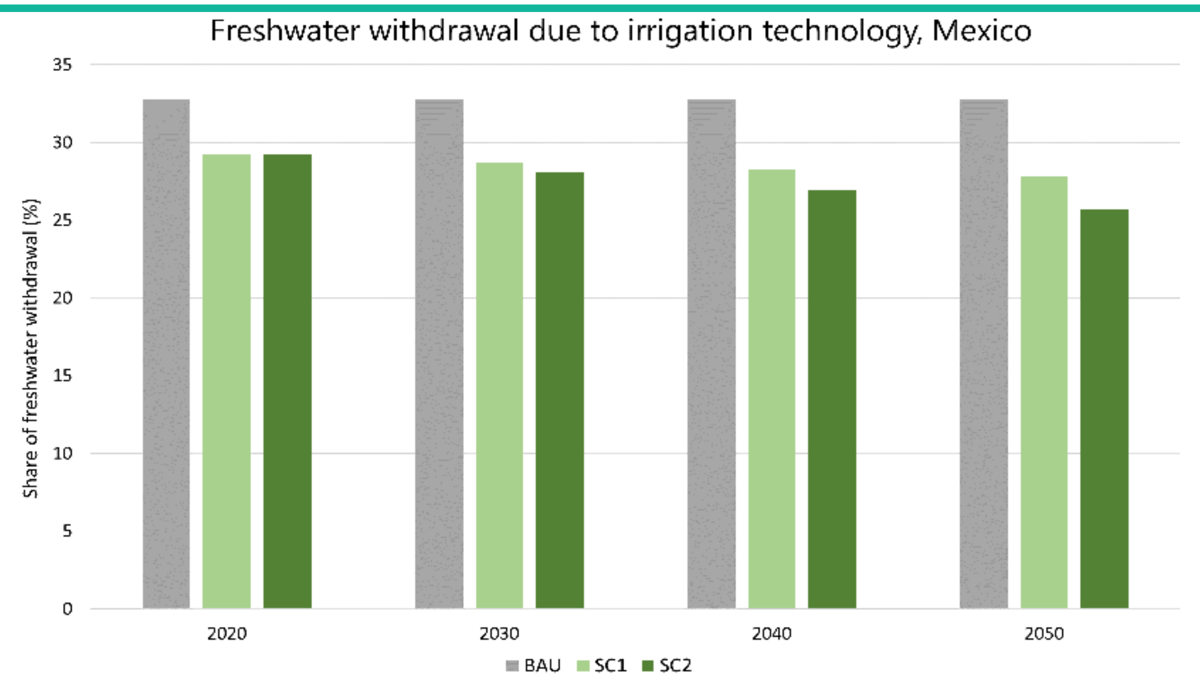
The changes in irrigated areas are observed to have a greater impact on the share of freshwater withdrawal to available freshwater resources (EW2) in Mexico than Hungary (Figure 18a and b). For example, under a high technology scenario (SC2), increasing localized irrigation by 30% closely pushes Mexico towards a no water stress classification. The opposite is observed for Hungary, as while Figure 18a may show a significant difference between SC1/SC2 scenarios and the BAU, the percentage change is minimal (less than 0.05%) and does not decrease significantly over time in both scenarios SC1 and SC2. This may be due to Hungary already having a higher proportion of irrigated area with efficient technologies within its baseline year, thereby further increasing highly efficient irrigated land only result in incremental decreases in freshwater withdrawal as the land approaches its maximum efficiency threshold. In comparison, Mexico has a lower proportion of localized irrigation area within its baseline year, therefore the implementation of either scenario SC1 or SC2 will have a greater effect on improving agricultural water withdrawal as previously irrigation efficiency was low.

Figure 18a. Changes in freshwater withdrawal from improved irrigation technology in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios include BAU, 10% increase in localized irrigation area or low technology ambition (SC1), and 30% increase in localized irrigation area or high technology ambition (SC2).

Figure 18b. Changes in freshwater withdrawal from improved irrigation technology in Mexico, 2020-2050

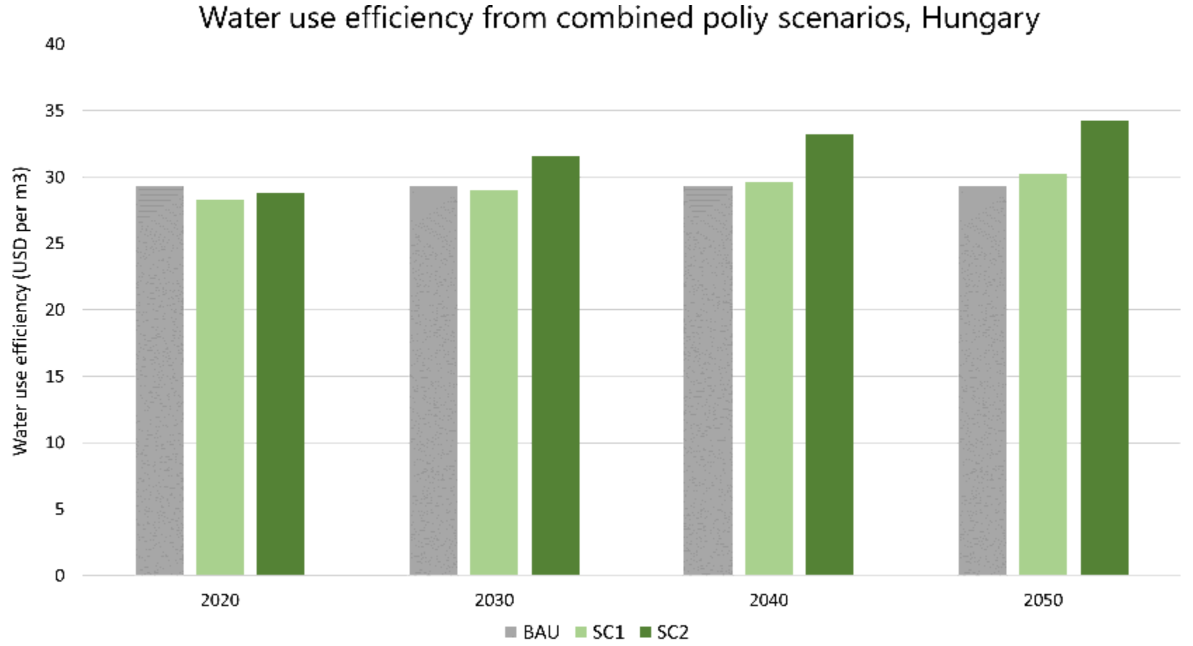


Note: Baseline year is 2017. Scenarios include BAU, 10% increase in localized irrigation area or low technology ambition (SC1), and 30% increase in localized irrigation area or high technology ambition (SC2).

4.2.3 Changes in water use efficiency and freshwater withdrawals from combined policy scenarios

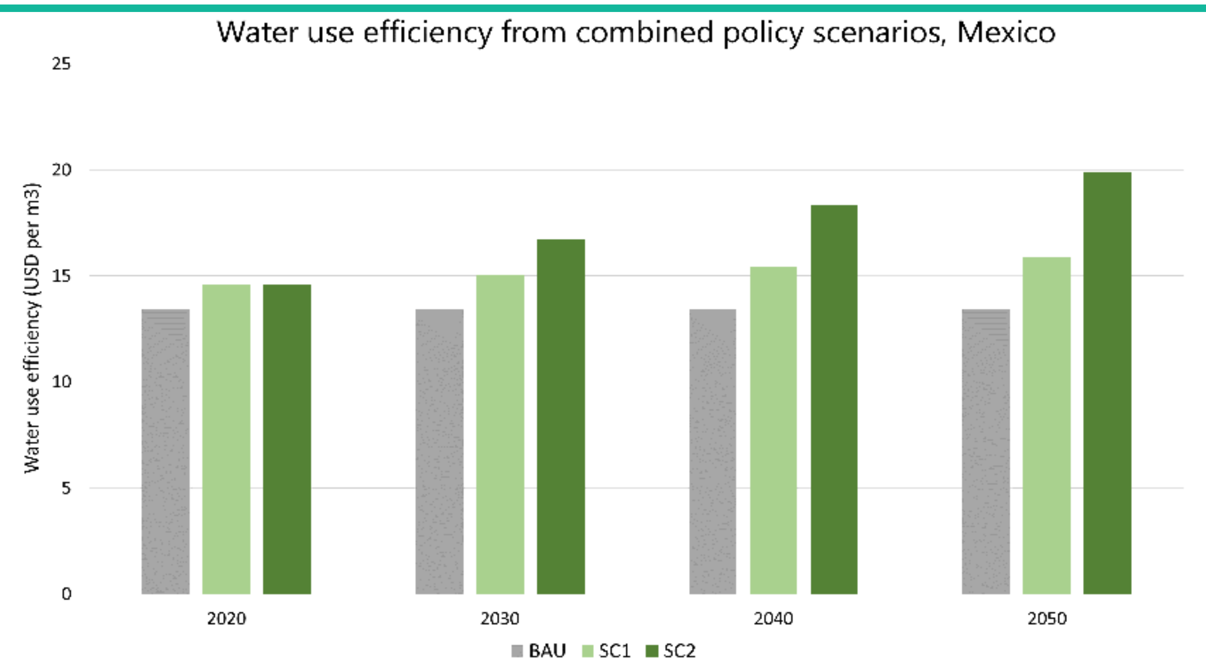
A combination of sectoral policies was also conducted to see the influence on both water use efficiency (EW1) and share of freshwater withdrawal to available water resources (EW2), which can be defined as low-moderate irrigation and water price (SC1) versus implementing the most ambitious irrigation policy and high water price (SC2). Under SC2, Hungary and Mexico both show that water use efficiency will improve by 2050, by approximately $5 USD per m^3 for each country (Figure 19a and b). However, the implementation of the SC1 scenario results in only small improvements in this indicator, moving only by a total value of $1 USD per m^3 over the whole simulated time horizon.

Figure 19a. Changes in water use efficiency from increase water price and improved irrigation technology in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios include BAU, 5% increase in water price and 10% increase in localized irrigation area (SC1), and 20% increase in water price and 30% increase in localized irrigation area (SC2).

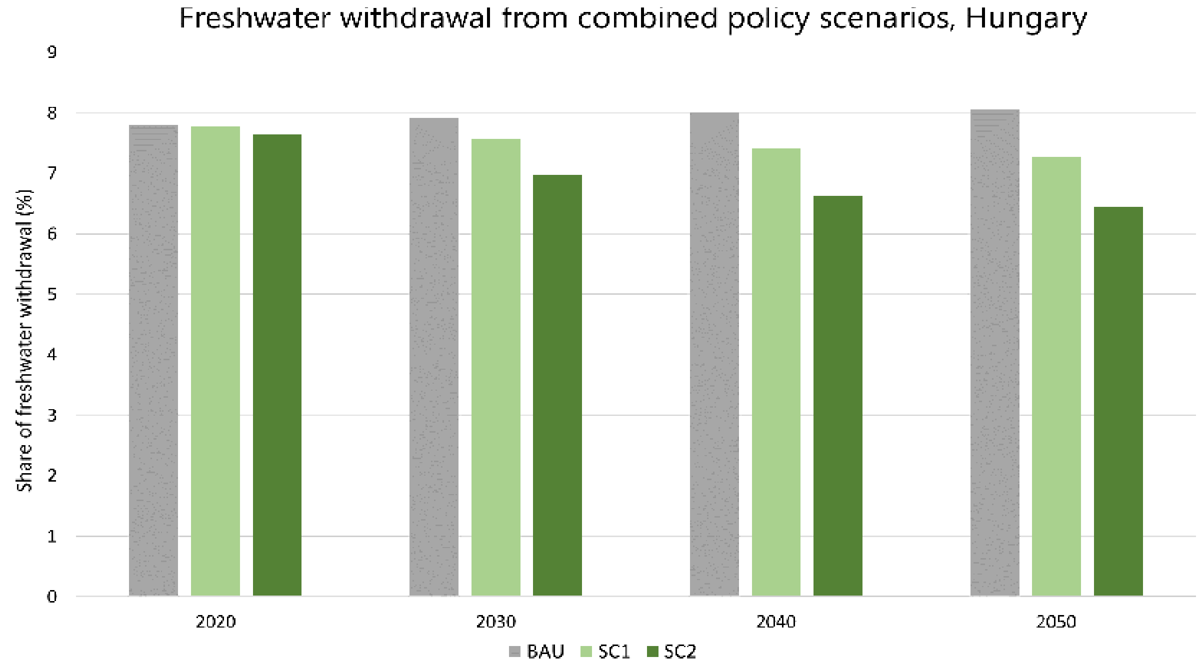
Figure 19b Changes in water use efficiency from increase water price and improved irrigation technology in Mexico, 2020-2050



Note: Baseline year is 2017. Scenarios include BAU, 5% increase in water price and 10% increase in localized irrigation area (SC1), and 20% increase in water price and 30% increase in localized irrigation area (SC2).

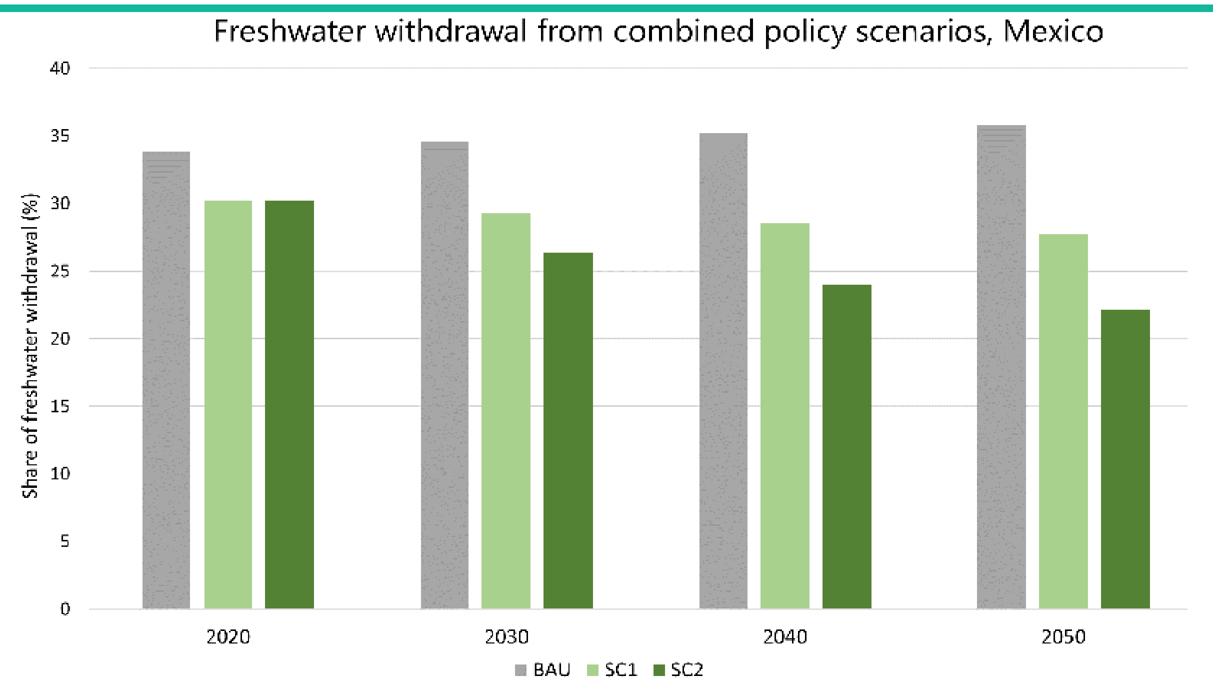
Figure 20a and b show the impacts of combining both agricultural and municipal water policies on the share of freshwater withdrawal to available water resources (EW2). Under the SC2 scenario, freshwater withdrawal moves from 7.8% in 2020 to just below 6.7% by 2050, indicating an improvement in water stress for Hungary (Figure 20a). Greater improvements in water stress are observed for Mexico under this scenario as freshwater withdrawal was 30% in 2020, falling to 23% by 2050 (Figure 20b), resulting in a 7% overall decrease and Mexico achieving the sustainability target for freshwater withdrawal (i.e., no water stress) by 2040. Looking at the SC1 scenario, Hungary only falls to 7.4% by 2050. This suggests that this combination of policy measures has a very small impact on improving the freshwater management in the country. Although it should be noted that Hungary's performance in the share of freshwater withdrawal from 2020 to 2050 under all scenarios still results in the country classifying as low water stress. Mexico does not show an increase in water stress under SC1, although only a smaller improvement in the indicator score is observed moving from 30% in 2020 to 26% by 2050.

Figure 20a. Changes in freshwater withdrawal from increase water price and improved irrigation technology in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios include BAU, 5% increase in water price and 10% increase in localized irrigation area (SC1), and 20% increase in water price and 30% increase in localized irrigation area (SC2).

Figure 20b. Changes in freshwater withdrawal from increase water price and improved irrigation technology in Mexico, 2020-2050



Note: Baseline year is 2017. Scenarios include BAU, 5% increase in water price and 10% increase in localized irrigation area (SC1), and 20% increase in water price and 30% increase in localized irrigation area (SC2).

4.3. Land use in Hungary and Uganda

For the Phase 1 application of the Simulation Tool, the land use model was used to assess the impacts of changes in food demand on sustainable land use including the indicators on soil nutrient budget and agricultural land use (Table 8), GHG emissions (Table 14), and forest area (Table 16). Two sets of scenarios were developed for both Hungary and Uganda. The first set of scenarios, which was applied to determine the impacts on soil nutrient budget, includes BAU, where there is no reduction in food waste and demand, reduction in food waste by 25% and food consumption per capita by 10% by 2050 (SC1), and reduction in food waste by 50% and food consumption per capita by 20% by 2050 (SC2). The second set of scenarios, which assesses the impacts on non-CO_2 emissions, assumes that in addition to the reduction in food waste and demand, agricultural lands that were freed up from reduction in food demand were converted to forest lands. The other set of scenarios includes BAU where there is no reduction in food waste and demand as well as no conversion from agricultural to forest lands, reduction in food waste by 25% and food consumption per capita by 10% as well as conversion of 20% freed-up agricultural lands to forests (SC1), and reduction in food waste by 50% and food consumption per capita by 20% as well as conversion of 30% freed-up agricultural lands to forests (SC2).

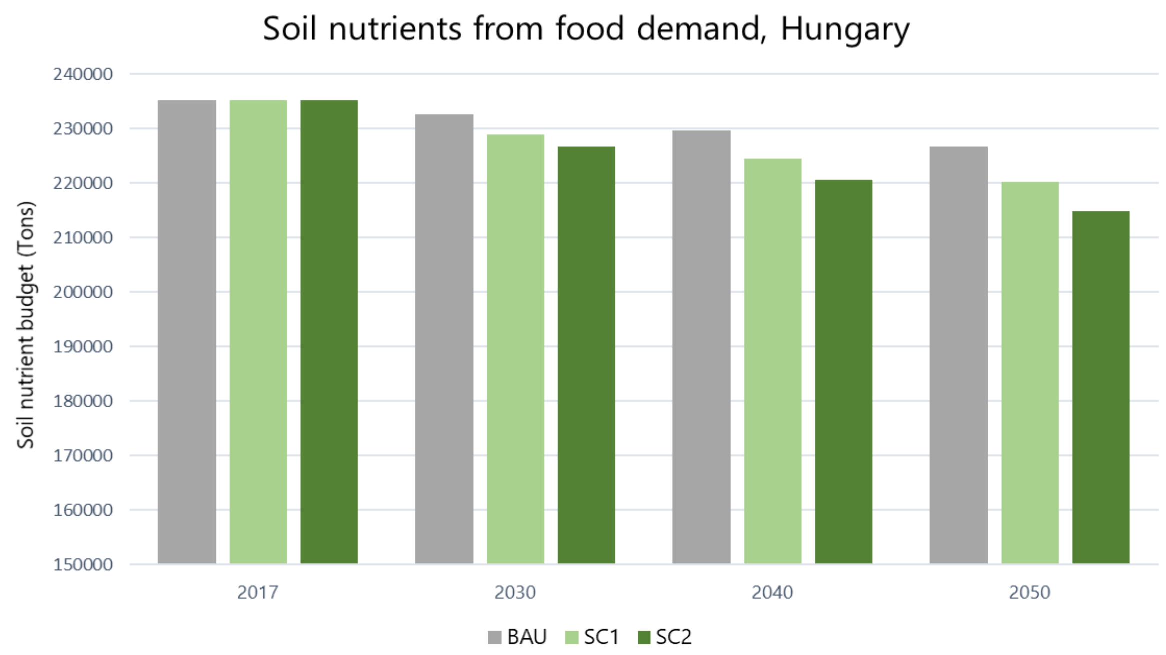
The assumptions made for the scenarios on the land use models are as follows:

- First, for both Hungary and Uganda, the total population projections from FAOSTAT were used as the main driver of a change in food demand for each food group. Other types of demand, such as non-food or seed production, were assumed constant over the years. Other parameters, such as the fertilizer use per hectare, emission factors, or the ratio of production animals to the total animal population, were also assumed constant for each country.
- Secondly, changes in forest area were assumed to be directly related to a change in the cropland demand and a reforestation rate. Also, the crop yields used to compute the total cropland demand for each crop type were assumed constant over the years. Factors such as technological change, which could increase the crop yields, were not yet considered in the first phase of the model.
- The model computes the non-CO_2 emissions for three types of manure, enteric fermentation, fertilizer use, and land-use change. While these are generally the most important emission groups in the agricultural sector, it should be noted that other emission groups such as emissions from rice cultivation or the burning of crop residues were not modelled and kept constant throughout the years.

4.3.1 Changes in soil nutrient budget due to reduction in food waste and demand

The soil nutrient budget is related to the fertilizer use per crop, consumption of crop-based food stuff, and animal manure application to soils. Figure 21 shows the results of the three scenarios on soil nutrient budget (SL1) for Hungary and Uganda. Hungary shows a decreasing soil nutrient balance for all three scenarios up to 2050 (Figure 21a). As the population of Hungary is declining, this will cause lower food demand, which will consequently lead to a lower fertilizer and manure application. When policies are made to reduce food waste and food consumption, this decreasing trend will continue. On the other hand, Uganda's population is expected to more than double in size in 2050. This will lead to an increase in food demand which will negatively affect the soil nutrient budget (Figure 21b). Even though fertilizer and manure application will increase the nutrients added to soils, there will be an overall decrease in the nutrient budget as the increase in crops harvested is much bigger. In this case, food waste and consumption reducing policies will cause the food demand to decrease, which will cause the nutrient budget to increase relative to the BAU scenario.

Figure 21a. Changes in soil nutrient budget from food waste and demand reduction in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios are BAU, reduction in food waste by 25% and food consumption per capita by 10% (SC1), and reduction in food waste by 50% and food consumption per capita by 20% (SC2).

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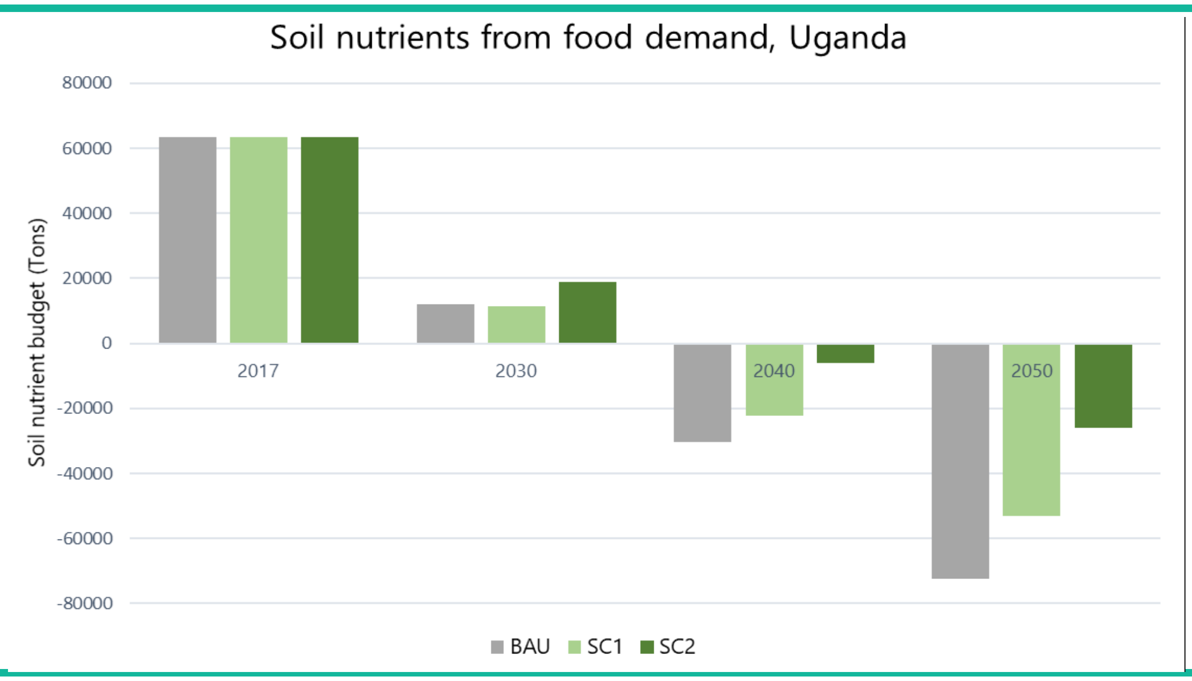
Figure 21b. Changes in soil nutrient budget from food waste and demand reduction in Uganda, 2020-2050

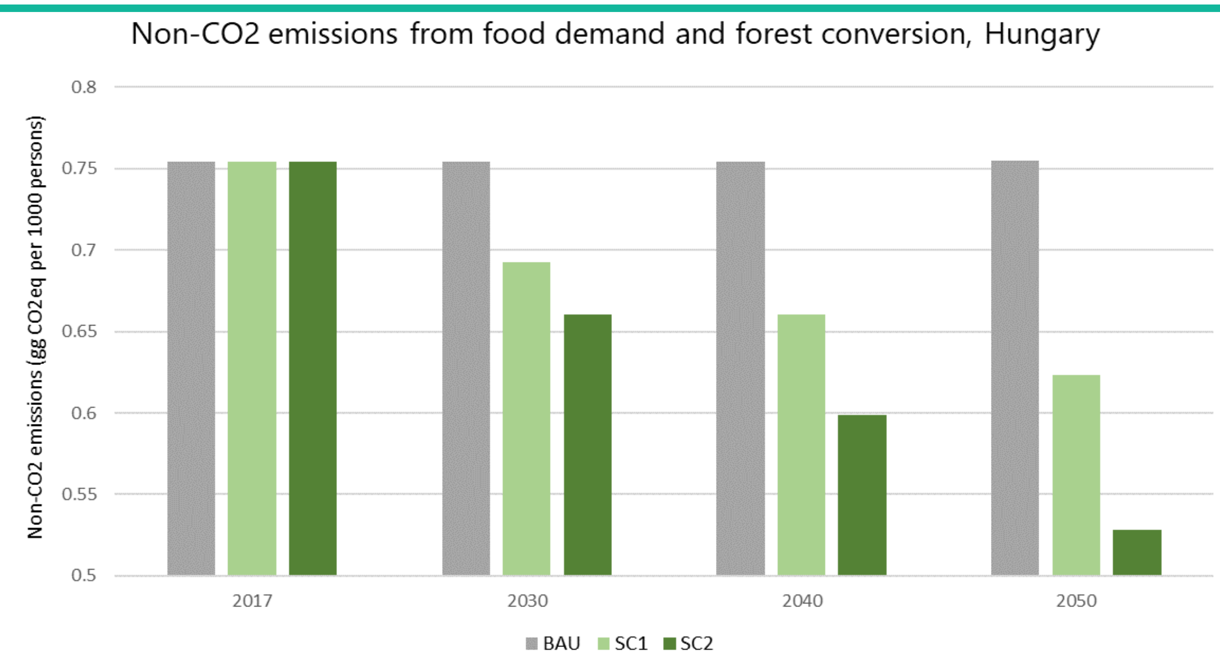


Note: Baseline year is 2017. Scenarios are BAU, reduction in food waste by 25% and food consumption per capita by 10% (SC1), and reduction in food waste by 50% and food consumption per capita by 20% (SC2).

4.3.2 Changes in non-CO_2 emissions due to reduction in food waste, food demand, and reforestation

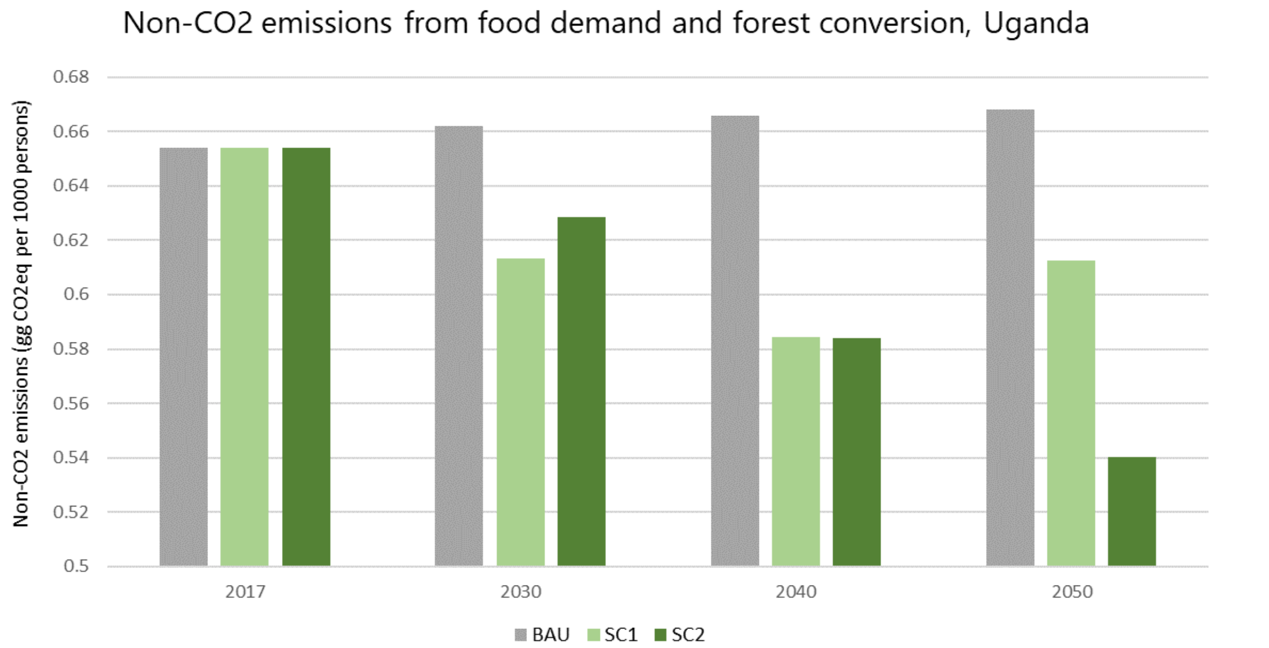
Figure 22a and b show the changes in non-CO_2 emissions (GE3) in Hungary and Uganda for the three scenarios. The changes in the BAU scenario are relatively constant for both countries. The scenario on 25% reduction in food waste, 10% reduction in food demand, and 20% conversion to forest (SC1) causes a decreasing trend in non-CO_2 for Hungary (Figure 22a) and shows a decline until 2040 and increase in 2050 in Uganda (Figure 22b). A possible explanation for this increase in 2050 could be that the population increase is flattening. The scenario on 25% reduction in food waste, 20% reduction in food demand, and 30% conversion to forest (SC2) shows a decreasing trend across the years for both countries. In Hungary, the consistent decline in non-CO_2 emissions for both SC1 and SC2 scenarios can be mainly attributed to the decrease in food demand and waste. In Uganda, this decrease is at least partly caused by the strong increase in population, which causes emissions per capita to decrease, even though the total emissions are increasing.

Figure 22a. Changes in Non-CO_2 emissions from reduction in food demand and conversion into forests in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios are BAU, reduction in food waste and consumption per capita by 25% and 10%, respectively, and conversion of 20% freed-up agricultural lands to forests (SC1), and reduction in food waste and consumption per capita by 50% and 20%, respectively, and conversion of 30% freed-up agricultural lands to forests (SC2).

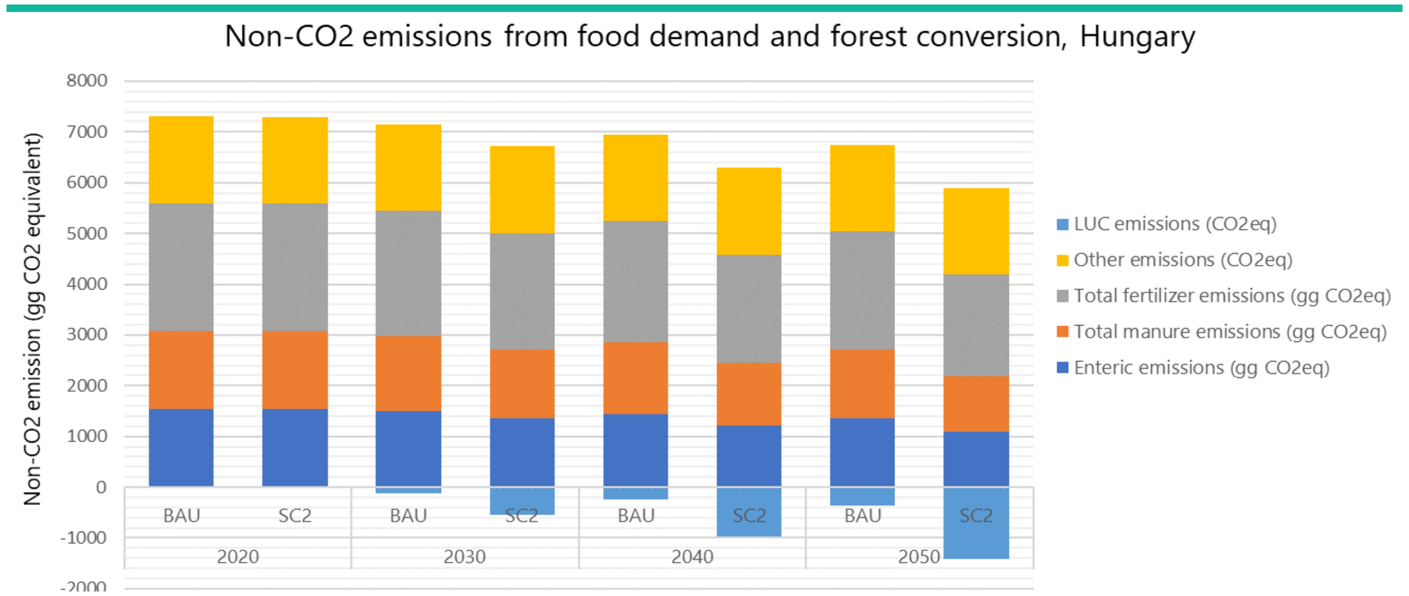
Figure 22b. Changes in Non-CO_2 emissions from reduction in food demand and conversion into forests in Uganda, 2020-2050



Note: Baseline year is 2017. Scenarios are BAU, reduction in food waste and consumption per capita by 25% and 10%, respectively, and conversion of 20% freed-up agricultural lands to forests (SC1), and reduction in food waste and consumption per capita by 50% and 20%, respectively, and conversion of 30% freed-up agricultural lands to forests (SC2).

Figure 23a and b show the changes in non-CO_2 emissions for different sources of emissions from the agriculture sector. The results for Hungary show a decreasing trend in agricultural and land use change (LUC) emissions for both BAU and SC2 scenarios (Figure 23a). As the population is decreasing, and some of the newly available agricultural land is converted to forest area in the SC2 scenario, there will be a net update in emissions stemming from land. This is most visible in 2050 for the SC2 scenario, where land use change emissions decrease with 1432 gg CO_2eq. Overall, the emissions stemming from the agricultural sector and LUC decrease with 12.8% in the BAU scenario and with 39% in the SC2 scenario in Hungary. Interestingly, Uganda has positive LUC emissions in both scenarios (Figure 23b). The total agricultural and LUC emissions increase in 2050 by 122.0% and 79.5% for BAU and SC2 scenarios, respectively. Especially emissions from enteric processes and the application of manure to soils will increase. Additionally, due to the growing population levels, no land is available for reforestation, which could mitigate part of the agricultural emissions.

Figure 23a. Changes in Non-CO_2 emissions from reduction in food demand and conversion into forests by source of emissions in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios are BAU, reduction in food waste and consumption per capita by 25% and 10%, respectively, and conversion of 20% freed-up agricultural lands to forests (SC1), and reduction in food waste and consumption per capita by 50% and 20%, respectively, and conversion of 30% freed-up agricultural lands to forests (SC2).

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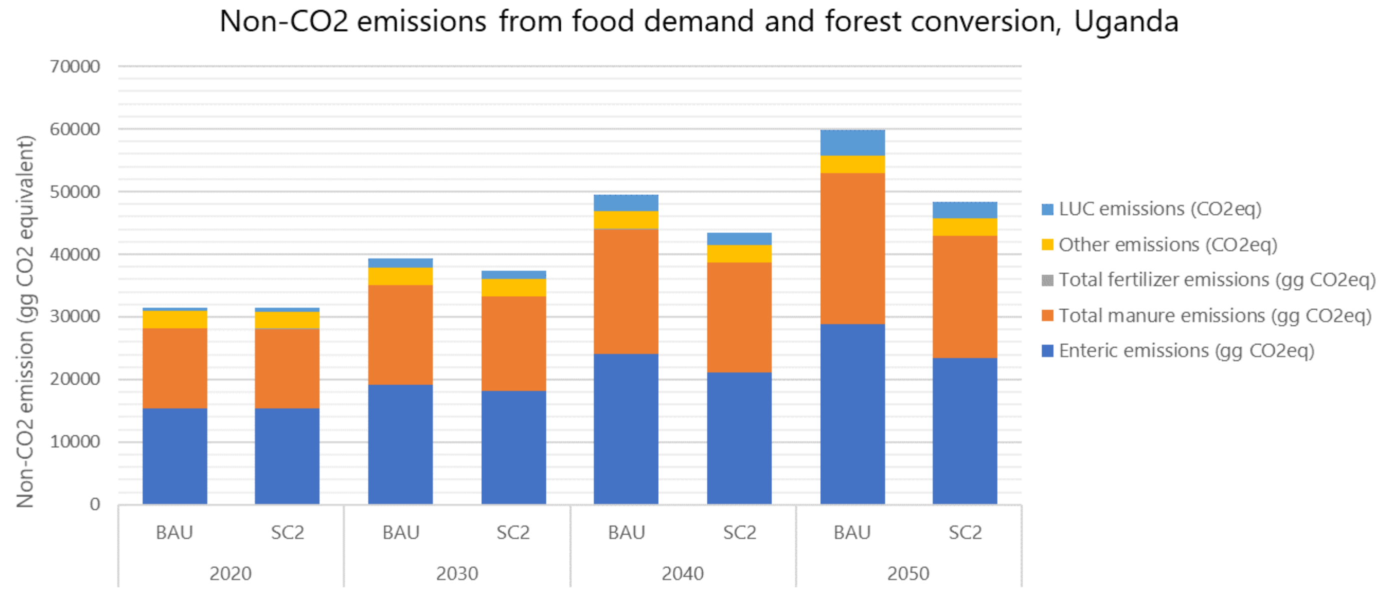
Figure 23b. Changes in Non-CO_2 emissions from reduction in food demand and conversion into forests by source of emissions in Uganda, 2020-2050

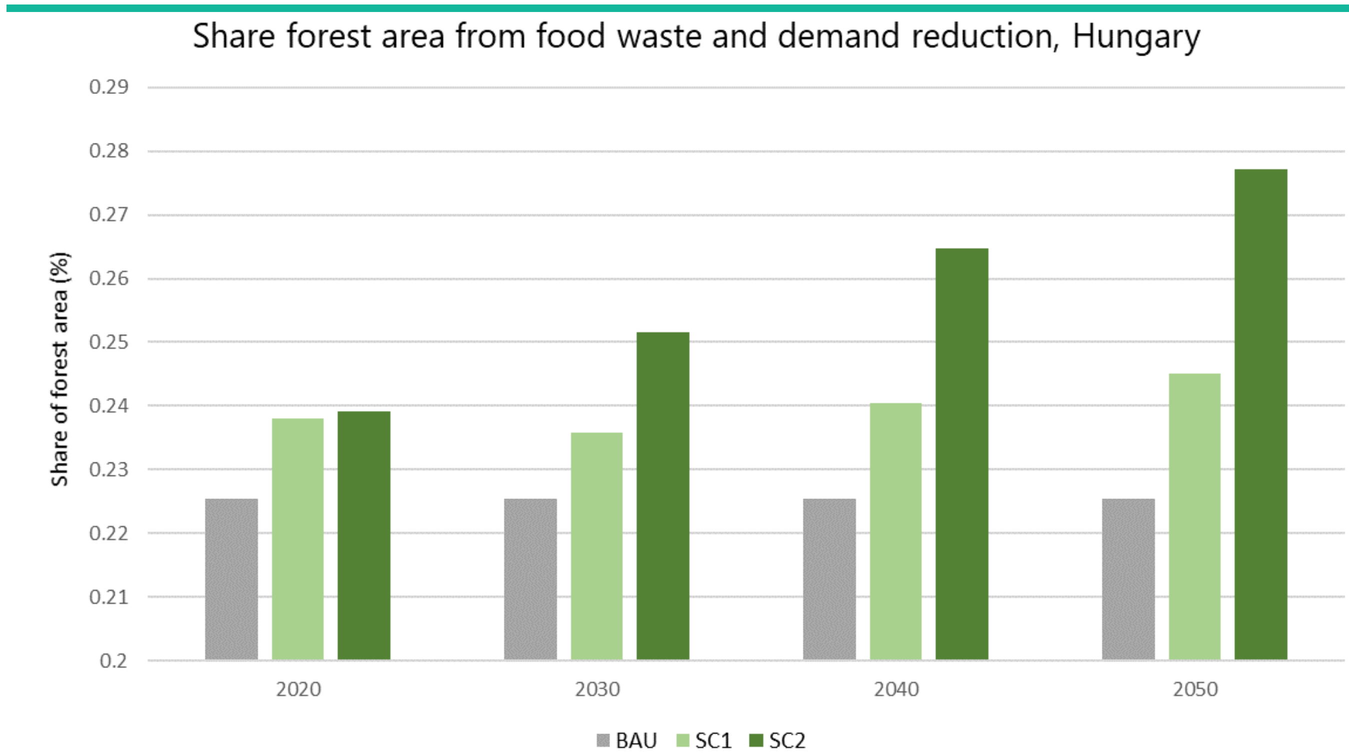


Note: Baseline year is 2017. Scenarios are BAU, reduction in food waste and consumption per capita by 25% and 10% , respectively, and conversion of 20% freed-up agricultural lands to forests (SC1), and reduction in food waste and consumption per capita by 50% and 20%, respectively, and conversion of 30% freed-up agricultural lands to forests (SC2).

4.3.3 Changes in share of forest area to total land area due to reduction in food waste and demand

The impacts of the scenarios on the indicator on the share of forest to total land area (BE2) were also computed (Figure 24). Because Uganda did not have any agricultural land available for reforestation in any of the scenarios (due to increase in population), no changes on this indicator has been identified for this country. In Hungary, the share of forest area to total land area increases by 6.5% and 9.7% for SC1 and SC2 scenarios in 2050, respectively.

Figure 24. Changes in share in forest area to total land area from reduction in food waste and demand in Hungary, 2020-2050



Note: Baseline year is 2017. Scenarios are BAU, reduction in food waste and consumption per capita by 25% and 10%, respectively, and conversion of 20% freed-up agricultural lands to forests (SC1), and reduction in food waste and consumption per capita by 50% and 20%, respectively, and conversion of 30% freed-up agricultural lands to forests (SC2).

5.1. Limitations

5.1.1 Availability of data

The application of many models identified for the Simulation Tool was challenged by data availability. The mathematical models applied for the Phase 1 of the Simulation Tool were limited to those which were available from online databases or previous studies. In some cases, the availability of global data for conducting regression analysis also posed challenges in developing the models for indicators which have not been closely investigated in the past, particularly those for green economic opportunities, social equity, and social protection. Modelling the indicators on biodiversity and ecosystem largely relies on GIS maps, which are not readily available online. The inclusion of GIS maps will allow the development of spatial dynamics in the Tool. In the development of the Phase 2 Simulation Tool, an important step will be to identify the data availability to implement the models identified in Phase 1.

5.1.2 Absence of models

Because green growth is a relatively new concept and many of the indicators have not been widely used, it was difficult to find appropriate models for those indicators. This is particularly true for indicators on green economic opportunities. Moreover, many economic and social indicators were modelled using highly disaggregated data or bottom-up approaches (e.g., sectoral input-output, agent behavior, etc.). Such models are not appropriate for a simulation tool such as the one being developed for the Green Growth Index, which requires models for 36 indicators and interlinked models for these indicators. It is expected that more indicators will be included in the Index as more relevant data become available for the SDGs. The Simulation Tool is also envisaged to function as an online tool, thus, it should have the capacity to run and generate results in less than a minute. It is thus important to find a balance between the complexity and functionality of the models.

5.1.3 Integration of models

Developing the model interlinkages between the indicators across dimensions is a challenging scientific task, but indispensable for conducting co-benefits analysis of policy and investment measures. While the green growth indicators were selected based on the established concepts (i.e., low carbon economy, resilient society, ecosystem health, and inclusive growth), many of their interlinkages have not been well investigated yet. Ecosystem health and low carbon economy are so far the foci of many studies in recent years, particularly on renewable energy and land use, and their links to GHG emissions, green employment, and green investment. While many models on the indicators' impacts on emissions are well studied and documented, those on employment and investment have only received attention in recent years. Many models for the latter are so far heavily dependent on theoretical assumptions, firm- or project-based data, and expert judgement. The applications of such models will affect the comparability of the simulation results across countries. The models for the indicators on resilient society are usually implemented at the local or community contexts, which use survey data. Identifying interlinkages are most challenging for inclusive growth because this concept has not been the focus of model and scenario development, at least not for the social inclusion and green economic opportunities indicators in the Green Growth Index. The development of model interlinkages for these indicators in the Phase 2 Simulation Tool will thus rely on expert consultations.

5.1.4 Applicability of models

An important application of the Simulation Tool will be to identify the impacts of policy and investment measures on the global scores and regional ranks of countries, which measure the changes in country performance in the Green Growth Index. Downscaling the global models and upscaling national models to regional contexts are two challenges in developing the models for the Simulation Tool. Many models were applied at the national level and the parameters were estimated based on the country's social, economic, and environmental contexts. While these maybe relevant for many social inclusion indicators, it could be less appropriate for natural capital protection for which the improvement on indicators require transboundary agreements. These include, for example, indicators on biodiversity and protected areas. Few other indicators are also based on global trade, which need to be considered to provide consistencies in the interlinkages of the indicators. These include for example, energy supply (EE1) and renewable consumption (EE2), domestic material consumption (ME1) and material footprint (ME2), and agricultural production and food demand (SL1, SL2). While the issue on transboundary indicators can be addressed by including global or regional spatial maps, that on global trade will be more challenging because of the complexity of global trade models, which cannot be easily integrated in an online simulation tool.

5.2. Steps for Phase 2

5.2.1 Data inventory

The first task for the application of the Phase 2 Simulation Tool will be to identify sources and collect data for the models which were already identified during the Phase 1. Three types of data will be collected:

- Input variables – Data will be collected from national statistical agencies.
- Input parameters – If data are not available from literature, they will be estimated using statistical analysis. Time-series data for the analysis will be collected from national statistical agencies or international organizations' online databases.
- Input scenarios – Data will be policy and investment scenarios, which will be identified in collaboration with the government partners.

Data collection will continue after scenario building because, depending on the scenarios identified for the Simulation Tool, new models will have to be developed to implement these scenarios.

5.2.2 Scenario building

Building scenarios for the Simulation Tool will require series of stakeholder dialogues with the policymakers and experts to identify input scenarios. The types of scenarios will depend on the objectives of applying the Simulation Tool, which are to assess, for example, performance in the Green Growth Index, impacts of LEDS and NDC targets, etc. These scenarios will include policy and investment options for sectors, economic and demographic development, and climate change impacts. Building scenarios through a participatory approach will allow the policymakers and experts from different agencies to agree on the assumptions not only on the scenarios but also on the model inputs. For example, for some input parameters, which data are not available from literature or cannot be estimated due to lack of time-series data, the values can also be identified from stakeholder dialogues. Finally, the dialogues will facilitate communication of the model uncertainties to and transfer of knowledge on the use of the Simulation Tool by the policymakers.

5.2.3 Model improvements

The data and knowledge collected from data inventory and scenario building will be important for further improving the models in the Simulation Tool. The model improvements will include the following activities:

- Inclusion of models identified but not applied in Phase 1 due to lack of data;
- Addition of spatial dynamics in the Simulation Tool by using GIS data for indicators of land use and natural capital protection;
- Identification and addition of new models that are necessary to implement the scenarios identified from stakeholder dialogues;
- Development of models from regression analysis with time-series data collected from national agencies; and
- Creation of interlinkages between existing and new models as well as models between indicators that have been identified to achieve the objective of applying the Simulation Tool.

5.3 Link to the Green Growth Index

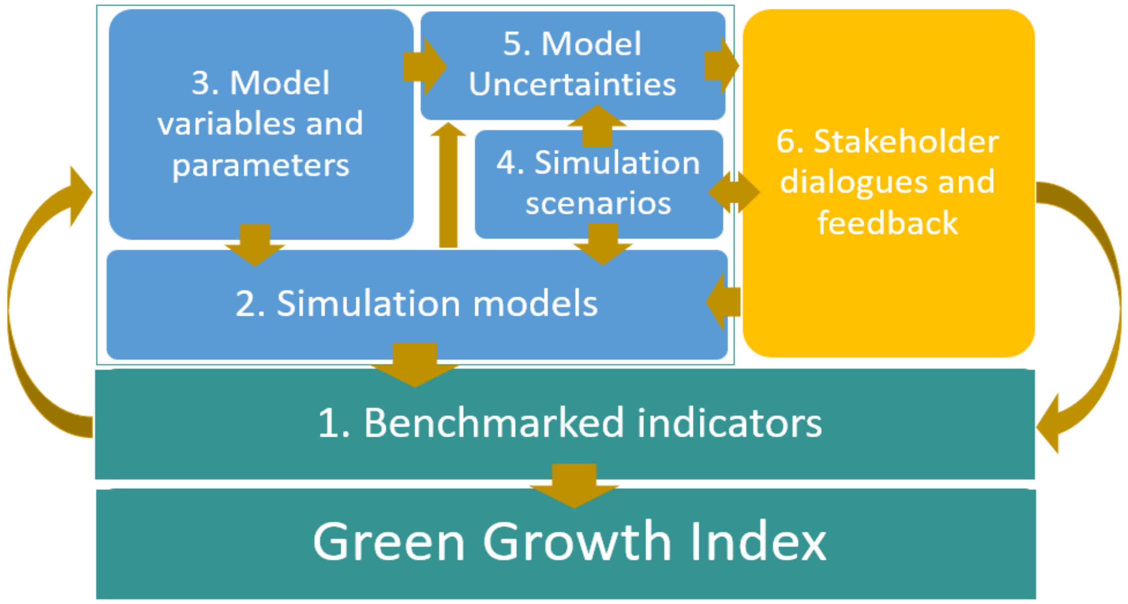
To sum up this report, the main components of the Simulation Tool are as follows:

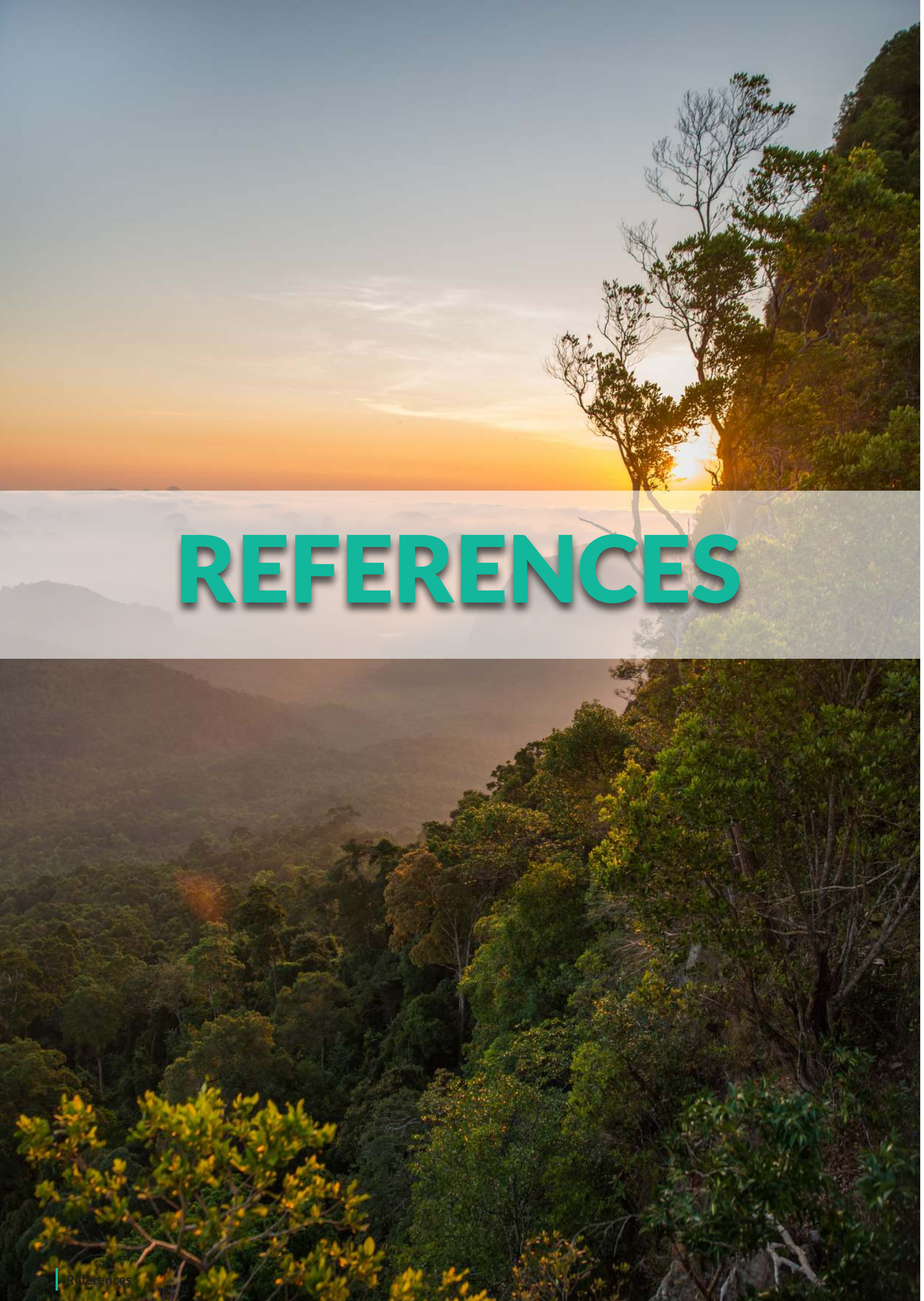
- **Benchmarked indicators**, which are normalized dataset with values ranging from 1 to 100, that measures the distance to sustainability targets and is used in the aggregation of the Green Growth Index;
- **Simulation models**, which are mathematical equations that express the relationship of the green growth indicators to given policies and/or investments;
- **Model variables and parameters**, which are inputs to the equations to measure the relationship between the green growth indicators and policy/investment parameters and simulate changes on the green growth indicators and Index;
- **Simulation scenarios**, which are a set of feasible alternative policy objectives (e.g., implement carbon tax) and/or investment strategies (e.g., invest on renewables) that a country plans to implement to achieve green growth and sustainability targets;
- **Model uncertainties**, which are factors that will affect the policy and investment outcomes including stochastic (unpredictable dynamics and out of human control), scientific (lack of information and data), and epistemic (political and societal preferences); and
- **Stakeholder feedback**, which are both qualitative and quantitative information that are used to appraise and validate the scientific robustness, policy relevance, and uncertainty limits of the Simulation Tool.

Figure 25 presents how the different outputs are linked to each other in assessing the impacts of feasible alternative policies and investments on the Green Growth Index. The model parameters and simulation scenarios will be necessary inputs to the simulation models, which will generate changes in the benchmarked indicators resulting from the policy and investment scenarios. The benchmarked green growth indicators create the link between the Simulation Tool and Green Growth Index. The Simulation Tool will generate changes on the baseline values of these indicators resulting from the simulation scenarios. The values are measured on the units of the respective indicators, as presented in Figure 3. These simulated values of the green growth indicators will be normalized and used to compute the Green Growth Index. The normalized green growth indicators are referred to as benchmarked indicators because in the normalization, they are benchmarked against sustainability indicators (Acosta et al., 2019). It is important to note here that the normalization takes the minimum and maximum values of the global datasets and used global sustainability targets. Only by embedding the results of the Simulation Tool to the methods of the Green Growth Index will make possible the assessment of the improvement in country performance due to policy and investment measures.

Finally, uncertainties are inevitable at the different levels of model applications. These uncertainties will need to be identified and communicated to the stakeholders to facilitate the development of participatory scenarios and more informed assessment of the impacts on performance in green growth indicators.

Figure 25. Link of the Simulation Tool to the Green Growth Index





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APPENDIX 1

ONLINE TOOLS REVIEWED FOR THE GREEN GROWTH SIMULATION TOOL

Code	Name of online tool	Developer/Publisher	Website
T1	EUCalc	Potsdam Institute for Climate Impact Research	http://www.european-calculator.eu/
T2	Aqueduct	World Resources Institute	https://www.wri.org/aqueduct#aqueduct-tools
T3	Water Scarcity Atlas – Futures Tool	Water & Development Research Group – Aalto University and Water Program – International Institute for Applied Systems Analysis	https://waterscarcityatlas.org/
T4	Water Risk Filter	World Wildlife Fund	https://waterriskfilter.panda.org/
T5	The Global Calculator	United Kingdom Department of Energy & Climate Change	https://tool.globalcalculator.org/
T6	Belgium 2050 Calcu-lator	Belgian Federal Climate Change Section of the Federal Public Service Health, Food Chain Safety and Environment	https://klimaat.be/2050-nl/expert-tool
T7	InVEST	Stanford University	https://naturalcapitalproject.stanford.edu/software/invest
T8	SIGI Policy Simulator	Organization for Economic Co-operation and Development	https://sim.oecd.org/Default.ashx?lang=En&ds=SIGI
T9	ADePT Social Pro-tection	World Bank	http://surveys.worldbank.org/adept
T10	EN-ROADS	Climate Interactive	https://en-roads.climateinteractive.org/scenario.html?v=2.7.19
T11	MAMS	World Bank	https://www.worldbank.org/en/research/brief/MAMS
T12	iSDG	Millenium Institute	https://www.millennium-institute.org/isdg
T13	Climate Action Im-pact Tool	United Nations Development Programme	https://climateimpact.undp.org/#!/toolbar/side/as-sess-impact
T14	Mitigation Action Assessment Protocol	World Bank	https://maap.worldbank.org/#/homepage
T15	Data Integration Model for Air Quality	World Health Organization	https://www.who.int/airpollution/data/modelled-esti-mates/en/
T16	EnergyPATHWAYS	Energy and Environmental Economics and Evolved Energy Research	https://usddpp.org/energypathways/
T17	EnergyNumbers-Bal-ancing	University College London Energy Insti-tute	https://wiki.openmod-initiative.org/wiki/EnergyNum-bers-Balancing
T18	LEAP	Stockholm Environment Institute	https://leap.sei.org/default.asp
T19	PRIMES Model	E3MLab	https://ec.europa.eu/clima/policies/strategies/analysis/models_en#:~:text=PRIMES,each%20of%20its%20Member%20States.
T20	SIMPACTS	International Atomic Energy Agency	https://www.iaea.org/OurWork/ST/NE/Pess/PESSen-ergymodels.shtml
T21	BenMAP-CE	United States Environmental Protection Agency	https://www.epa.gov/benmap
T22	Japan Low Carbon Navigator	Institute for Global Environmental Strat-egies	http://www.en-2050-low-carbon-navi.jp/
T23	IMAGE 3.0	PBL Netherlands Environmental Assess-ment Agency	https://models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation

Code	Name of online tool	Developer/Publisher	Website
T24	Global CLEWS Model	United Nations Development Programme	https://unite.un.org/sites/unite.un.org/files/app-global-clews-v-1-0/landingpage.html
T25	SimuED	United Nations Educational, Scientific and Cultural Organization	https://en.unesco.org/news/unesco-launches-new-simulation-model-education
T26	OnSSET	Division of Energy Systems – KTH Royal Institute of Technology	http://www.onsset.org/get-started.html
T27	Energy Transition Model	Quintel Intelligence	https://energytransitionmodel.com/
T28	World Energy Model	International Energy Agency	https://www.iea.org/reports/world-energy-model
T29	GAINS-Europe	International Institute for Applied Systems Analysis	https://gains.iiasa.ac.at/models/gains_models3.html
T30	POLES	Enerdata	https://www.enerdata.net/solutions/poles-model.html
T31	Energy Policy Simulator	Energy Innovation: Policy and Technology LLC	https://www.energypolicy.solutions/
T32	Eco-Innovation Index	European Commission	https://ec.europa.eu/environment/ecoap/indicators/index_en
T33	Global Biodiversity Score	Mission Économie de la Biodiversité	http://www.mission-economie-biodiversite.com/wp-content/uploads/2019/05/N14-TRAVAUX-DU-CLUB-B4B-GBS-UK-WEB.pdf
T34	WASP8	United States Environmental Protection Agency	https://www.epa.gov/ceam/wasp8-download#download
T35	MOVES	United States Environmental Protection Agency	https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves#download
T36	EnviroAtlas	United States Environmental Protection Agency	https://www.epa.gov/enviroatlas
T37	EU Resource Efficiency Scoreboard	European Commission	https://ec.europa.eu/eurostat/web/europe-2020-indicators/scoreboard
T38	STAR Metric	International Union for Conservation of Nature	https://www.iucn.org/regions/washington-dc-office/our-work/species-threat-abatement-and-recovery-star-metric
T39	REST	United Nations Economic and Social Commission for Asia and the Pacific	https://sdghelpdesk.unescap.org/re/index.html
T40	BPT	Solagro	https://bpt.biodiversity-performance.eu/login
T41	Bioscore 1	European Centre for Nature Conservation	https://www.synbiosys.alterra.nl/bioscore/
T42	FREEWAT	European Commission	http://www.freewat.eu/
T43	Air Q+	World Health Organization Regional Office for Europe	https://www.euro.who.int/en/health-topics/environment-and-health/air-quality/activities/airq-software-tool-for-health-risk-assessment-of-air-pollution
T44	GHG Calculator for Solid Waste	Institute for Global Environmental Strategies	https://www.iges.or.jp/en/pub/ghg-calculator-solid-waste-ver-ii-2013/en
T45	GREET	Argonne National Laboratory	https://greet.es.anl.gov/
T46	Design Our Climate Simulation	The King's Centre for Visualization in Science	https://applets.kcvs.ca/DesignOurClimate/DesignOurClimateSim.html
T47	AIM/SLCP Tool	University of Tokyo	https://www-iam.nies.go.jp/aim/data_tools/S12/S12_en.html
T48	ClimateSim	Science by simulation	https://www.sciencebysimulation.com/climatesim/Simulator.aspx
T49	SimRiver	Tokyo Gakugei University	http://www.u-gakugei.ac.jp/~diatom/en/simriver/index.html
T50	C-ROADS	Climate Interactive	https://croadsworldclimate.climateinteractive.org/
T51	Energy Access Explorer	World Resources Institute	https://www.energyaccessexplorer.org/about/
T52	Greenhouse Gas Emissions Simulator	Massachusetts Institute of Technology	http://scripts.mit.edu/~jsterman/climate/master/

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Code	Name of online tool	Developer/Publisher	Website
T53	Climate Bathtub Simulation	Massachusetts Institute of Technology	https://www.climateinteractive.org/tools/climate-bathtub-simulation/
T54	2050 Energy and Emissions Calculator	United Kingdom Department of Energy & Climate Change	http://2050-calculator-tool.decc.gov.uk/#/guide
T55	I-JEDI	National Renewable Energy Laboratory	https://www.nrel.gov/analysis/jedi/models.html
T56	CLEER	United States Agency for International Development	https://www.cleertool.org/
T57	SWEET	United States Environmental Protection Agency, ABt Associates, and SCS Engineers	https://www.waste.ccacoalition.org/document/solid-waste-emissions-estimation-tool-sweet-version-30
T58	Water Footprint Assessment Tool	Water Footprint Network	https://www.waterfootprint.org/en/resources/interactive-tools/
T59	IPCC Waste Model	Intergovernmental Panel on Climate Change and United Nations Environment Programme	https://www.waste.ccacoalition.org/document/ipcc-waste-model
T60	GCAM	Joint Global Change Research Institute	http://jgcri.github.io/gcam-doc/
T61	EnergyPLAN	Department of Development and Planning –Aarlborg University	https://www.energyplan.eu/training/introduction/
T62	PCR-GLOBWB 2.0	Utrecht University	http://www.globalhydrology.nl/models/pcr-globwb-2-0/
T63	REAP	Stockholm Environment Institute	https://www.sei.org/projects-and-tools/tools/reap-resources-energy-analysis-programme/
T64	WEAP	Stockholm Environment Institute	https://www.sei.org/projects-and-tools/tools/weap/
T65	National Bioenergy Investment Model	Stockholm Environment Institute	https://www.sei.org/projects-and-tools/tools/nbim-national-bioenergy-investment-model/
T66	TRIM3	The Urban Institute	https://boreas.urban.org/T3Welcome.php
T67	REMIND	Potsdam Institute for Climate Impact Research (PIK)	https://www.pik-potsdam.de/research/transformation-pathways/models/remind/remind
T68	ALPS	Climate Interactive	https://www.climateinteractive.org/tools/agriculture-and-land-policy-simulator-alps/
T69	Climate Change Mitigation Simulator	Koshland Science Museum	https://www.koshland-science-museum.org/sites/all/exhibits/mitigationsim/index.html
T70	WARM	United States Environmental Protection Agency	https://www.epa.gov/warm
T71	Product Biodiversity Footprint	Product Biodiversity Footprint	http://www.productbiodiversityfootprint.com/simplified-calculator/
T72	ORCHIDEE	Institute Pierre Simon Laplace	https://orchidee.ipsl.fr/
T73	SOLVES 3.0	United States Geological Survey	https://www.usgs.gov/centers/gecsc/science/social-values-ecosystem-services-solves?qt-science_center_objects=0#qt-science_center_objects
T74	GEMIS	International Institute for Sustainability Analysis and Strategy	http://iinas.org/gemis-download.html
T75	EUREAPA	Stockholm Environment Institute	https://www.sei.org/projects-and-tools/tools/eureapa/
T76	OPAL	Stanford University	https://naturalcapitalproject.stanford.edu/software/opal
T77	ROOT	Stanford University	https://naturalcapitalproject.stanford.edu/software/root
T78	Inclusive Internet Index Simulator	Economist Intelligence Unit	https://theinclusiveinternet.eiu.com/simulator
T79	DICE&RICE	Yale University	http://webdice.rdcep.org/
T80	COBRA	United States Environmental Protection Agency	https://www.epa.gov/statelocalenergy/co-benefits-risk-assessment-cobra-health-impacts-screening-and-mapping-tool
T81	Monash Simple Climate Model	Monash University	http://vera206.its.monash.edu.au/mscm/greb/cgi-bin/scny_i18n.py?scenario=99&variable=01&locale=EN

Code	Name of online tool	Developer/Publisher	Website
T82	Climate Challenge	British Broadcasting Corporation	http://www.bbc.co.uk/sn/hottopics/climatechange/climate_challenge/
T83	Map of Life	Map of Life	https://mol.org/species/projection/landuse/Kobus_megaceros
T84	Freshwater Health Index	Fresh Water Health Index & Conservation International	https://www.freshwaterhealthindex.org/
T85	Natural Environmental Valuation Online (NEVO) tool	Land, environment, Economics and Policy Institute, University of Exeter	https://www.exeter.ac.uk/leep/research/nevo/
T86	ORVAL	Land, environment, Economics and Policy Institute, University of Exeter	https://www.leep.exeter.ac.uk/orval/
T87	Balmorel Lite	Ea Energy Analyses	http://ens.energycalculator.dk/balmorellite.html
T88	FABLE calculator	International Institute for Applied Systems Analysis and Sustainable Development Solutions Network	https://www.abstract-landscapes.com/fable-calculator
T89	Co-click'eau	Institut national de la recherche agronomique	http://coclickeau.webistem.com/bac/index.php?r=site/index
T90	Energy access tool	International Institute for Applied Systems Analysis	https://tntcat.iiasa.ac.at/ENACT/AccessTool.html
T91	ENE-MCA tool	International Institute for Applied Systems Analysis	https://tntcat.iiasa.ac.at/GeaMCA/McaTool.html
T92	Health Insurance Policy Simulation Model	Urban Institute	https://www.urban.org/research/data-methods/data-analysis/quantitative-data-analysis/microsimulation/health-insurance-policy-simulation-model-hipsm
T93	MINT	Urban Institute	https://www.urban.org/research/data-methods/data-analysis/quantitative-data-analysis/microsimulation/model-income-near-term-mint
T94	Dynamic Simulation of Income Model	Urban Institute	https://www.urban.org/research/data-methods/data-analysis/quantitative-data-analysis/microsimulation/dynamic-simulation-income-model-dynasim
T95	Tax Policy Simulation Tool	Urban Institute, Brookings Institute	https://www.urban.org/research/data-methods/data-analysis/quantitative-data-analysis/microsimulation/tax-policy-center-microsimulation-model
T96	Unemployment Insurance Simulation Model	World Bank	http://documents.worldbank.org/curated/en/775321468158985677/Unemployment-Insurance-Simulation-Model-UISIM
T97	PROST	World Bank	https://openknowledge.worldbank.org/handle/10986/11074
T98	ENPEP-BALANCE	Center for Energy, Environmental, and Economic Systems Analysis	https://ceeesa.es.anl.gov/projects/Enpepwin.html
T99	engage	National Renewable Energy Laboratory	https://engage.nrel.gov/en/login/?next=/en/
T100	ELAS	University of Natural Resources and Life Sciences, Vienna	http://www.elas-calculator.eu/?lang=en
T101	Bioenergy simulator	International Renewable Energy Agency	https://irena.masdar.ac.ae/bioenergy/
T102	FISH-e	Food and Agriculture Organization of the United Nations	http://www.fao.org/fishery/affris/affris-home/fish-e-faos-tool-for-quantifying-the-greenhouse-gas-emissions-arising-from-aquaculture/en/
T103	HUGSI	Husqvarna	https://hugsi.green/
T104	Integrated Urban Water Model	Water Research Institute	https://pypi.org/project/iuwm/
T105	RIOS	Rich Sharp	https://pypi.org/project/natcap.rios/
T106	WUDESIM	Massachusetts Institute of Technology	https://pypi.org/project/WUDESIM-Py/
T107	flexiGIS	Deutsches Zentrum für Luft- und Raumfahrt- Institute of Networked Energy Systems	https://github.com/FlexiGIS/FlexiGIS

Code	Name of online tool	Developer/Publisher	Website
T108	Land Use Harmonization	University of Maryland	https://luh.umd.edu/code.shtml
T109	SimClimat	e Cabinet d'Études Informatiques Alain Deseine	http://gama.nicolas.free.fr/parismontagne/climat/
T110	Swiss EnergyScope	École polytechnique fédérale de Lausanne	http://calculator.energyscope.ch/
T111	Witch model	European Institute on Economics and the Environment	https://www.witchmodel.org/simulator/index.php?-modulo=1
T112	Ecopath with Ecosim (EwE)	Ecopath International Initiative	http://ecopath.org/downloads/
T113	STREAM	System Analysis,Technical University of Denmark	https://www.esymodels.man.dtu.dk/stream/model
T114	UK land use calculator	Friends of the Earth	https://policy.friendsoftheearth.uk/insight/uk-land-use-calculator
T115	SWAT (Soil and water assessment tool)	Texas A&M University	https://swat.tamu.edu/
T116	GLEAM-i (Global Livestock Environmental Assessment Model)	Food and Agriculture Organization of the United Nations	http://gleami.org/
T117	Co$ting Nature	King's College London	http://www.policysupport.org/costingnature
T118	CMAQ	United States Environmental Protection Agency	https://www.epa.gov/cmaq
T119	Environmental Performance Index	Yale university and Columbia university	https://epi.yale.edu/
T120	MPA size optimization tool	The Capturing Coral Reef & Related Ecosystem Services (CCRES) project	https://ccres.net/resources/ccres-tool/mpa-size-optimization-tool
T121	CTI 2050 roadmap Tool	European Climate Foundation	https://stakeholder.netzero2050.eu/
T122	Aichi Target 11 Dashboard	Protected Planet	https://www.protectedplanet.net/target-11-dashboard
T123	Green Economy Tracker	Green Economy Coalition	https://greeneconomytracker.org/
T124	RenPass	Sustainable Energy	https://github.com/fraukewiese/renpass
T125	E4ST Fast Predictor	Cornell University and Arizona State University	https://e4st.com/fp/
T126	Climate and Disaster Risk Screening Tools	World Bank	https://climatescreeningtools.worldbank.org/
T127	Diagnostic Tools for Investment (DTI) in water for agriculture and energy (Context tool, Institutional and Policy tool, Financial tool)	Food and Agriculture Organization of the United Nations	http://www.fao.org/land-water/databases-and-software/diagnostic-tools-for-investment/en/
T128	CRANE	Rho AI	https://cranetool.org/
T129	EUCalc: Agriculture & Land-Use Module	Potsdam Institute for Climate Impact Research	http://www.european-calculator.eu/
T130	EUCalc: Carbon Capture, Use and Sequestration Module	Potsdam Institute for Climate Impact Research	http://www.european-calculator.eu/
T131	EUCalc: Biodiversity Module	Potsdam Institute for Climate Impact Research	http://www.european-calculator.eu/

Note: The references from T129 were not included in the assessment of online tools presented in Table 1. These references were identified when developing interlinkages of mathematical models between indicators and acrosss dimensions.

APPENDIX 2

PUBLICATIONS REVIEWED FOR THE GREEN GROWTH SIMULATION TOOL

Code	Year	Author(s)	Publication (Title, Journal name, volume, issue)
A1	2019	Li, X. and Liu, Q.	Simulation Research on the Interaction between Environmental Protection Investment and Economic Growth in China, Natural Hazards, 95
A2	2017	Golzarpoor, H., González, V., et al.	An Input-Output Simulation Model for Assessing Production and Environmental Waste in Construction, Journal of Cleaner Production, 143
A3	2011	Lindskog, E., Lundh, L., et al.	A Method for Determining the Environmental Footprint of Industrial Products using Simulation, Proceedings of the 2011 Winter Simulation Conference, Phoenix, AZ, USA
A4	2010	Ahn, C., Pan, W., et al.	Enhanced Estimation of Air Emissions from Construction Operations based on Discrete-Event Simulation, Proceedings of the International Conference on Computing in Civil and Building Engineering, Nottingham, UK
A5	2018	Marcilio, G.P., de Assis Rangel, J.J., et al.	Analysis of Greenhouse Gas Emission in the Road Freight Transportation using Simulation, Journal of Cleaner Production, 170
A6	2020	Aristizabal, J., Azumendi, D., et al.	Simulation to Predict the Impacts of Public Transport Changes on Air Pollutants Emissions, 2020 4th International Conference on Modelling, Simulation and Applied Mathematics (MSAM)
A7	2006	Anand, S., Vrat, P., et al.	Application of a System Dynamics Approach for Assessment and Mitigation of CO_2 Emissions from the Cement Industry, Journal of Environmental Management, 79
A8	2019	Kuo, T.C., Lin, S., et al.	Biofuels for Vehicles in Taiwan: Using System Dynamics Modeling to Evaluate Government Subsidy Policies, Resources, Conservation & Recycling, 145
A9	2018	Wang, Y., Tong, H., et al.	Green Transformation: A System Dynamics Model on Endowment, Investment and Employment, Working Paper Series of New Structural Economics, No. E2018009
A10	2020	Luo, Y., Mou, Y., et al.	Scenario-Based Planning for a Dynamic Tourism System with Carbon Footprint Analysis: A Case Study of Xingwen Global Geopark, China, 254
A11	2013	Aregay, F.A., Minjuan, Z., et al.	Irrigation Water Pricing Policy for Water Demand and Environmental Management: A Case Study in the Weihe River Basin, 15, 5
A12	2018	Kou, L., Li X., et al.	Simulation of Urban Water Resources in Xiamen Based on a WEAP Model, 10, 6
A13	2017	Aidt, T., Jia, L., et al.	Are Prices Enough? The Economics of Material Demand Reduction, Philosophical Transactions of the Royal Society A, 375
A14	2010	Ahmad, S. and Prashar, D.	Evaluating Municipal Water Conservation Policies Using a Dynamic Simulation Model, Water Resources Management, 24
A15	2019	Li, M., Li, J., et al.	Efficient Allocation of Agricultural Land and Water Resources for Soil Environment using a Mixed Optimization-Simulation Approach under Uncertainty, Geoderma, 353
A16	2017	Mallor, F., Moler, J., et al.	Simulation of Household Electricity Consumption by Using Functional Data Analysis, Journal of Simulation
A17	2012	Meng, C. and Pfau, W.D.	Simulating the Impacts of Cash Transfers on Poverty and School Attendance: The Case of Cambodia, Journal of Family and Economic Issues, 33
A18	2019	Anjum, N. and Daly, A.	The Gender Wage Gap in Bangladesh: An Application of Olsen and Walby Simulation Method, Australian Journal of Labour Economics, 22,1
A19	2012	Filipski, M. and Taylor, J.E.	A Simulation Impact Evaluation of Rural Income Transfer in Malawi and Ghana, Journal of Development Effectiveness, 4, 1
A20	2015	Lyons, G.J. and Duggan, J.	System Dynamics Modelling to Support Policy Analysis for Sustainable Health Care, Journal of Simulation, 9, 2
A21	2017	Collste, D., Pedercini, M., et al.	Policy Coherence to Achieve the SDGs: Using Integrated Simulation Models to Assess Effective Policies, Sustainability Science, 12
A22	2013	Pruckner, M. and German, Re.	A Hybrid Simulation Model for Large-Scale Electricity Generation Systems, Proceedings of the 2013 Winter Simulation Conference, Washington, DC, USA

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Code	Year	Author(s)	Publication (Title, Journal name, volume, issue)
A23	2013	Feng, Y.Y., Chen, S.Q., et al.	System Dynamics Modeling for Urban Energy Consumption and CO_2 Emissions: A Case Study of Beijing, China, Ecological Modelling, 252
A24	2017	Mirzaei, M. and Bekri, M.	Energy Consumption and CO_2 Emissions in Iran, 2025, Environmental Research, 154
A25	2019	Batur, İ., Bayram, Islam S., et al.	Impact Assessment of Supply-side and Demand-side Policies on Energy Consumption and CO_2 Emissions from Urban Passenger Transportation: The Case of Istanbul, Journal of Cleaner Production, 219
A26	2014	Moumouni, Y., Ahmad, S., et al.	A System Dynamics Model for Energy Planning in Niger, International Journal of Energy and Power Engineering, 3, 6
A27	2016	Karlõševa, A., Nõmmann, S., et al.	Marine Trade-offs: Comparing the Benefits of Off-shore Wind Farms and Marine Protected Areas, Energy Economics, 55
A28	2014	Sigurardóttir, S., Johansson, B., et al.	Assessing the Impact of Policy Changes in the Icelandic Cod Fishery Using a Hybrid Simulation Model, The Scientific World Journal, 2014
A29	2013	Hanasaki, N., Fujimori, S., et al.	A Global Water Scarcity Assessment Under Shared Socio-economic Pathways – Part 1: Water Use, Hydrology and Earth System Sciences, 17
A30	2017	Fujimori, S., Hanasaki, N., et al.	Projections of Industrial Water Withdrawal under Shared Socioeconomic Pathways and Climate Mitigation Scenarios, Sustainability Science, 12
A31	2012	Prambudia, Y. and Nakano, M.	Integrated Simulation Model for Energy Security Evaluation, Energies, 12
A32	2016	Ke, W., Lei, Y., et al.	Dynamic Simulation of Water Resource Management Focused on Water Allocation and Water Reclamation in Chinese Mining Cities, Water Policy, 18
A33	2019	Chawre, B.	Estimation of Domestic Water Demand and Supply Using System Dynamics Approach, Advances in Water Resources Engineering and Management, 39
A34	2019	de Blas, I., Miguel, L.J., et al.	Modelling of Sectoral Energy Demand through Energy Intensities in MEDEAS Integrated Assessment Model, Energy Strategy Reviews, 26
A35	2020	Laimon, M., Mai, T., et al.	Energy Sector Development: System Dynamics Analysis, Applied Sciences, 10
A36	2010	Hou, J. and Zhou, D.	Agent-Based Modeling of Distributed Energy System, 2010 Third International Conference on Information and Computing
A37	2019	Arroyo, F. and Miguel, L.J.	Analysis of Energy Demand Scenarios in Ecuador: National Government Policy Perspectives and Global Trend to Reduce CO_2 Emissions, International Journal of Energy Economics and Policy, 9, 2
A38	2017	Zuo, Y., Shi, Y., et al.	Research on the Sustainable Development of an Economic-Energy-Environment (3E) System Based on System Dynamics (SD): A Case Study of the Beijing-Tianjin-Hebei Region in China, Sustainability, 9
A39	2020	Iwanaga, T., Partington, D., et al.	A Socio-environmental Model for Exploring Sustainable Water Management Futures: Participatory and Collaborative Modelling in the Lower Campaspe Catchment, Journal of Hydrology: Regional Studies, 28
A40	2019	Haavisto, R., Santos, D., et al.	Determining Payments for Watershed Services by Hydro-economic Modeling for Optimal Water Allocation between Agricultural and Municipal Water Use, Water Resources Management, 26
A41	2011	Zhonghua, C. and Yu, S.	Environmental Protection Investment and Sustainable Development-Policy Simulation Based on Nonlinear Dynamics, Energy Procedia, 5
A42	2019	Bigerna, S., Wen X., et al.	Green Electricity Investments: Environmental Target and the Optimal Subsidy, European Journal of Operational Research, 279, 2
A43	2012	Dumont, E., William, R., et al.	Modelling Indicators of Water Security, Water Pollution and Aquatic Biodiversity in Europe, Hydrological Sciences Journal, 57, 7
A44	2006	Klepeis, N.E.	Modeling Human Exposure to Air Pollution, Human Exposure Analysis
A45	2020	Nunez, S., Verboom, J., et al.	Assessing Land-based Mitigation Implications for Biodiversity, Environmental Science and Policy, 106
A46	2014	Fakhimi, M., Anagnostou, A., et al.	A Hybrid Agent-based and Discrete Event Simulation Approach for Sustainable Strategic Planning and Simulation Analytics, Proceedings of the 2014 Winter Simulation Conference, Savannah, GA, USA
A47	2017	Limsawasd, C. and Athigakunagorn, N.	An Application of Discrete-Event Simulation in Estimating Emissions from Equipment Operations in Flexible Pavement Construction Projects, Engineering Journal, 21, 7

Code	Year	Author(s)	Publication (Title, Journal name, volume, issue)
A48	2018	Jassim, H.S.H., Lu, W., et al.	Assessing Energy Consumption and Carbon Dioxide Emission of Off-highway Trucks in Earthwork Operations: An Artificial Neural Network Model, Journal of Cleaner Production, 198
A49	2014	Kohl, J., Spreng, S., et al.	Discrete Event Simulation of Individual Energy Consumption for Product-varieties, Procedia CIRP, 17
A50	2020	Hanski, I.	Extinction Debt and Species Credit in Boreal Forests: Modelling the Consequences of Different Approaches to Biodiversity Conservation, Annales Zoologici Fennici, 37
A51	2019	Gu, S., Fu, B., et al.	Coupled LMDI and System Dynamics Model for Estimating Urban CO2 Emissions Mitigation Potential In Shanghai, China, Journal of Cleaner Production, 240
A52	2018	Barisa, A. and Rosa, M.	A System Dynamic Model for CO_2 Emission Mitigation Policy Design in Road Transport Sector, Energy Procedia, 147
A53	2019	Pfeiffer, B., Rabe, C., et al.	Assessing Urban Policies Using a Simulation Model with Formal and Informal Housing, Policy Research Working Paper, 8921
A54	2014	Löeffler, M., Peichl, A., et al.	Documentation IZAΨMOD v3.0: The IZA Policy Simulation Model, IZA Discussion Papers, 8553
A55	2010	Fehr, H., Kallweit, M., et al.	Pension Reform with Variable Retirement Age – A Simulation Analysis for Germany, Netspar Discussion Paper, 013
A56	2016	Kim, J., Lee, J., et al.	A Model of Gender Inequality and Economic Growth, ADB Economics Working Paper Series, 475
A57	2006	Obonyo, E. and Omenya, A.	Agent-Based Modelling of Urban Sanitation: Informal Settlements in Nairobi, Joint International Conference on Computing and Decision Making in Civil and Building Engineering, June 14-16, Montréal, Canada
A58	2020	Kabir, K. and Dudu, H.	Using Computable General Equilibrium Models to Analyze Economic Benefits of Gender-Inclusive Policies, MTI Practice Notes, 8
A59	2012	Araar, A. and Verme, P.	Reforming Subsidies: A Tool-kit for Policy Simulations, Policy Research Working Paper, 6148
A60	2015	Cuesta, J., El-Lahga, A., et al.	The Socioeconomic Impacts of Energy Reform in Tunisia: A Simulation Approach, Policy Research Working Paper, 7312
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A219	2017	Dafermos, Y., Niko-laidi, M., et al.	A Stock-Flow-Fund Ecological Macroeconomic Model, Ecological Economics, 131
A220	2018	Dafermos, Y., Niko-laidi, M., et al.	Dynamic Ecosystem-FINance-Economy (DEFINE) model, technical description and data, version 1 .0
A221	2017	Garrett-Peltier, H.	Green versus brown: Comparing the Employment Impacts of Energy Efficiency, Renewable Energy, and Fossil Fuels using an Input-Output Model, Economic Modelling, 61
A222	2020	IEA	Energy Efficiency Indicators June 2020 Edition: Database Documentation World Energy Balances 2020 Edition: Database Documentation
A223	2012	ICCT	Global Transportation Roadmap Model
A224	2012	Frenken K. & Gillet V.	Irrigation Water Requirement and Water Withdrawal by Country, AQUASTAT Report

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Code	Year	Author(s)	Publication (Title, Journal name, volume, issue)
A225	2019	UNSTATS	Indicator 6.4.1: Change in Water-Use Efficiency over Time
A226	2016	Alexander P., Brown, C., et al.	Human Appropriation of Land for Food: The Role of Diet, Global Environmental Change, 41
A227	2017	Vivid Economics	Methodology Statement: Report prepared for GGGI
A228	n.d. (a)	FAOSTAT	FAOSTAT: Fertilizers by Nutrient
A229	2018a	UNSTAT	Indicator 8.4.1: Material Footprint, material footprint per capita, and material foot-print per GDP
A230	n.d. (b)	FAOSTAT	FAOSTAT: Synthetic Fertilizers
A231	n.d. (c)	FAOSTAT	FAOSTAT: Land Use Indicators
A232	2006	Marklund, L. & Schoene D.	Global Assessment of Growing Stock, Biomass and Carbon Stock, In The Forest Resources Assessment (FRA) Working Paper Series, 106
A233	2016	Costelloe, B., Collen, B., et al.	Global Biodiversity Indicators Reflect the Modeled Impacts of Protected Area Policy Change. Conservation Letters, 9, 1
A234	2013	OHI	Supplementary Methods
A235	2018	de Alba, J. & Todor-ov, V.	Green Industrial Performance: The GIP Index, World Review of Science, Technology and Sustainable Development, 14, 2/3
A236	2019	UNICEF & WHO	Progress on Household Drinking Water, Sanitation and Hygiene 2000-2017: Special Focus on Inequalities
A237	2017	UNSTATS	Indicator 6.1.1: Proportion of population using safely managed drinking water services Indicator 6.2.1: Proportion of population using safely managed sanitation services, including a handwashing facility with soap and water
A238	2015	Bhatia, M. & Angelou, N.	Beyond Connections: Energy Access Redefined, ESMPA Technical Report, 008/15
A239	2013	Lin, M. & Wu, F.	Identifying the Determinants of Broadband Adoption by Diffusion Stage in OECD Countries, Telecommunications Policy, 37
A240	2012	Gulati, J. & Yates, D	Different Paths to Universal Access: The Impact of Policy and Regulation on Broad-band Diffusion in the Developed and Developing Worlds, Telecommunications Policy, 36
A241	n.d.	OECD SIGI data	Social Institutions and Gender Index
A242	2017	Global Findex Data-base	Global Findex Database
A243	n.d.	OECD data	OECD database
A244	n.d.	World Bank Data	Gender statistics
A245	2019	World Bank Group	Women, Business, and the Law 2019: A Decade of Reform
A246	2018b	UNSTATS	Indicator 8.4.2: Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP
A247	2020	FAO	AQUASTAT Glossary
A248	2020	UNSTATS	Indicator 6.4.2: Level of water stress: freshwater withdrawal as a proportion of avail-able freshwater resource
A249	2016	Cui, F., Zhang, L., et al.	Estimation of the Disease Burden Attributable to 11 Risk Factors in Hubei Province, China: A Comparative Risk Assessment, International Journal of Environmental Research and Public Health, 13, 10

Note: The references from A222 were not included in the assessment of peer-reviewed articles presented in Table 1. These references were identified when developing interlinkages of mathematical models between indicators and across dimensions.

APPENDIX 3

FLOW DIAGRAMS OF THE MODELS FOR THE SIMULATION TOOL

Figure A1. Flow diagram of the equations for efficient and sustainable energy (Primary energy supply)

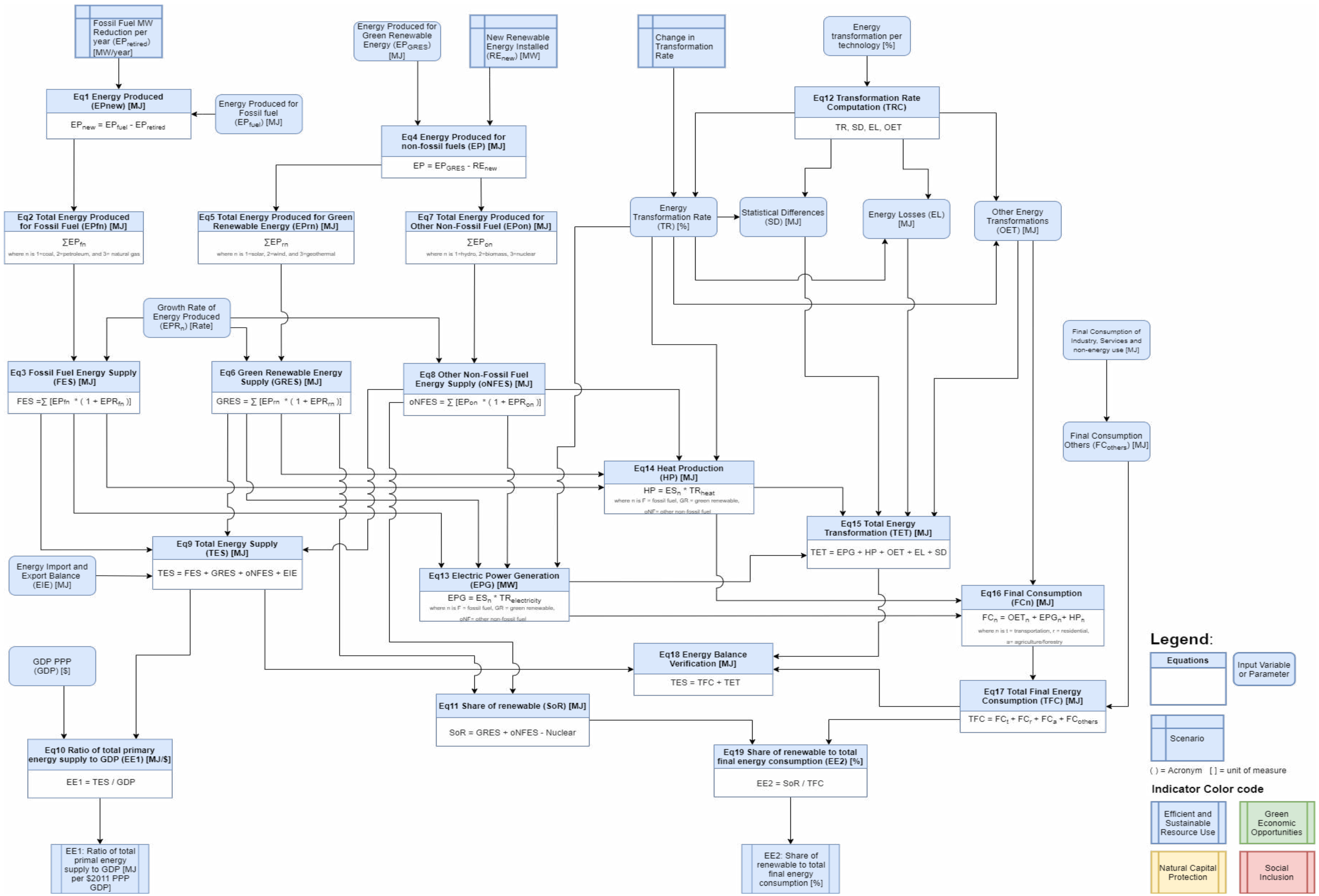

Figure A2. Flow diagram of the equations for efficient and sustainable energy (Renewables in transport)

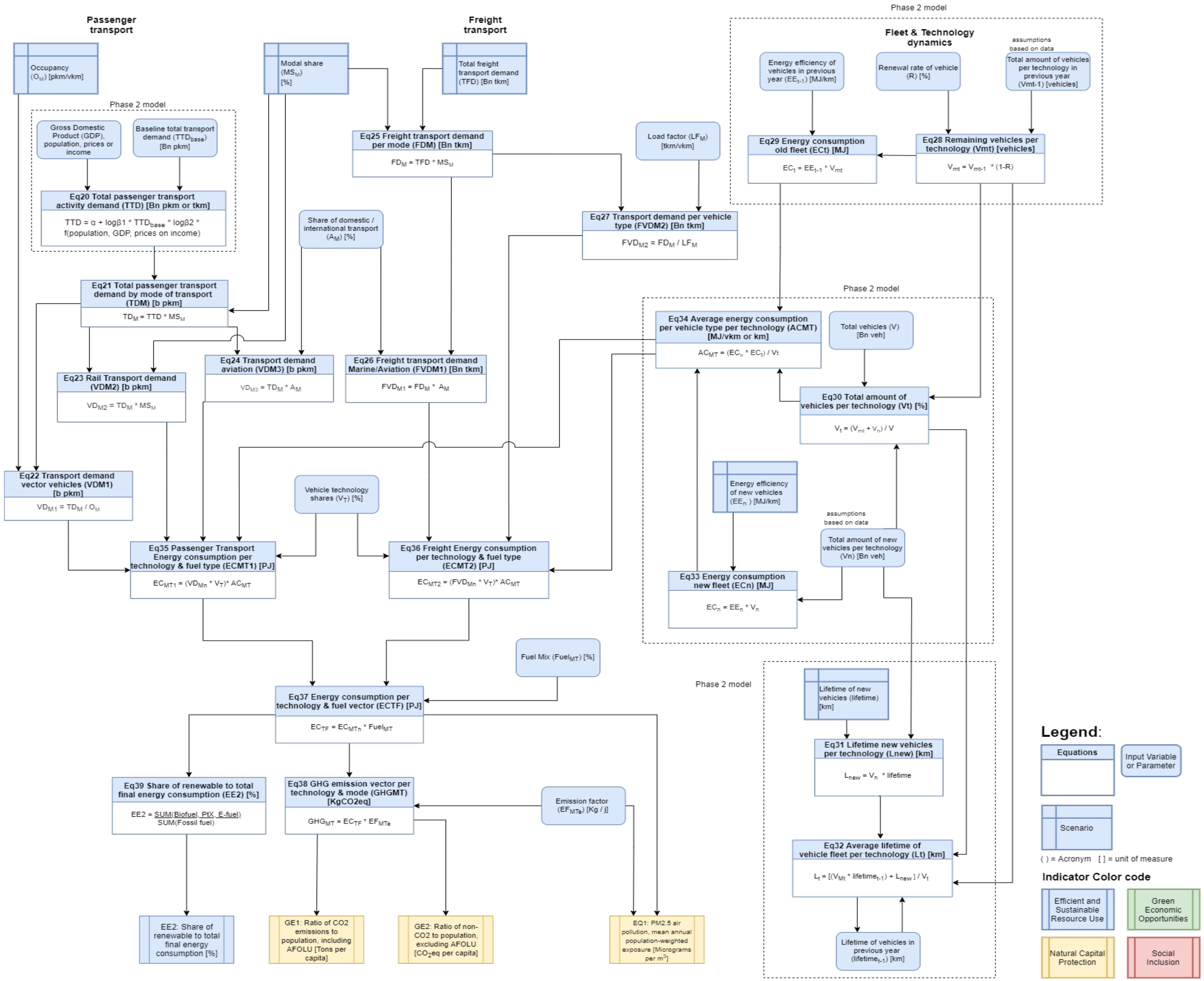

Figure A3. Flow diagram of the equations for efficient and sustainable water use (Water use efficiency and freshwater withdrawal)

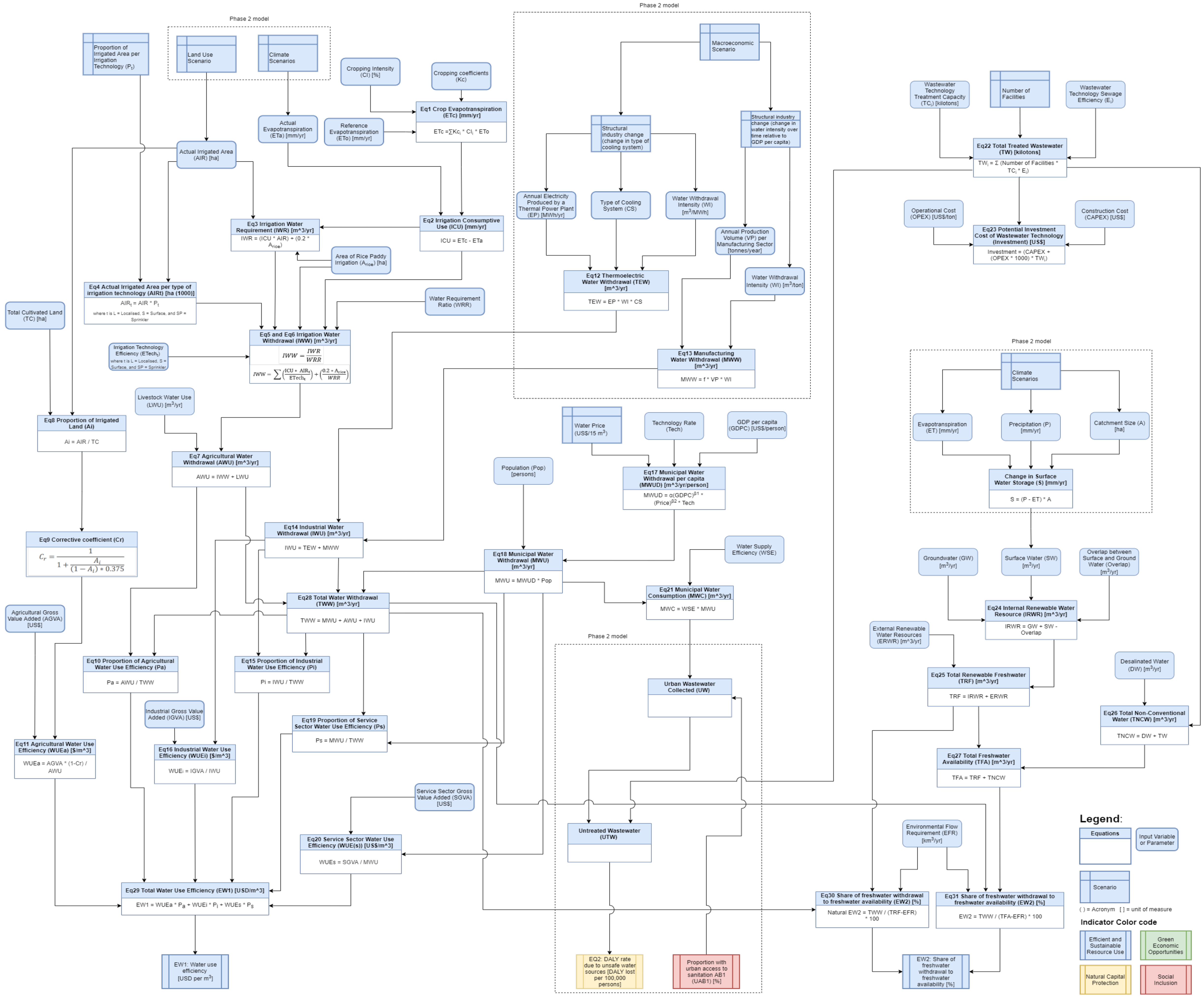

Figure A4. Flow diagram of the equations for sustainable land use and biodiversity and ecosystem protection

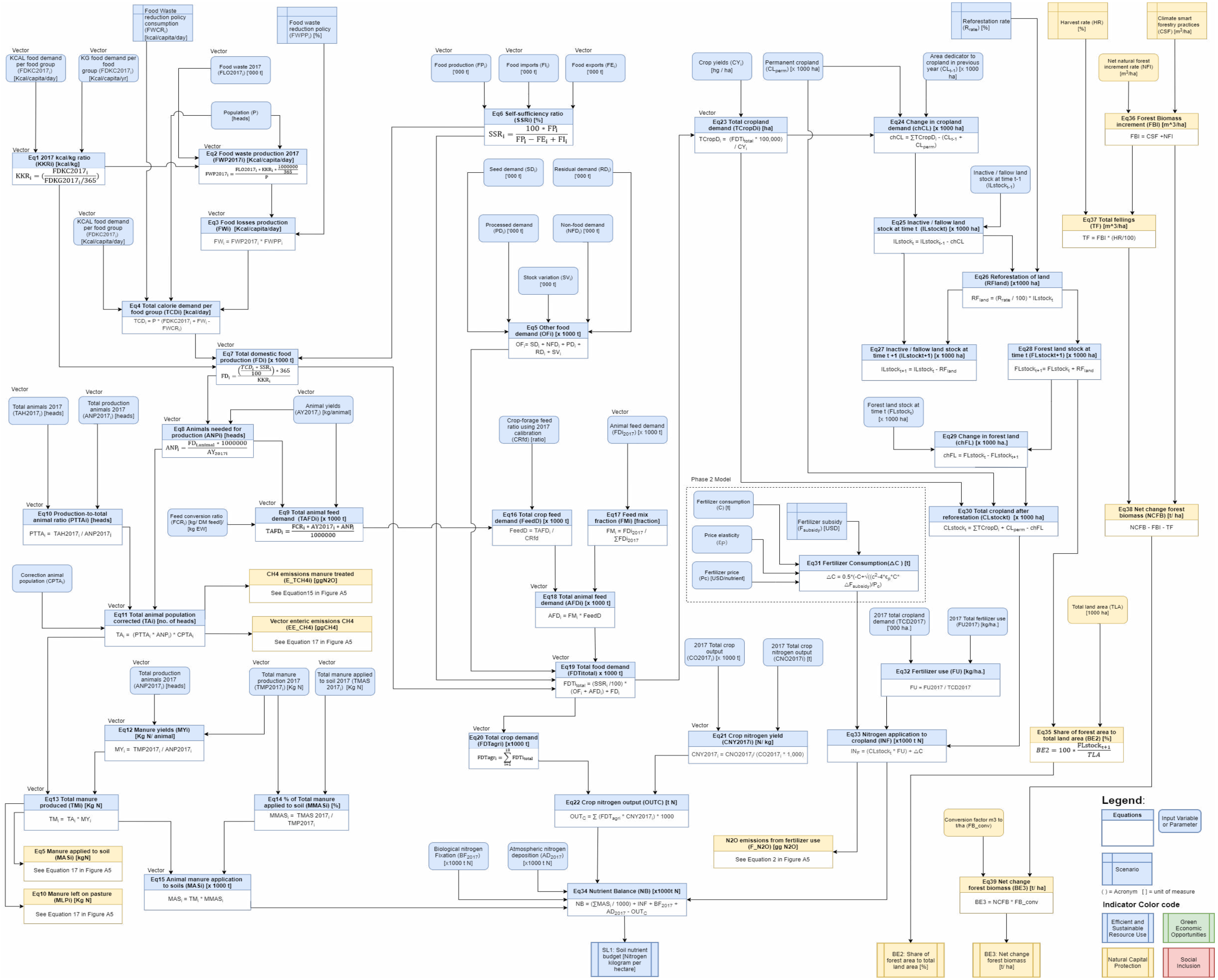

Figure A5. Flow diagram of the equations for GHG emissions reduction

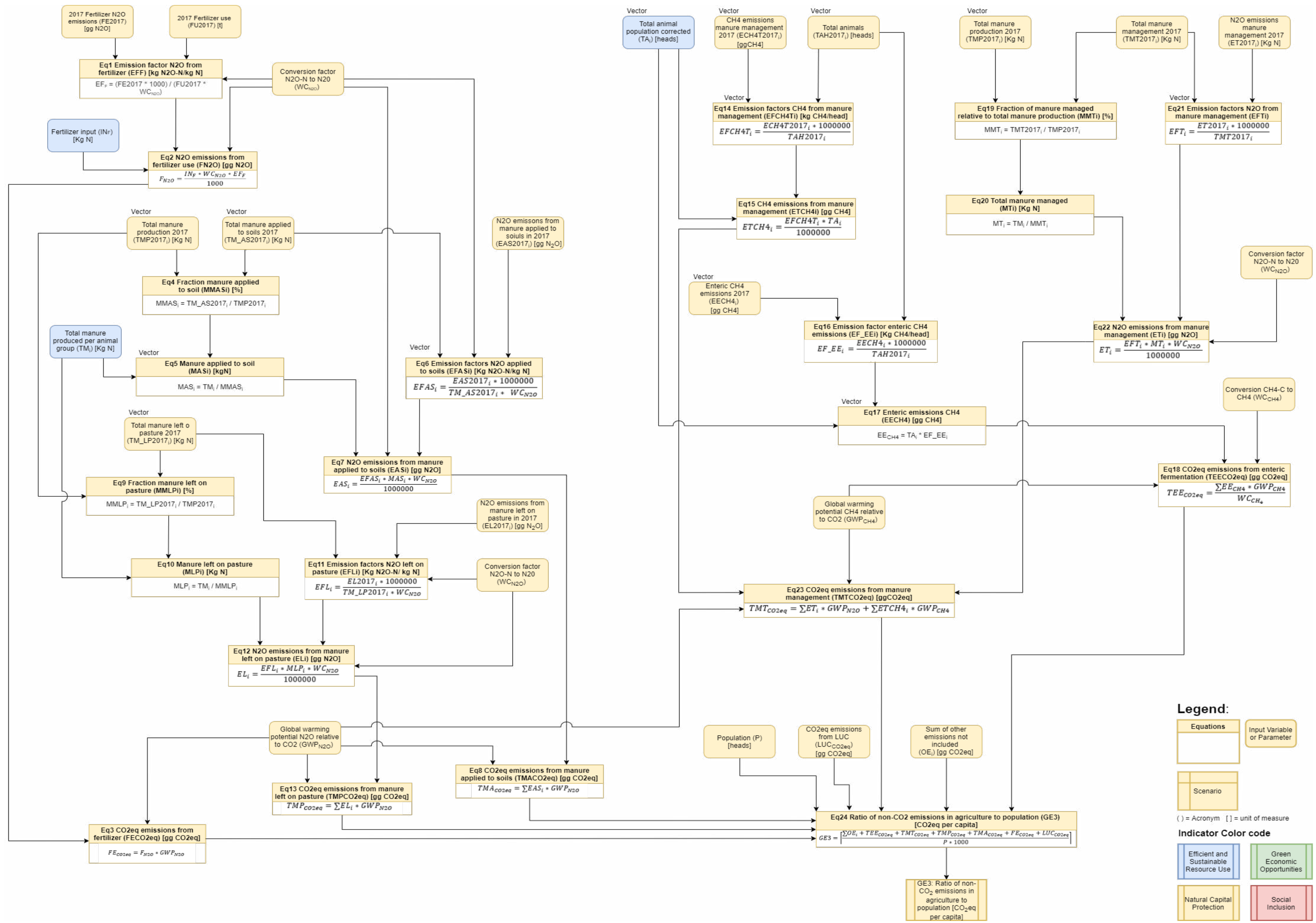

Figure A6. Flow diagram of the equations for material use efficiency (Domestic material consumption and material footprint)

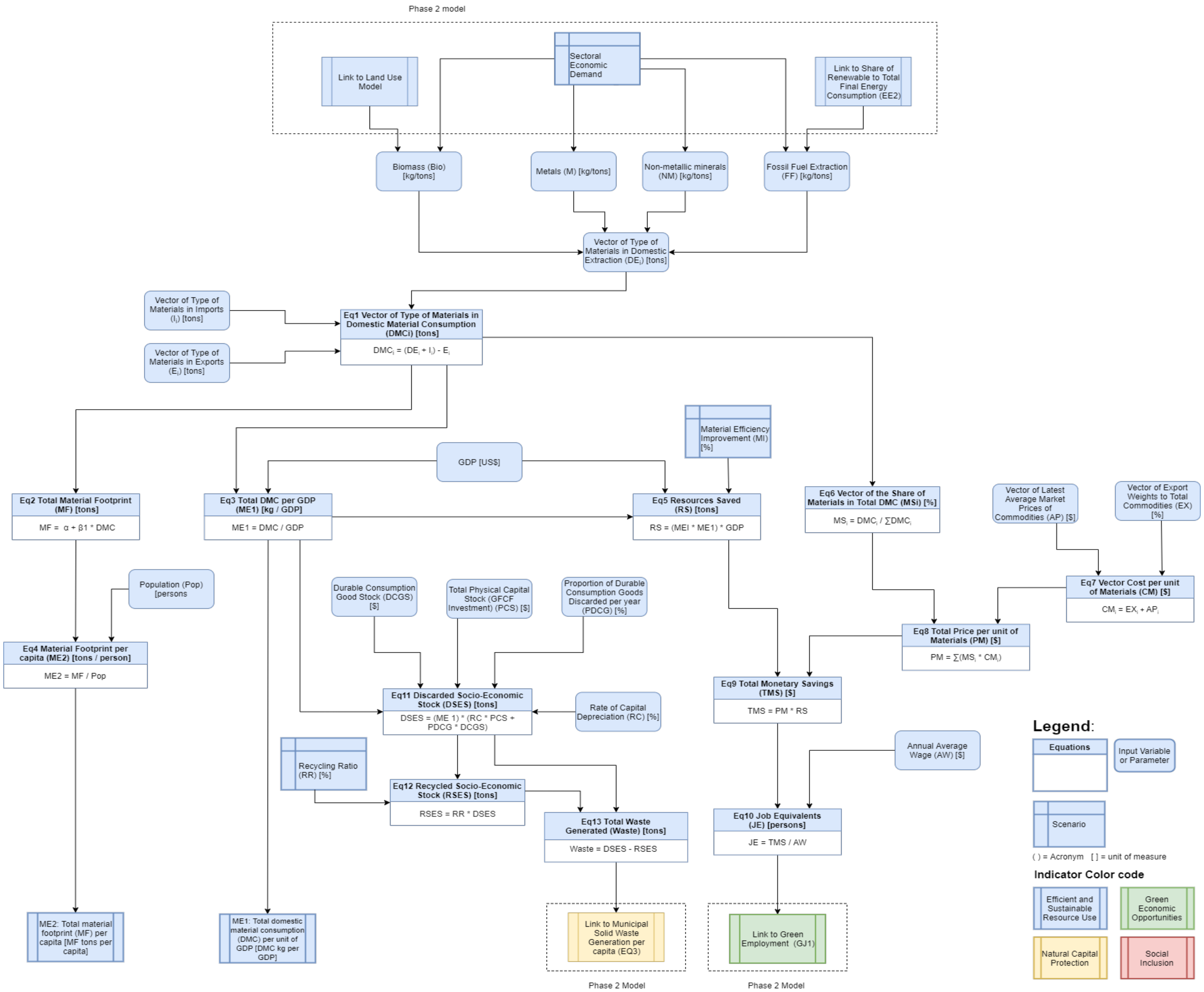

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Figure A7. Flow diagram of the equations for environmental quality (DALY rate)

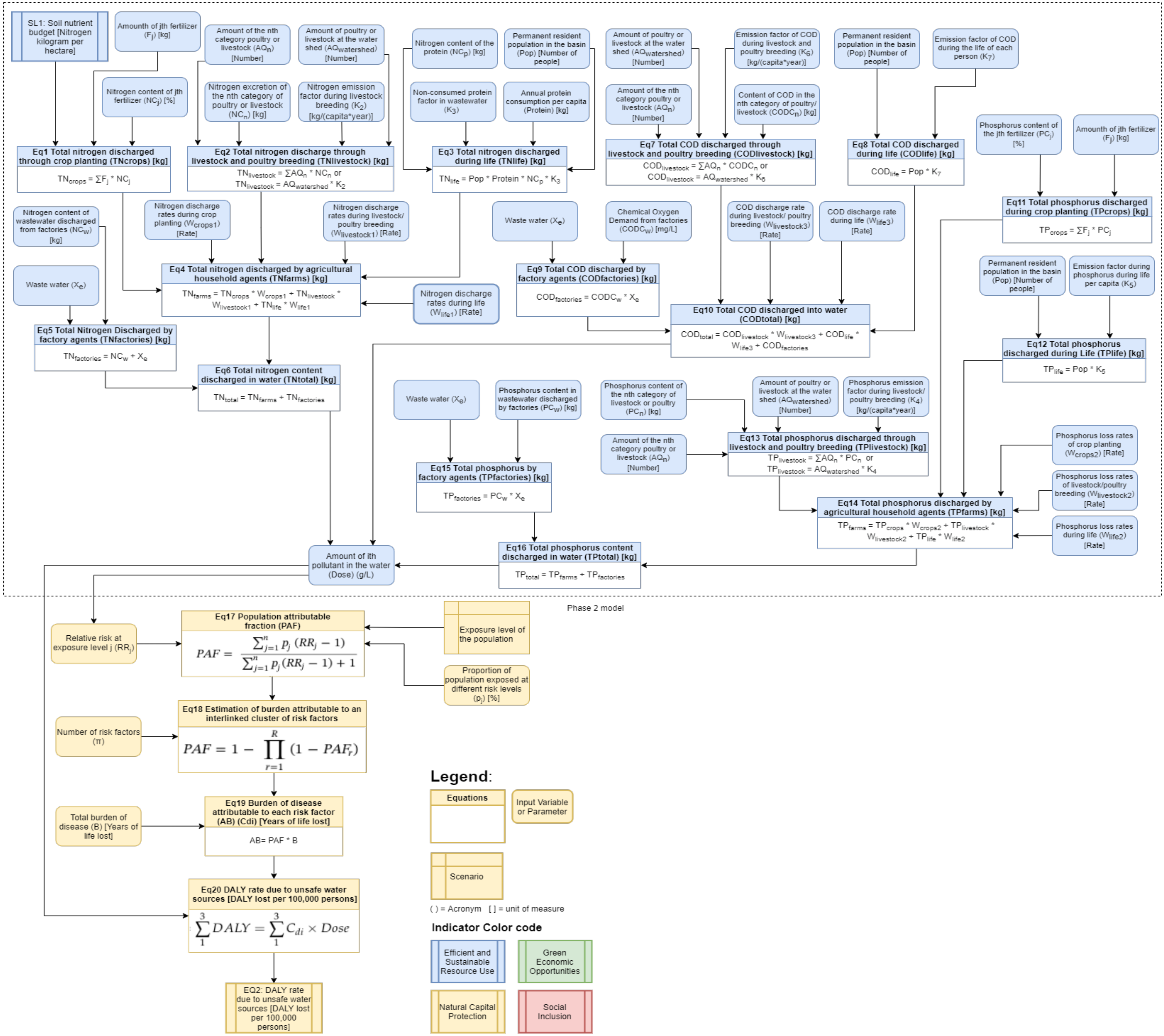


Figure A8. Flow diagram of the equations for cultural and social value (Red list index and Tourism and recreation)

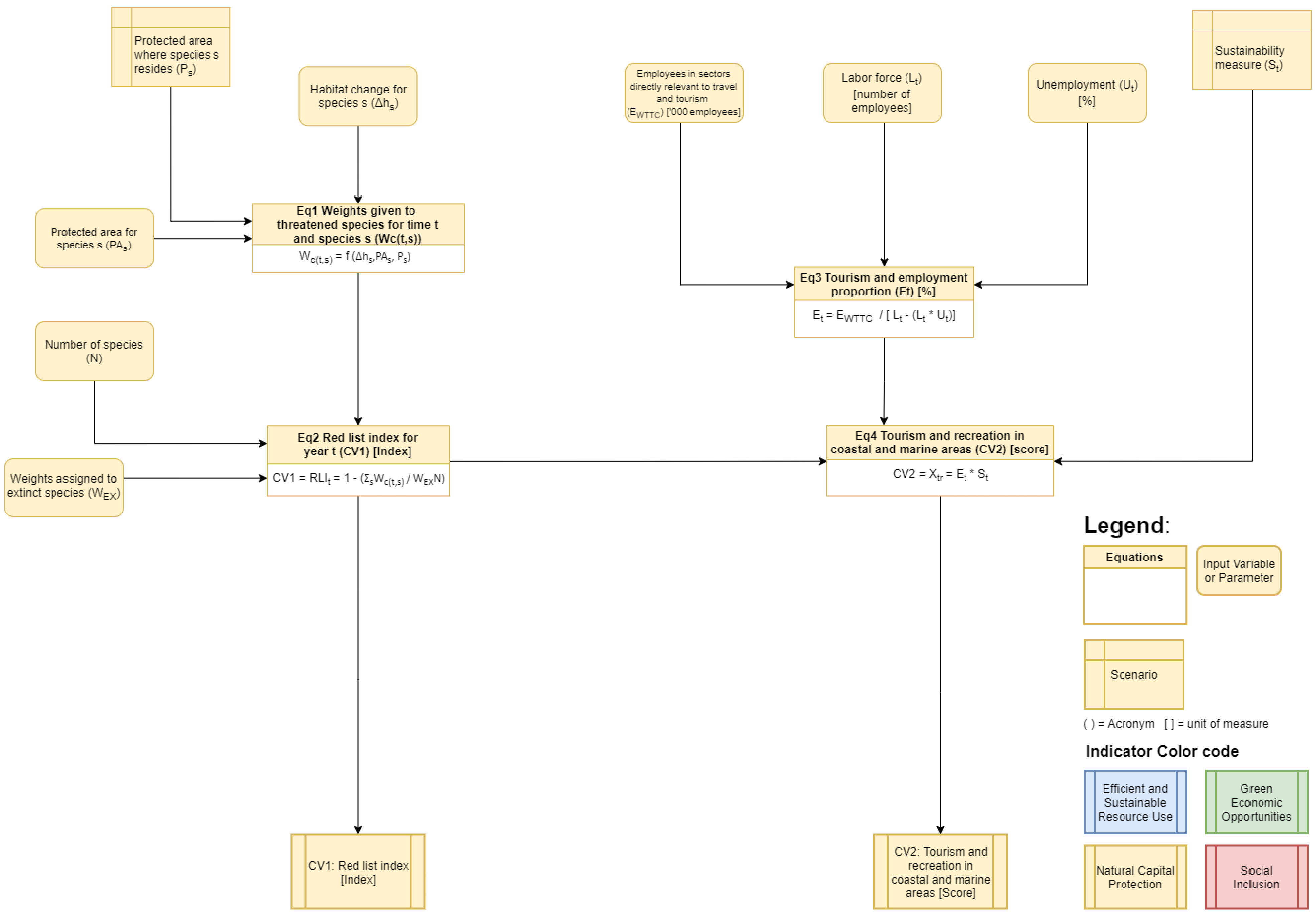


Figure A9. Flow diagram of the equations for green economic opportunities (Green trade, employment, and innovation)

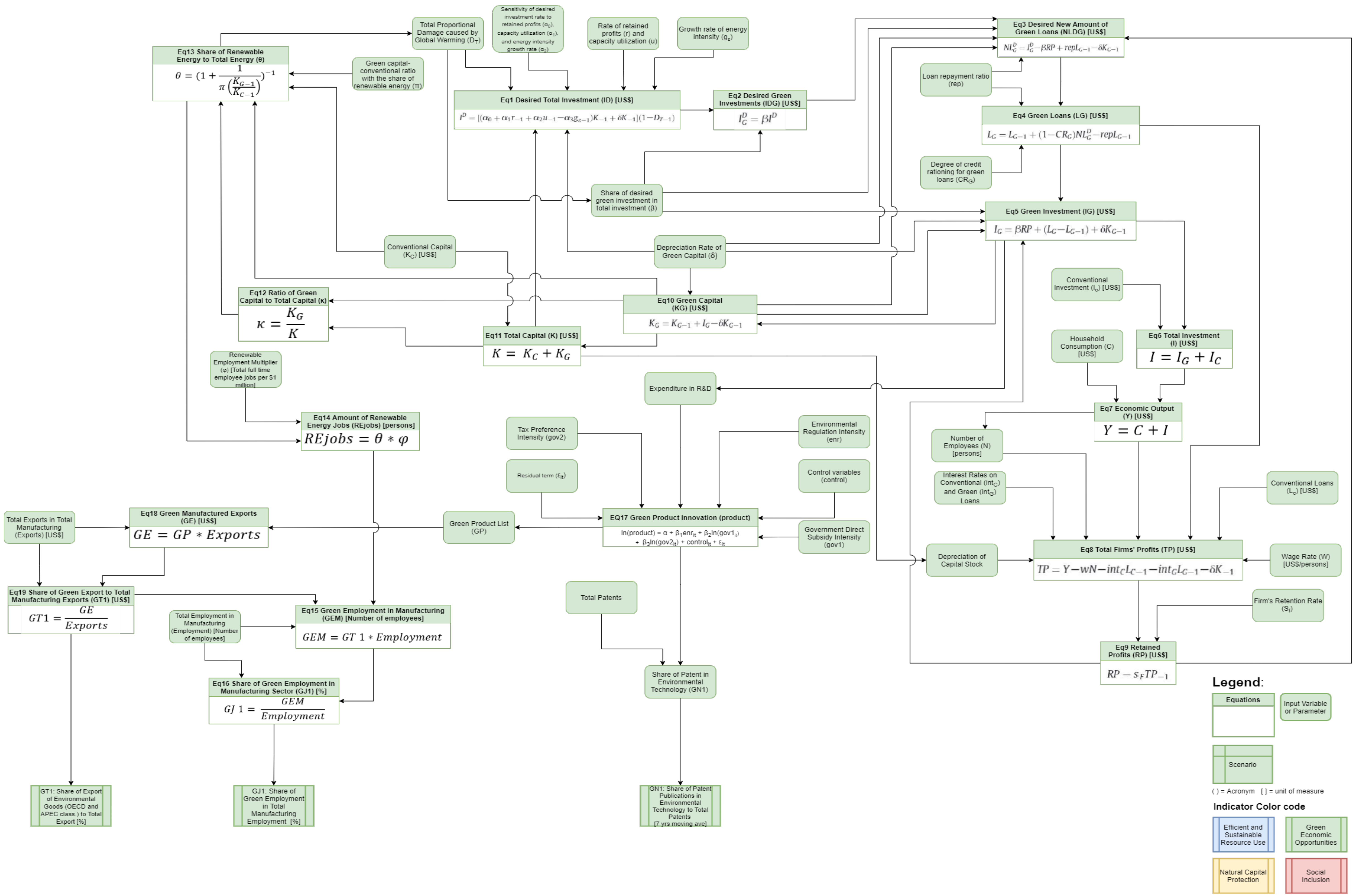


Figure A10. Flow diagram of the equations for access to basic services and resources

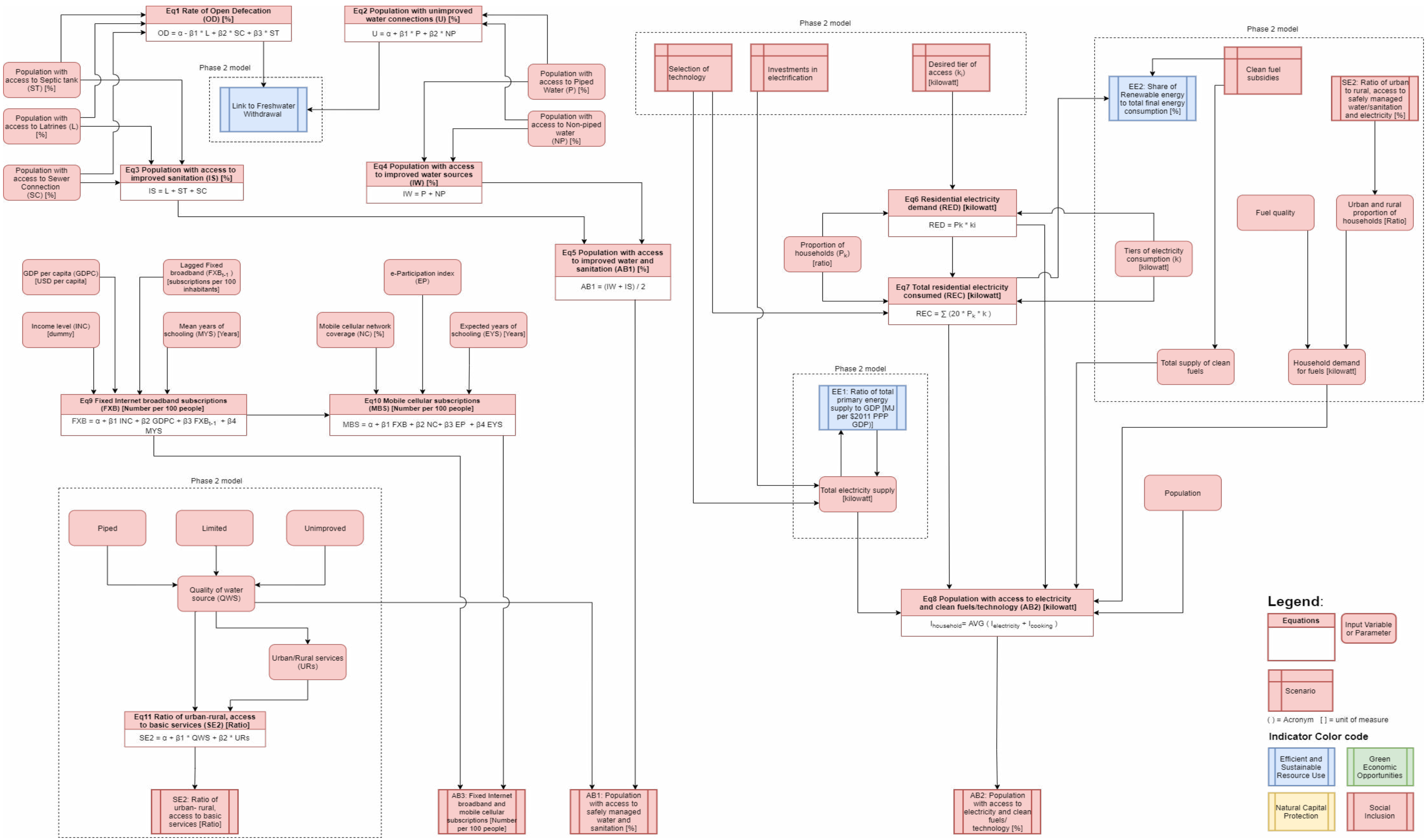


Figure A11. Flow diagram of the equations for gender balance

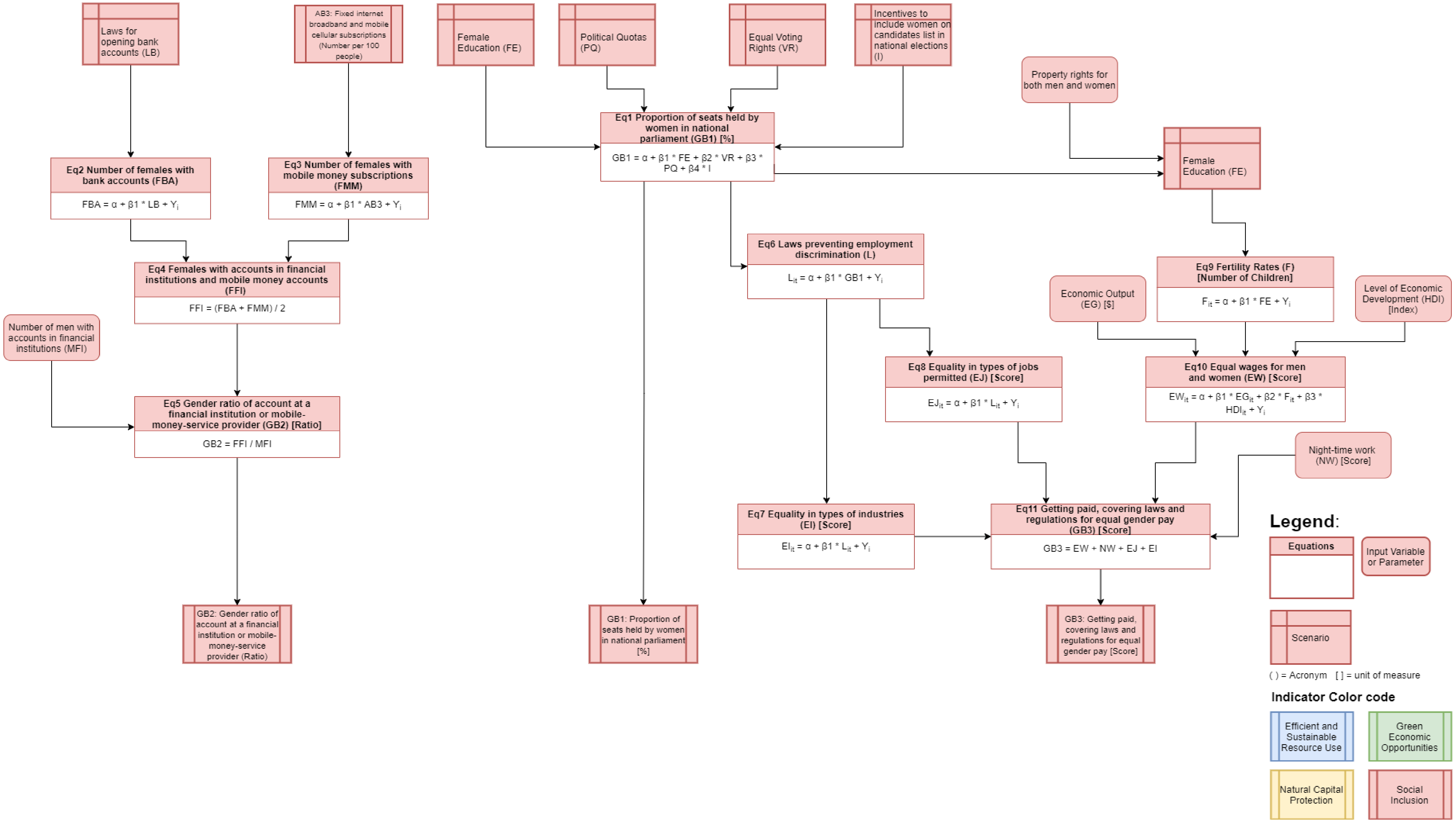


Figure A12. Flow diagram of the equations for social equity (Youth in NEET)

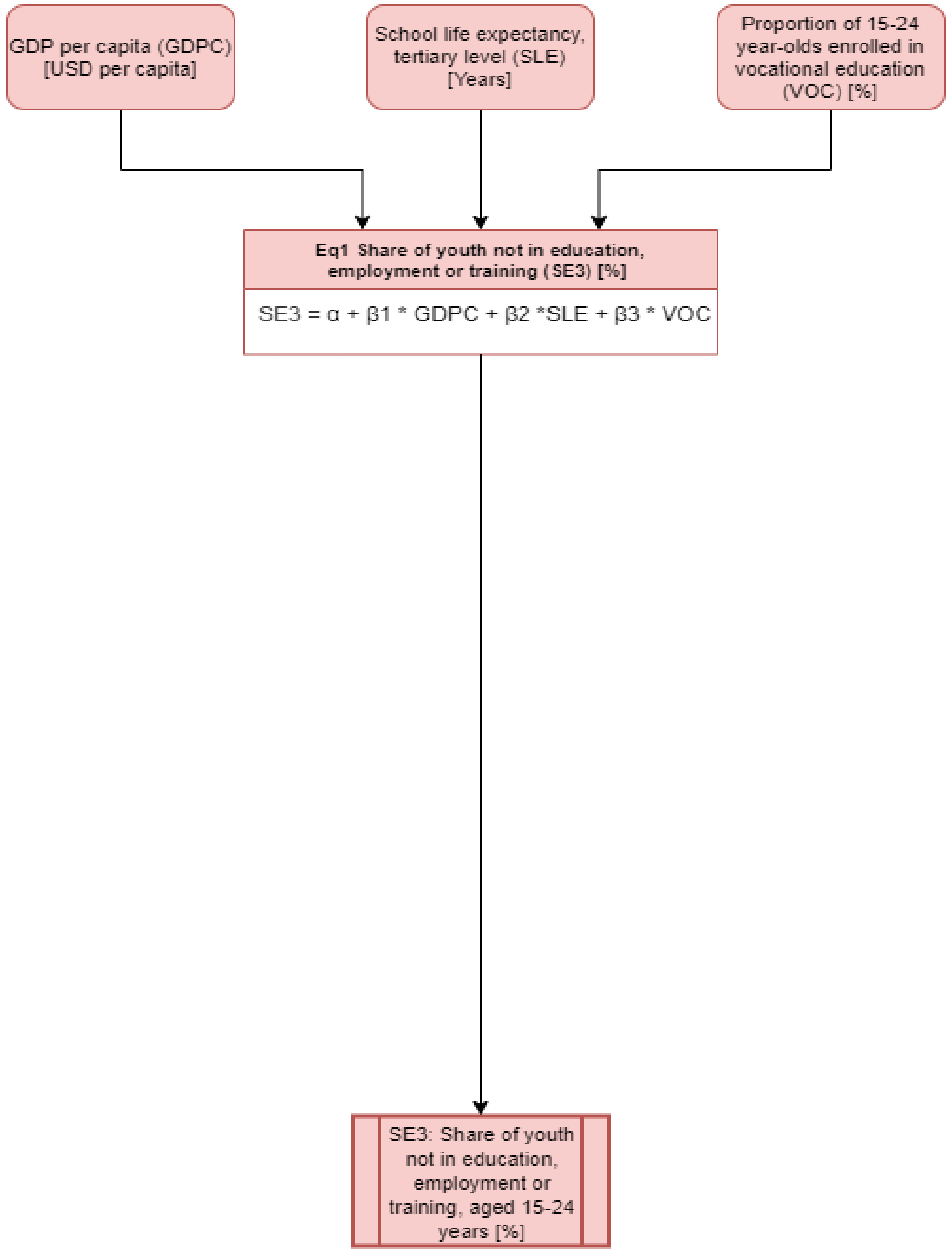
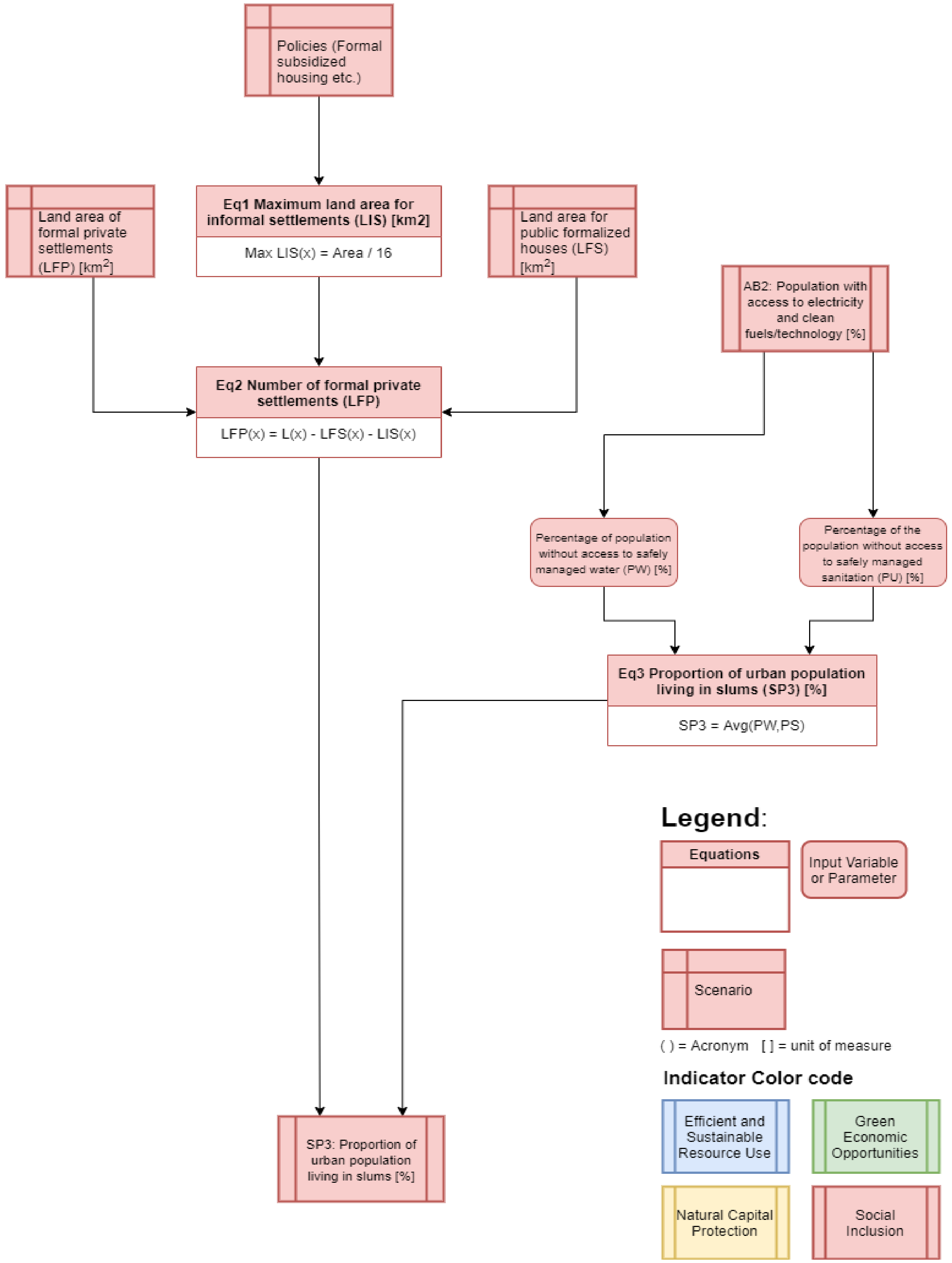


Figure A13. Flow diagram of the equations for social protection (Urban population living in slums)



APPENDIX 4

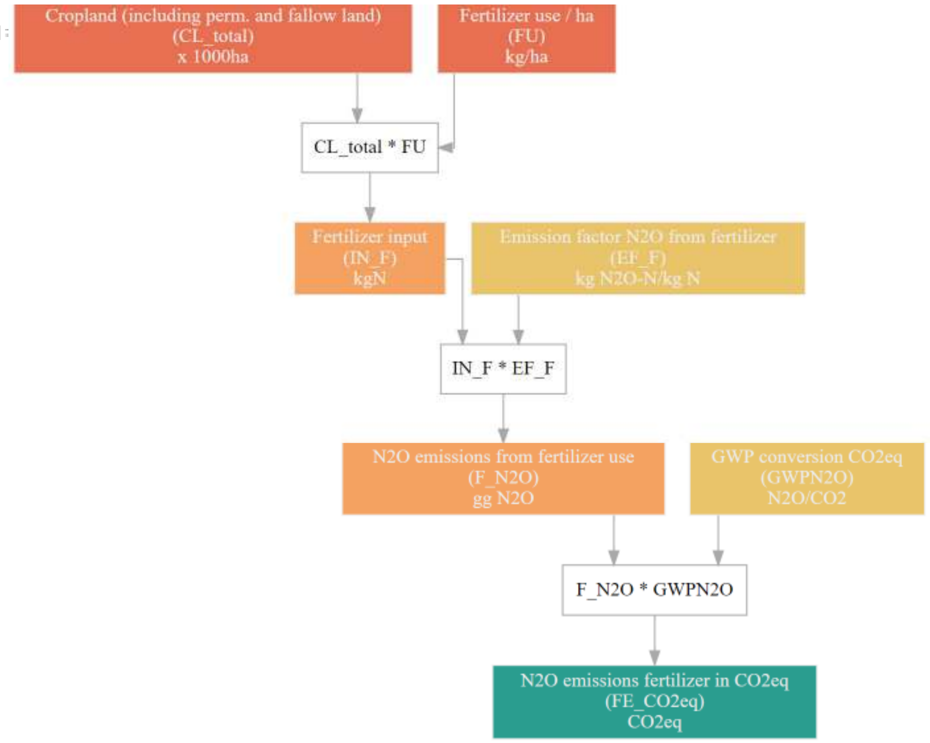
PYTHON CODES TO IMPLEMENT SIMULATION MODELS FOR THE PHASE 1 SIMULATION TOOL

A. Simulation model for sustainable land use and links to GHG emissions reduction and above-ground biomass

In [1]:

```
__publisher__ = 'Global Green Growth Institute'
__author__ = 'GGPM Team'
__model_lead__ = 'H. Luchtenbelt'
__programmer__ = 'S. Zabrocki'

import pandas as pd
import numpy as np
from graphmodels.graphmodel import GraphModel

FE_CO2eq_nodes = [
    {'type': 'input',
     'id': 'CL_total',
     'name': 'Cropland (including perm. and fallow land)',
     'unit': 'x 1000ha',
     },
    {'type': 'input',
     'unit': 'kg/ha',
     'id': 'FU',
     'name': 'Fertilizer use / ha',
    },
    {'type': 'variable',
     'unit': 'kgN',
     'id': 'IN_F',
     'name': 'Fertilizer input',
     'in': ['CL_total', 'FU'],
     'computation': {'name': 'CL_total * FU',
                     'formula': lambda X: X['CL_total'] * X['FU']}
     },
    {'type': 'parameter',
     'unit': 'kg N2O-N/kg N',
     'id': 'EF_F',
     'name': 'Emission factor N2O from fertilizer',
     },
    {'type': 'variable',
     'unit': 'gg N2O',
     'id': 'F_N2O',
     'name': 'N2O emissions from fertilizer use',
     'in': ['IN_F', 'EF_F'],
     'computation': {'name': 'IN_F * EF_F',
                     'formula': lambda X: X['IN_F'] * X['EF_F']}
     },
    {'type': 'parameter',
     'unit': 'N2O/CO2',
     'id': 'GWPN2O',
     'name': 'GWP conversion CO2eq',
     },
    {'type': 'output',
     'unit': 'CO2eq',
     'id': 'FE_CO2eq',
     'name': 'N2O emissions fertilizer in CO2eq',
     'in': ['GWPN2O', 'F_N2O'],
     'computation': {'name': 'F_N2O * GWPN2O',
                     'formula': lambda X: X['F_N2O'] * X['GWPN2O']}
     }


]

model_FE_CO2eq = GraphModel(FE_CO2eq_nodes)

model_FE_CO2eq.draw()
```

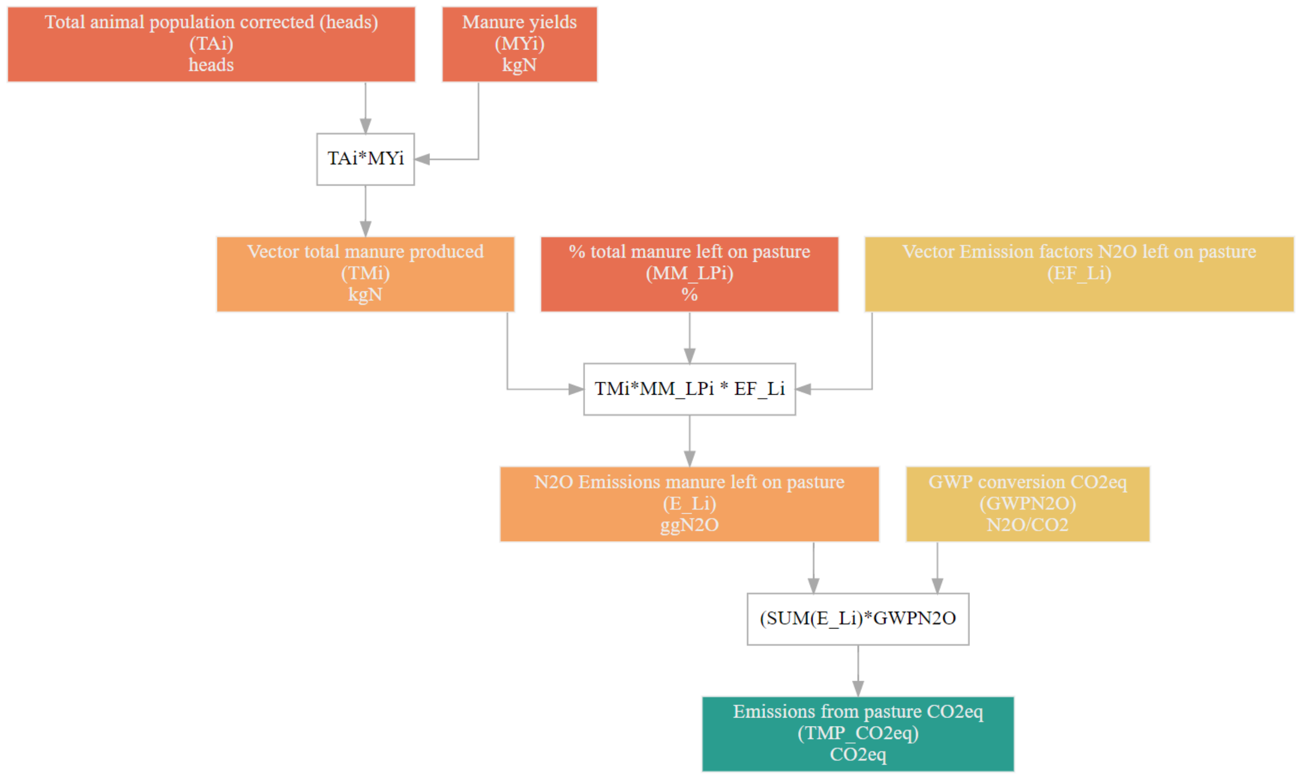

Out[1]:



In [2]:

```
TMP_CO2eq_nodes = [

    {'type': 'input',
     'unit': 'heads',
     'id': 'TAi',
     'name': 'Total animal population corrected (heads)',
     },
    {'type': 'input',
     'unit': 'kgN',
     'id': 'MYi',
     'name': 'Manure yields',
     },
    {'type': 'variable',
     'unit': 'kgN',
     'id': 'TMi',
     'name': 'Vector total manure produced',
     'in': ['MYi', 'TAi'],
     'computation': {'name': 'TAi*MYi',
                     'formula': lambda X: X['TAi'] * X['MYi']}
     },

    {'type': 'input',
     'unit': '%',
     'id': 'MM_LPi',
     'name': '% total manure left on pasture',
     },


    {'type': 'variable',
     'unit': 'ggN2O',
     'id': 'E_Li',
     'name': 'N2O Emissions manure left on pasture',
     'in': ['TMi', 'MM_LPi', 'EF_Li'],
     'computation': {'name': 'TMi*MM_LPi * EF_Li',
                     'formula': lambda X: X['TMi'] * X['MM_LPi'] *  X['EF_Li']}
     },
    {'type': 'parameter',
     'unit': '',
     'id': 'EF_Li',
     'name': 'Vector Emission factors N2O left on pasture',
     },
    {'type': 'parameter',
     'unit': 'N2O/CO2',
     'id': 'GWPN2O',
     'name': 'GWP conversion CO2eq',
     },

    {'type': 'output',
     'unit': 'CO2eq',
     'id': 'TMP_CO2eq',
     'name': 'Emissions from pasture CO2eq',
     'in': ['E_Li', 'GWPN2O'],
     'computation': {'name': '(SUM(E_Li)*GWPN2O',
                     'formula': lambda X: np.nansum(X['E_Li']) * X['GWPN2O']}
     }



]

model_TMP_CO2eq = GraphModel(TMP_CO2eq_nodes)

model_TMP_CO2eq.draw()
```

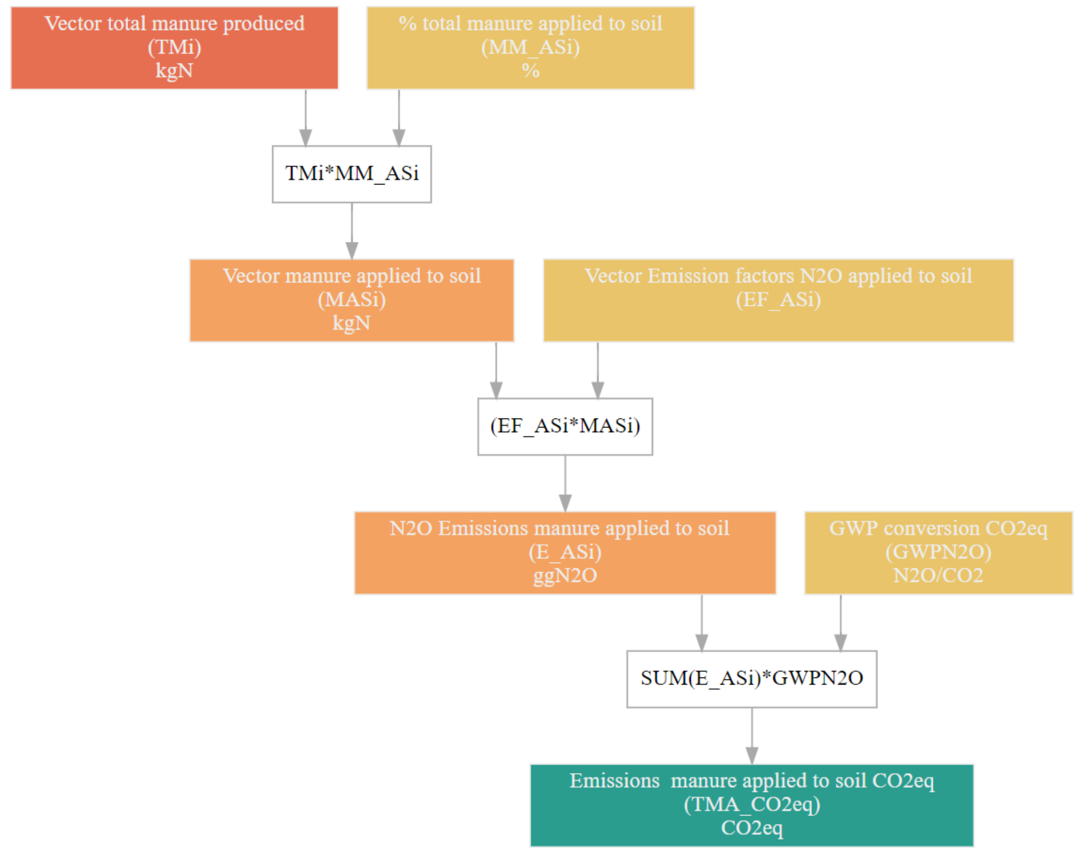
Out[2]:



In [3]:

```
TMA_CO2eq_nodes = [
    {'type': 'input',
     'unit': 'kgN',
     'id': 'TMi',
     'name': 'Vector total manure produced',
     },
    {'type': 'parameter',
     'unit': '%',
     'id': 'MM_ASi',
     'name': '% total manure applied to soil',
     },
    {'type': 'variable',
     'unit': 'kgN',
     'id': 'MASi',
     'name': 'Vector manure applied to soil',
     'in': ['TMi', 'MM_ASi'],
     'computation': {'name': 'TMi*MM_ASi',
                     'formula': lambda X: X['TMi'] * X['MM_ASi']}
     },
    {'type': 'parameter',
     'unit': '',
     'id': 'EF_ASi',
     'name': 'Vector Emission factors N2O applied to soil',
     },
    {'type': 'variable',
     'unit': 'ggN2O',
     'id': 'E_ASi',
     'name': 'N2O Emissions manure applied to soil ',
     'in': ['EF_ASi', 'MASi'],
     'computation': {'name': '(EF_ASi*MASi)',
                     'formula': lambda X:X['EF_ASi'] * X['MASi']}
     },
    {'type': 'parameter',
     'unit': 'N2O/CO2',
     'id': 'GWPN2O',
     'name': 'GWP conversion CO2eq',
     },
    {'type': 'output',
     'unit': 'CO2eq',
     'id': 'TMA_CO2eq',
     'name': 'Emissions  manure applied to soil CO2eq',
     'in': ['E_ASi', 'GWPN2O'],
     'computation': {'name': 'SUM(E_ASi)*GWPN2O',
                     'formula': lambda X: sum(X['E_ASi']) * X['GWPN2O']}
     }
]

model_TMA_CO2eq = GraphModel(TMA_CO2eq_nodes)

model_TMA_CO2eq.draw()
```

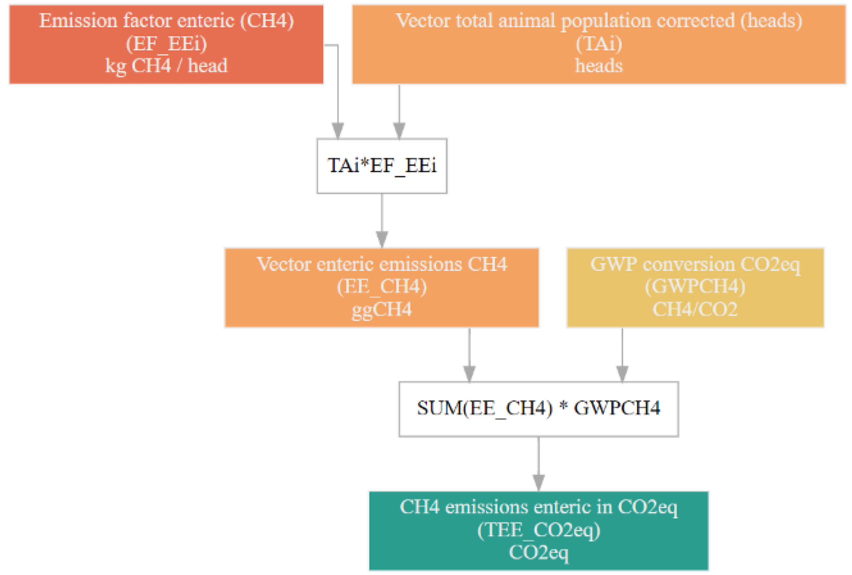

Out[3]:



In [4]:

```
TEE_CO2eq_nodes = [
    {'type': 'input',
     'unit': 'kg CH4 / head',
     'id': 'EF_EEi',
     'name': 'Emission factor enteric (CH4)',
     },

    {'type': 'variable',
     'unit': 'heads',
     'id': 'TAi',
     'name': 'Vector total animal population corrected (heads)',
     },


    {'type': 'variable',
     'unit': 'ggCH4',
     'id': 'EE_CH4',
     'name': 'Vector enteric emissions CH4',
     'in': ['TAi', 'EF_EEi'],
     'computation': {'name': 'TAi*EF_EEi',
                     'formula': lambda X: X['TAi']*X['EF_EEi']}
     },



    {'type': 'parameter',
     'unit': 'CH4/CO2',
     'id': 'GWPCH4',
     'name': 'GWP conversion CO2eq',
     },

    {'type': 'output',
     'unit': 'CO2eq',
     'id': 'TEE_CO2eq',
     'name': 'CH4 emissions enteric in CO2eq',
     'in': ['GWPCH4', 'EE_CH4'],
     'computation': {'name': 'SUM(EE_CH4) * GWPCH4 ',
                     'formula': lambda X: sum(X['EE_CH4']) * X['GWPCH4']}
     },


]


TEE_CO2eq_model = GraphModel(TEE_CO2eq_nodes)

TEE_CO2eq_model.draw()
```

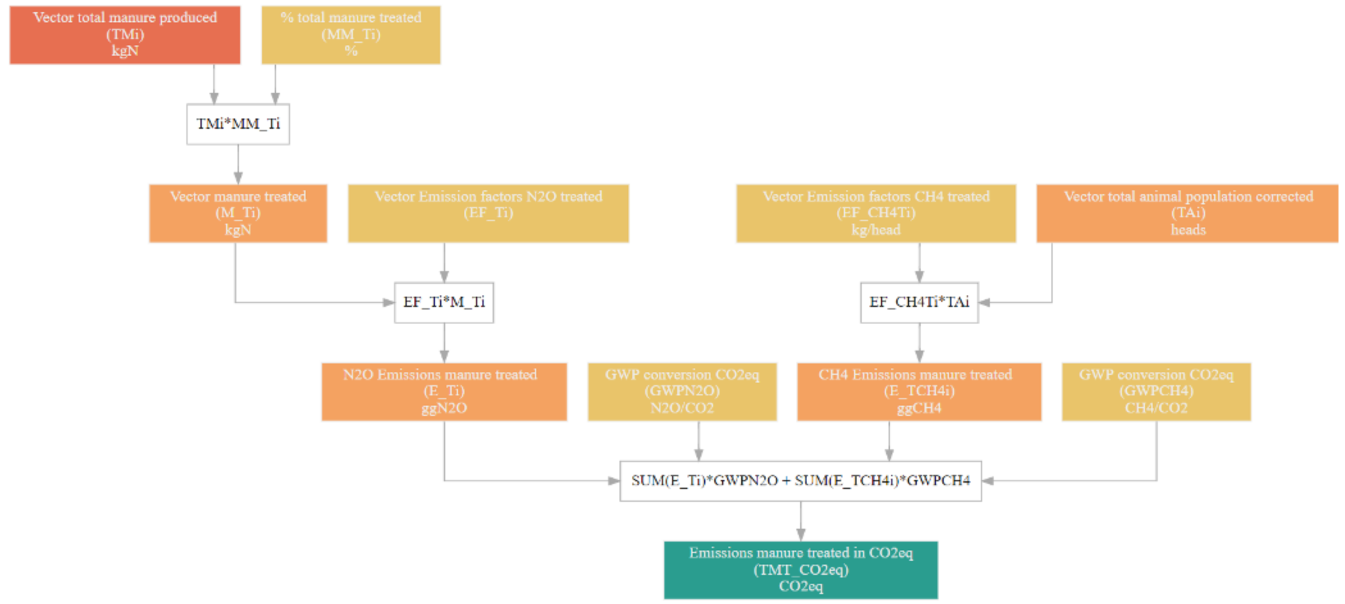
Out[4]:



In [5]:

```
TMT_CO2eq_nodes = [

    # N2O emissions treated

    {'type': 'input',
     'unit': 'kgN',
     'id': 'TMi',
     'name': 'Vector total manure produced',
     },
    {'type': 'parameter',
     'unit': '%',
     'id': 'MM_Ti',
     'name': '% total manure treated',
     },


    {'type': 'variable',
     'unit': 'kgN',
     'id': 'M_Ti',
     'name': 'Vector manure treated',
     'in': ['TMi', 'MM_Ti'],
     'computation': {'name': 'TMi*MM_Ti',
                     'formula': lambda X: X['TMi']*X['MM_Ti']}
     },


    {'type': 'parameter',
     'unit': '',
     'id': 'EF_Ti',
     'name': 'Vector Emission factors N2O treated',
     },


    {'type': 'variable',
     'unit': 'ggN2O',
     'id': 'E_Ti',
     'name': 'N2O Emissions manure treated ',
     'in': ['EF_Ti', 'M_Ti'],
     'computation': {'name': 'EF_Ti*M_Ti',
                     'formula': lambda X: X['EF_Ti']*X['M_Ti']}
     },

    {'type': 'parameter',
     'unit': 'N2O/CO2',
     'id': 'GWPN2O',
     'name': 'GWP conversion CO2eq',
     },


    {'type': 'parameter',
     'unit': 'kg/head',
     'id': 'EF_CH4Ti',
     'name': 'Vector Emission factors CH4 treated',
     'in': ['E_TCH4i_baseline', 'TAHi_2'],
     },



    {'type': 'variable',
     'unit': 'ggCH4',
     'id': 'E_TCH4i',
     'name': 'CH4 Emissions manure treated ',
     'in': ['TAi', 'EF_CH4Ti'],
     'computation': {'name': 'EF_CH4Ti*TAi',
                     'formula': lambda X: X['EF_CH4Ti']*X['TAi']}
     },

    {'type': 'variable',
     'unit': 'heads',
     'id': 'TAi',
     'name': 'Vector total animal population corrected',
     },

    {'type': 'parameter',
     'unit': 'CH4/CO2',
     'id': 'GWPCH4',
     'name': 'GWP conversion CO2eq',
     },



    {'type': 'output',
     'unit': 'CO2eq',
     'id': 'TMT_CO2eq',
     'name': 'Emissions manure treated in CO2eq',
     'in': ['GWPCH4', 'E_TCH4i', 'E_Ti', 'GWPN2O'],
     'computation': {'name': 'SUM(E_Ti)*GWPN2O + SUM(E_TCH4i)*GWPCH4',
                     'formula': lambda X: X['E_Ti'].sum() * X['GWPN2O'] + X['E_TCH4i'].sum() * X['GWPCH4']}
     },
]


TMT_CO2eq_model = GraphModel(TMT_CO2eq_nodes)

TMT_CO2eq_model.draw()
```

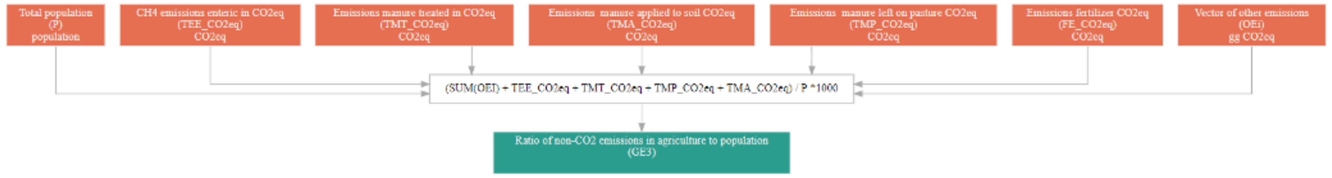
Out[5]:



In [6]:

```
GE3_nodes = [
    {'type': 'input',
     'unit': 'population',
     'id': 'P',
     'name': 'Total population',
     },
    {'type': 'input',
     'unit': 'CO2eq',
        'id': 'TEE_CO2eq',
     'name': 'CH4 emissions enteric in CO2eq',
     },
    {'type': 'input',
     'unit': 'CO2eq',
     'id': 'TMT_CO2eq',
     'name': 'Emissions manure treated in CO2eq',
     },
    {'type': 'input',
     'unit': 'CO2eq',
     'id': 'TMA_CO2eq',
     'name': 'Emissions  manure applied to soil CO2eq',
     },
    {'type': 'input',
     'unit': 'CO2eq',
     'id': 'TMP_CO2eq',
     'name': 'Emissions  manure left on pasture CO2eq',
     },
    {'type': 'input',
     'unit': 'CO2eq',
     'id': 'FE_CO2eq',
     'name': 'Emissions fertilizer CO2eq',
     },
    {'type': 'input',
     'unit': 'gg CO2eq',
     'id': 'OEi',
     'name': 'Vector of other emissions',
     },
    {'type': 'output',
     'unit': '',
     'id': 'GE3',
     'name': 'Ratio of non-CO2 emissions in agriculture to population',
     'in': ['TMP_CO2eq', 'TMA_CO2eq', 'TMT_CO2eq', 'TEE_CO2eq', 'FE_CO2eq', 'OEi', 'P'],
     'computation': {'name': '(SUM(OEI) + TEE_CO2eq + TMT_CO2eq + TMP_CO2eq + TMA_CO2eq) / P *1000',
                     'formula': lambda X: (X['OEi'] + X['TEE_CO2eq'] + X['TMT_CO2eq'] + X['TMP_CO2eq'] + X['TMA_CO2eq'] + X['FE_CO2eq']) / X['P'] * 1e3}
     },


]

model_GE3 = GraphModel(GE3_nodes)

model_GE3.draw()
```

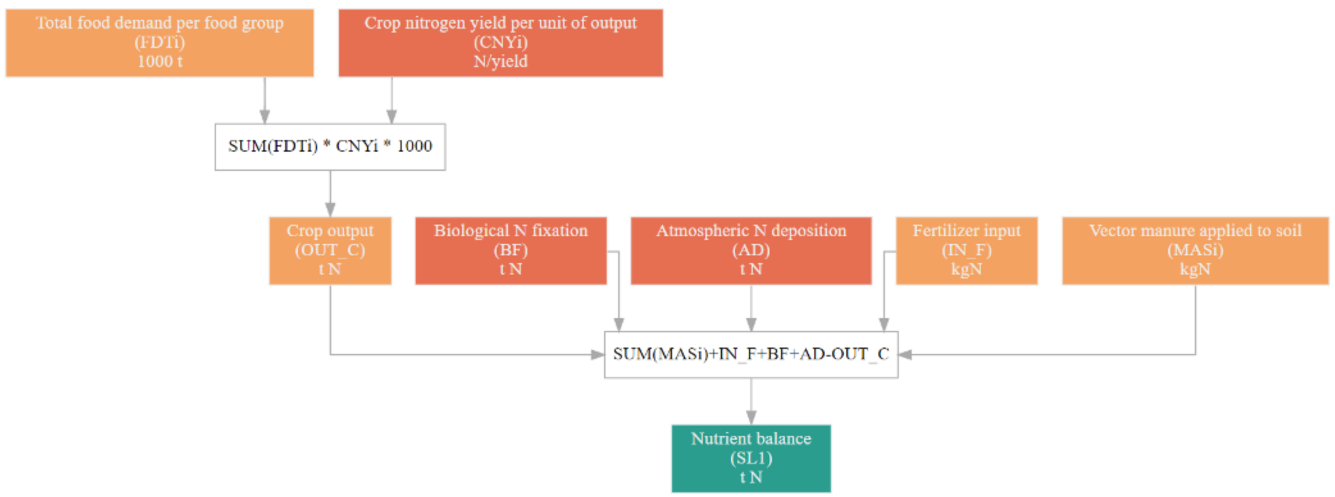
Out[6]:



In [7]:

```
Crop_group = ['Cereals - Excluding Beer', 'Starchy Roots', 'Sugar Crops', 'Sugar & Sweeteners', 'Pulses',
              'Treenuts', 'Oilcrops', 'Vegetable Oils', 'Vegetables', 'Fruits - Excluding Wine',
              'Stimulants', 'Spices']


SL1_nodes = [
    {'type': 'variable',
     'unit': '1000 t',
     'id': 'FDTi',
     'name': 'Total food demand per food group',
     },
    {'type': 'input',
     'unit': 'N/yield',
     'id': 'CNYi',
     'name': 'Crop nitrogen yield per unit of output',
     },
    # This assumes that all the crops in crop_group have the same nitrogen yields;  in phase 2 it would be nice to make the CNYi a vector
    {'type': 'variable',
     'unit': 't N',
     'id': 'OUT_C',
     'name': 'Crop output',
     'in': ['FDTi', 'CNYi'],
     'computation': {'name': 'SUM(FDTi) * CNYi * 1000',
                     'formula': lambda x: sum(x['FDTi'].loc[Crop_group]) * x['CNYi'] * 1e3}
     },
    {'type': 'input',
     'unit': 't N',
     'id': 'BF',
     'name': 'Biological N fixation',
     },
    {'type': 'input',
     'unit': 't N',
     'id': 'AD',
     'name': 'Atmospheric N deposition',
     },
    {'type': 'variable',
     'unit': 'kgN',
     'id': 'IN_F',
     'name': 'Fertilizer input',
     },
    {'type': 'variable',
     'unit': 'kgN',
     'id': 'MASi',
     'name': 'Vector manure applied to soil',
     },
    {'type': 'output',
     'unit': 't N',
     'id': 'SL1',
     'name': 'Nutrient balance',
     'in': ['MASi', 'IN_F', 'BF', 'AD', 'OUT_C'],
     'computation': {'name': 'SUM(MASi)+IN_F+BF+AD-OUT_C',
                     'formula': lambda x: ((sum(x['MASi']) / 1000+x['IN_F']+x['BF']+x['AD'])-x['OUT_C'])}
     }

]

GraphModel(SL1_nodes).draw()
```

Out[7]:



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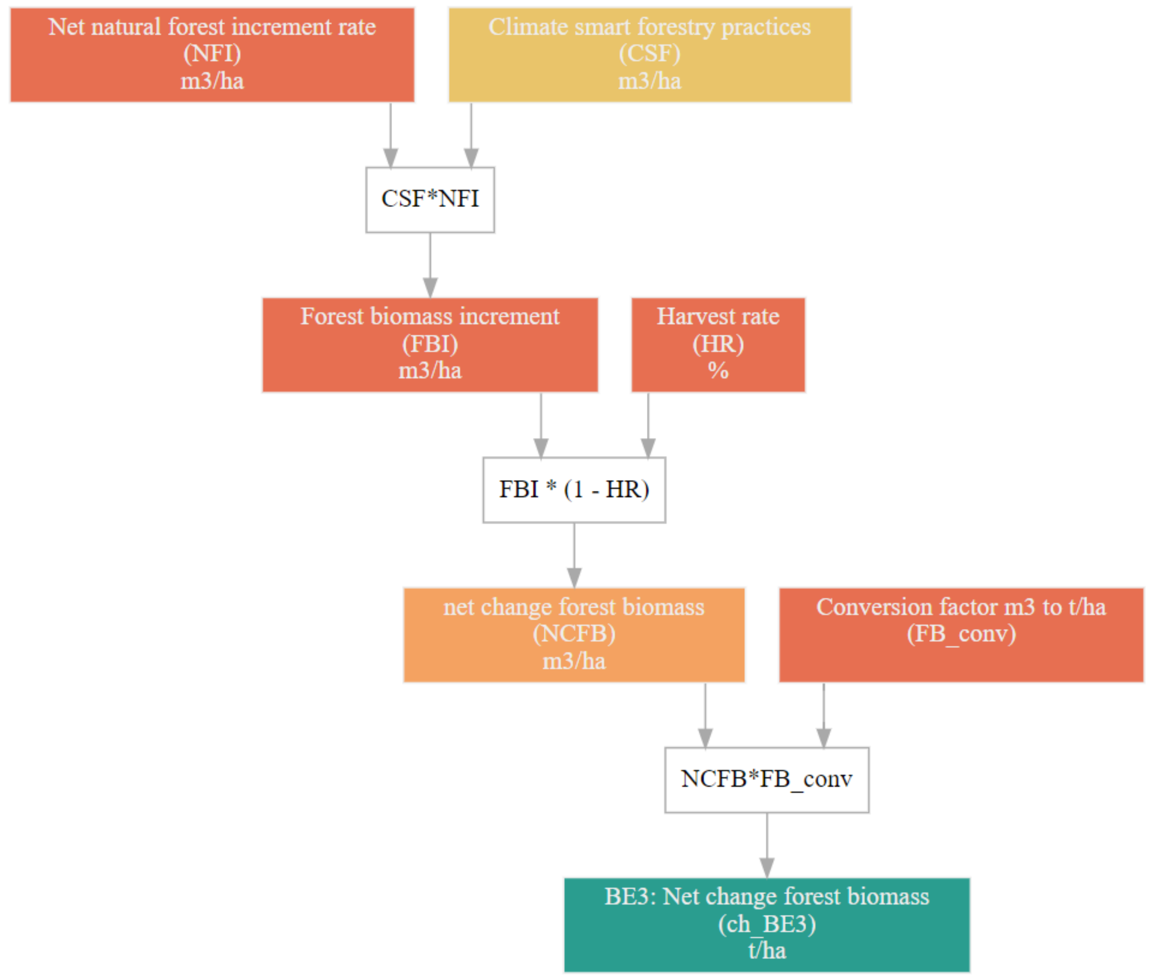
In [8]:

```
BE3_nodes = [
    # This data is only available for Europe.
    {'type': 'input',
     'unit': 'm3/ha',
     'id': 'NFI',
     'name': 'Net natural forest increment rate',
     },
    {'type': 'parameter',
     'unit': 'm3/ha',
     'id': 'CSF',
     'name': 'Climate smart forestry practices',
     },
    {'type': 'input',
     'unit': 'm3/ha',
     'id': 'FBI',
     'name': 'Forest biomass increment',
     'in': ['CSF', 'NFI'],
     'computation': {'name': 'CSF*NFI',
                     'formula': lambda x: x['CSF'] + x['NFI']}
     },
    {'type': 'input',
     'unit': '%',
     'id': 'HR',
     'name': 'Harvest rate',
     },

    {'type': 'variable',
     'unit': 'm3/ha',
     'id': 'NCFB',
     'name': 'net change forest biomass',
     'in': ['HR', 'FBI', ],
     'computation': {'name': 'FBI * (1 - HR)',
                     'formula': lambda x: x['FBI']* (1- x['HR']*1e-2)}
     },
    {'type': 'input',
     'unit': '',
     'id': 'FB_conv',
     'name': 'Conversion factor m3 to t/ha',
     },
    # changes made: BE3 not related to change in forest land & total land area -> change in BE3 t/ha calculated with conversion factor
    {'type': 'output',
     'unit': 't/ha',
     'id': 'ch_BE3',
     'name': 'BE3: Net change forest biomass',
     'in': ['NCFB', 'FB_conv'],
     'computation': {'name': 'NCFB*FB_conv',
                     'formula': lambda x: x['NCFB']*(x['FB_conv'])}
     },


]

GraphModel(BE3_nodes).draw()
```

Out[8]:



B. Simulation model to link sustainable land use to share of forest to total land area

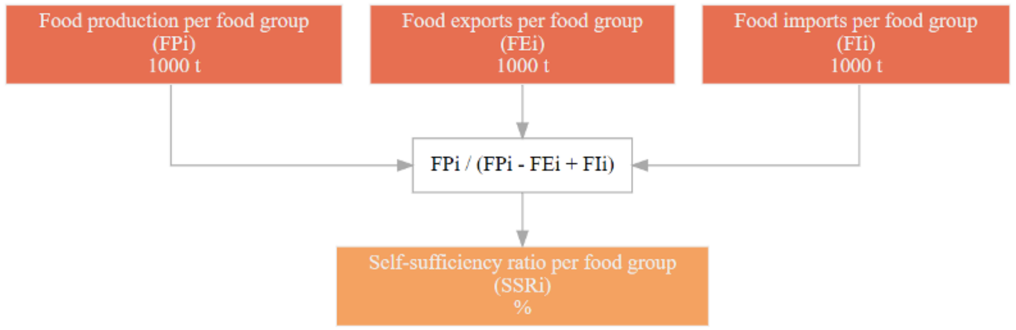
In [1]:

```python
__publisher__ = 'Global Green Growth Institute'
__author__ = 'GGPM Team'
__model_lead__ = 'H. Luchtenbelt'
__programmer__ = 'S. Zabrocki'


from graphmodels.graphmodel import GraphModel
import pandas as pd


animal_group = ['Bovine Meat', 'Pigmeat', 'Poultry Meat',
                'Eggs', 'Milk - Excluding Butter', 'Meat, Other']

crop_group = ['Cereals - Excluding Beer', 'Starchy Roots', 'Sugar Crops',
              'Sugar & Sweeteners', 'Pulses', 'Treenuts', 'Oilcrops',
              'Vegetable Oils', 'Vegetables', 'Fruits - Excluding Wine',
              'Stimulants', 'Spices', 'Alcoholic Beverages']
```

In [2]:

```python
SSRi_nodes = [
    {'type': 'input',
     'unit': '1000 t',
     'id': 'FPi',
     'name': 'Food production per food group',
     },
    {'type': 'input',
     'unit': '1000 t',
     'id': 'FEi',
     'name': 'Food exports per food group',
     },

    {'type': 'input',
     'unit': '1000 t',
     'id': 'FIi',
     'name': 'Food imports per food group',
     },
    {'type': 'variable',
     'unit': '%',
     'id': 'SSRi',
     'name': 'Self-sufficiency ratio per food group',
     'in': ['FPi', 'FEi', 'FIi'],
     'computation': {'name': 'FPi / (FPi - FEi + FIi)',
                     'formula': lambda X: X['FPi'] / (X['FPi'] - X['FEi'] + X['FIi'])}
     },
]

GraphModel(SSRi_nodes).draw()
```

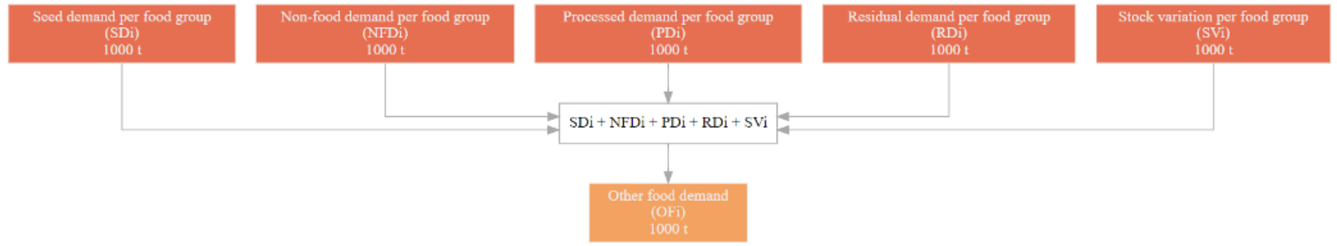
Out[2]:



In [3]:

```python
OFI_nodes = [
    {'type': 'variable',
     'unit': '1000 t',
     'id': 'OFi',
     'name': 'Other food demand',
     'in': ['SDi', 'NFDi', 'PDi', 'RDi', 'SVi'],
     'computation': {'name': 'SDi + NFDi + PDi + RDi + SVi',
                     'formula': lambda X: X['SDi'] + X['NFDi'] + X['PDi'] + X['RDi'] + X['SVi']}
     },
        {'type': 'input',
     'unit': '1000 t',
     'id': 'SDi',
     'name': 'Seed demand per food group',
     },
    {'type': 'input',
     'unit': '1000 t',
     'id': 'NFDi',
     'name': 'Non-food demand per food group',
     },
    {'type': 'input',
     'unit': '1000 t',
     'id': 'PDi',
     'name': 'Processed demand per food group',
     },
    {'type': 'input',
     'unit': '1000 t',
     'id': 'RDi',
     'name': 'Residual demand per food group',
     },
    {'type': 'input',
     'unit': '1000 t',
     'id': 'SVi',
     'name': 'Stock variation per food group',
     },
]

GraphModel(OFI_nodes).draw()
```


Out[3]:

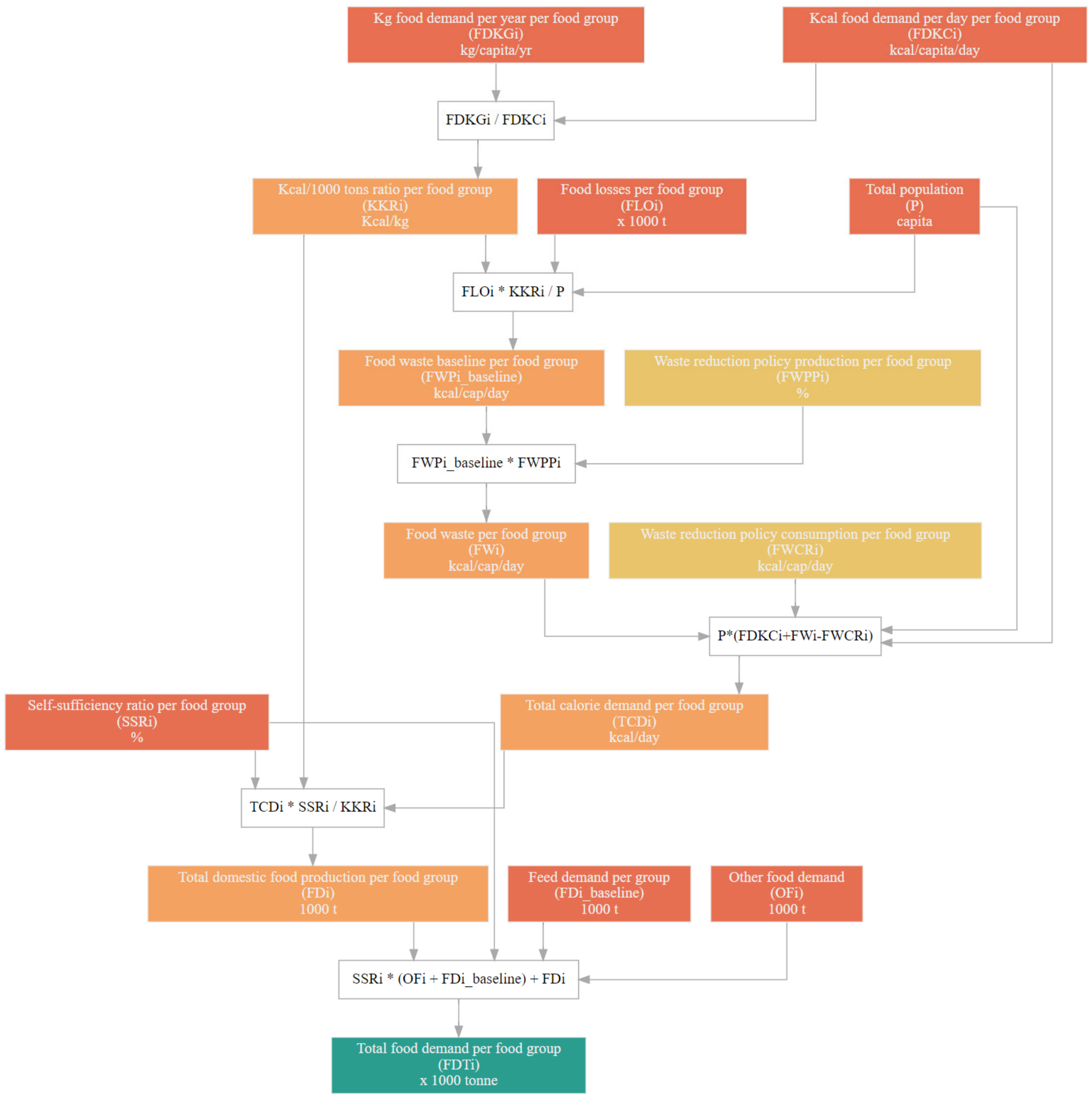


In [4]:

```python
# FOOD DEMAND PER FOOD GROUP AGGREGATION

FDTi_nodes = [
    {'type': 'variable',
     'unit': 'kcal/day',
     'id': 'TCDi',
     'name': 'Total calorie demand per food group',
     'in': ['P', 'FWi', 'FWCRi', 'FDKCi'],
     'computation': {'name': 'P*(FDKCi+FWi-FWCRi)',
                     'formula': lambda X: X['P'] * (X['FDKCi'] + X['FWi'] / 365 - X['FWCRi'])}
     },
    {'type': 'parameter',
     'unit': 'kcal/cap/day',
     'id': 'FWCRi',
     'name': 'Waste reduction policy consumption per food group',
     },
    {'type': 'parameter',
     'id': 'FWPPi',
     'unit': '%',
     'name': 'Waste reduction policy production per food group',
     },
    {'type': 'variable',
     'unit': 'kcal/cap/day',
     'id': 'FWi',
     'name': 'Food waste per food group',
     'in': ['FWPi_baseline', 'FWPPi'],
     'computation': {'name': 'FWPi_baseline * FWPPi',
                     'formula': lambda X: X['FWPi_baseline'] * X['FWPPi'] * 1e-2}
     },
    {'type': 'variable',
     'unit': 'kcal/cap/day',
     'id': 'FWPi_baseline',
     'name': 'Food waste baseline per food group',
     'in': ['FLOi', 'P', 'KKRi'],
     'computation': {'name': 'FLOi * KKRi / P',
                     'formula': lambda X: X['FLOi'] * X['KKRi'] / X['P']}
     },
    {'type': 'input',
     'unit': 'x 1000 t',
     'id': 'FLOi',
     'name': 'Food losses per food group',
     },
    {'type': 'variable',
     'id': 'KKRi',
     'name': 'Kcal/1000 tons ratio per food group',
     'unit': 'Kcal/kg',
     'in': ['FDKGi', 'FDKCi'],
     'computation': {'name': 'FDKGi / FDKCi',
                     'formula': lambda X: X['FDKCi'] / (X['FDKGi'] * 1e-6)}
     },
    {'type': 'input',
     'unit': 'kg/capita/yr',
     'id': 'FDKGi',
     'name': 'Kg food demand per year per food group',
     },
    {'type': 'input',
     'unit': 'kcal/capita/day',
     'id': 'FDKCi',
     'name': 'Kcal food demand per day per food group',
     },
    {'type': 'input',
     'unit': 'capita',
     'id': 'P',
     'name': 'Total population',
     },
    {'type': 'input',
     'unit': '%',
     'id': 'SSRi',
     'name': 'Self-sufficiency ratio per food group',
     },


    {'type': 'variable',
     'unit': '1000 t',
     'id': 'FDi',
     'name': 'Total domestic food production per food group',
     'in': ['KKRi', 'SSRi', 'TCDi'],
     'computation': {'name': 'TCDi * SSRi / KKRi',
                     'formula': lambda X: X['TCDi'] * X['SSRi'] / X['KKRi'] * 365}  # to check
     },
    {'type': 'input',
     'unit': '1000 t',
     'id': 'FDi_baseline',
     'name': 'Feed demand per group',

     },
    {'type': 'input',
     'unit': '1000 t',
     'id': 'OFi',
     'name': 'Other food demand',
     },
```

```
    {'type': 'output',
     'id': 'FDTi',
     'name': 'Total food demand per food group',
     'unit': 'x 1000 tonne',
     'in': ['FDi', 'OFi', 'FDi_baseline', 'SSRi'],
     'computation': {'name': 'SSRi * (OFi + FDi_baseline) + FDi',
                     'formula': lambda X: X['SSRi'] * (X['OFi'] + X['FDi_baseline']) + X['FDi']}
    },
]

FDTi_model = GraphModel(FDTi_nodes)


FDTi_model.draw()
```

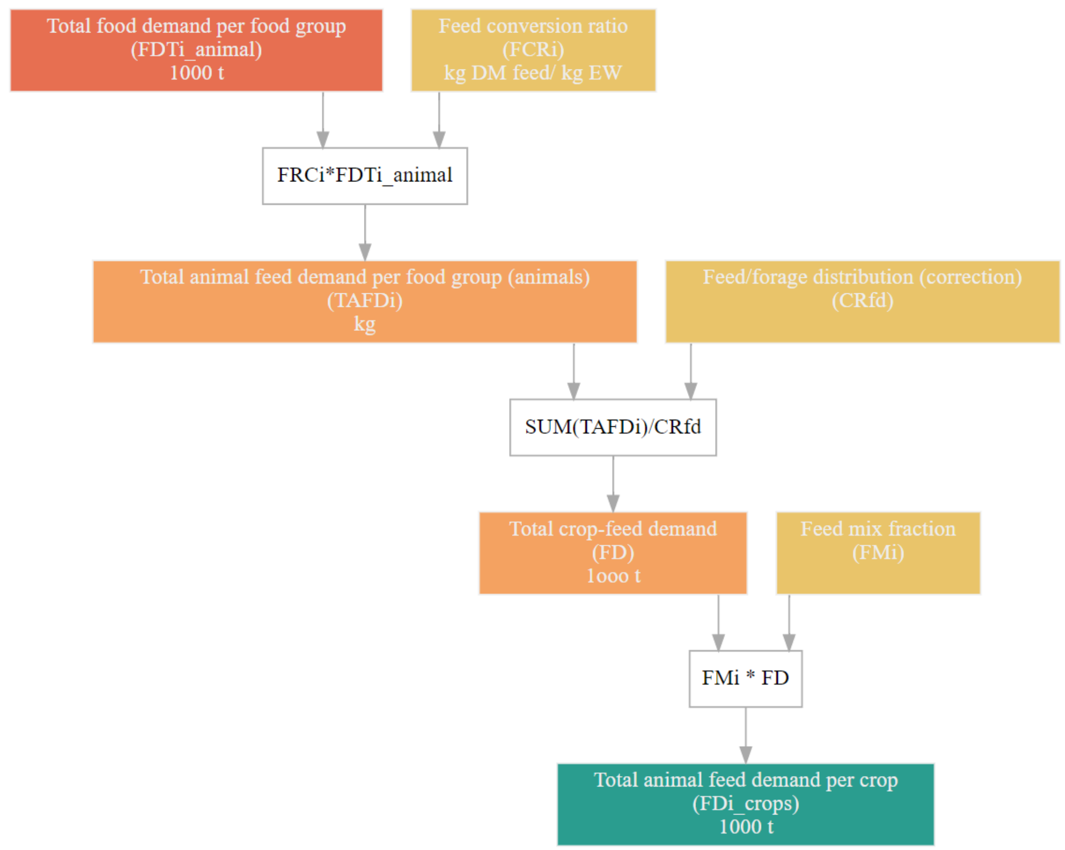
Out[4]:



In [5]:

```
# ANIMAL FEED DEMAND PER FOOD GROUP

FDi_nodes = [
    # FDTi from the previous function
    {'type': 'input',
     'unit': '1000 t',
     'id': 'FDTi_animal',
     'name': 'Total food demand per food group',

     },
    {'type': 'output',
     'unit': '1000 t',
     'id': 'FDi_crops',
     'name': 'Total animal feed demand per crop',
     'in': ['FMi', 'FD'],
     'computation': {'name': 'FMi * FD',
                     'formula': lambda X: X['FMi'] * X['FD']}
     },
    {'type': 'parameter',
     'unit': '',
     'id': 'FMi',
     'name': 'Feed mix fraction',
     },
    {'type': 'variable',
     'unit': '1ooo t',
     'id': 'FD',
     'name': 'Total crop-feed demand',
     'in': ['TAFDi', 'CRfd'],
     'computation': {'name': 'SUM(TAFDi)/CRfd',
                     'formula': lambda X: X['TAFDi'].sum() / X['CRfd']}
     },
    {'type': 'parameter',
     'unit': '',
     'id': 'CRfd',
     'name': 'Feed/forage distribution (correction)',
     },

    {'type': 'parameter',
     'unit': 'kg DM feed/ kg EW',
     'id': 'FCRi',
     'name': 'Feed conversion ratio',
     },
    {'type': 'variable',
     'unit': 'kg',
     'id': 'TAFDi',
     'name': 'Total animal feed demand per food group (animals)',
     'in': ['FCRi', 'FDTi_animal'],
     'computation': {'name': 'FRCi*FDTi_animal',
                     'formula': lambda X: (X['FCRi'] * X['FDTi_animal'])}
     }
]

FDi_crops_Model = GraphModel(FDi_nodes)

FDi_crops_Model.draw()
```

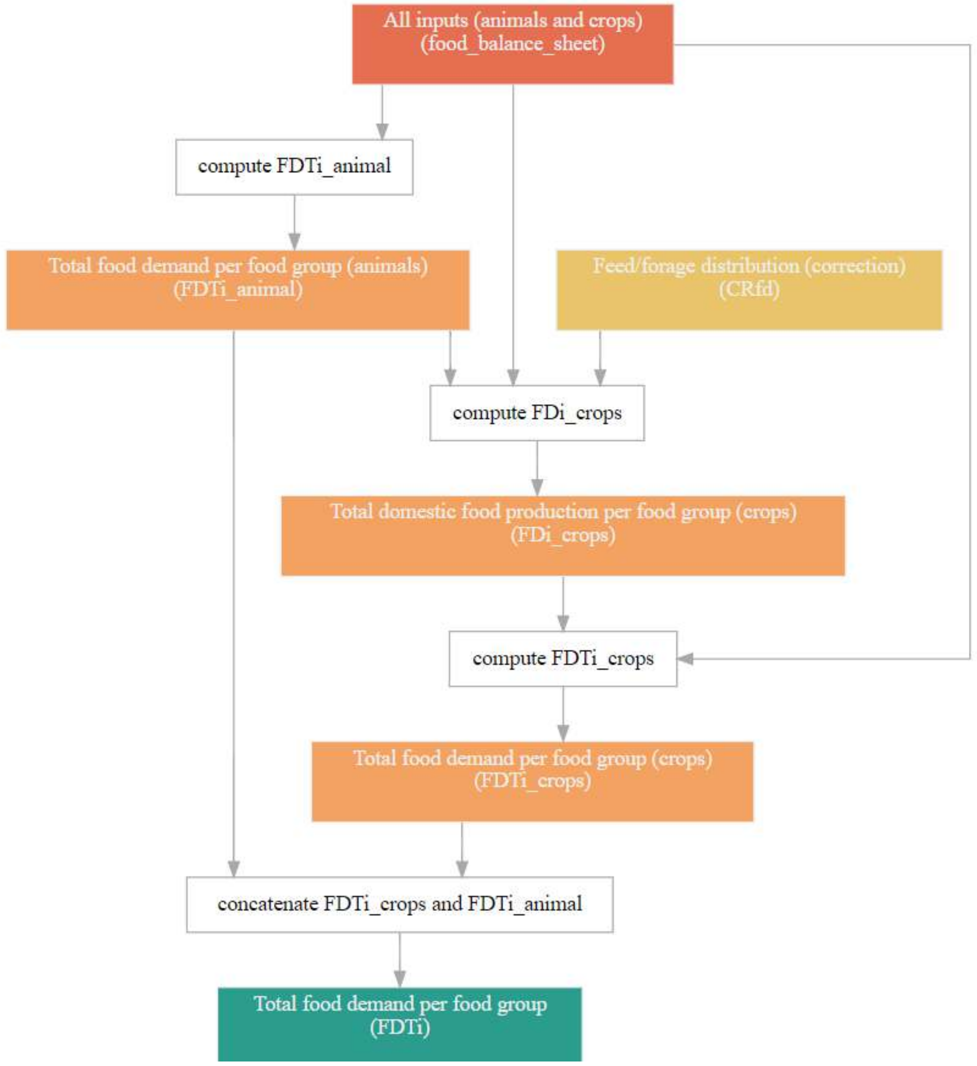
Out[5]:



In [6]:

```
# FOOD DEMAND PER FOOD GROUP AGGREGATION with feed taken into account

def compute_FDTi_animal(X):
    X = X.copy()
    X['FDi_baseline'] = X['FDi']
    result = FDTi_model.run(X)['FDTi']
    return result.loc[animal_group]


def compute_FDTi_crops(X):
    X = X.copy()
    X['FDi_baseline'] = X['FDi_crops']
    result = FDTi_model.run(X)['FDTi']
    return result.loc[crop_group]


def compute_FDi_crops(X):
    X = X.copy()
    X['FDi_baseline'] = X['FDi']
    result = FDi_crops_Model.run(X)['FDi_crops']
    return result


full_FDTi_nodes = [
    {
        'id': 'food_balance_sheet',
        'name': 'All inputs (animals and crops)',
        'unit': '',
        'type': 'input',
    },
    {
        'id': 'FDTi_animal',
        'name': 'Total food demand per food group (animals)',
        'unit': '',
        'type': 'variable',
        'in': ['food_balance_sheet'],
        'computation': {'name': 'compute FDTi_animal', 'formula': lambda X: compute_FDTi_animal(X)}
    },
    {
        'id': 'FDi_crops',
        'name': 'Total domestic food production per food group (crops)',
        'unit': '',
        'type': 'variable',
        'in': ['food_balance_sheet', 'FDTi_animal', 'CRfd'],
        'computation': {'name': 'compute FDi_crops', 'formula': lambda X: compute_FDi_crops(X)}
    },
    {
        'id': 'FDTi_crops',
        'name': 'Total food demand per food group (crops)',
        'unit': '',
        'type': 'variable',
        'in': ['food_balance_sheet', 'FDi_crops'],
        'computation': {'name': 'compute FDTi_crops', 'formula': lambda X: compute_FDTi_crops(X)}
    },
    {
        'id': 'FDTi',
        'name': 'Total food demand per food group',
        'unit': '',
        'type': 'output',
        'in': ['FDTi_animal', 'FDTi_crops'],
        'computation': {'name': 'concatenate FDTi_crops and FDTi_animal', 'formula': lambda X: pd.concat([X['FDTi_animal'], X['FDTi_crops']])}
    },
    {
        'id': 'CRfd',
        'name': 'Feed/forage distribution (correction)',
        'unit': '',
        'type': 'parameter',
    },
]


model_full_FDTi = GraphModel(full_FDTi_nodes)

model_full_FDTi.draw()
```

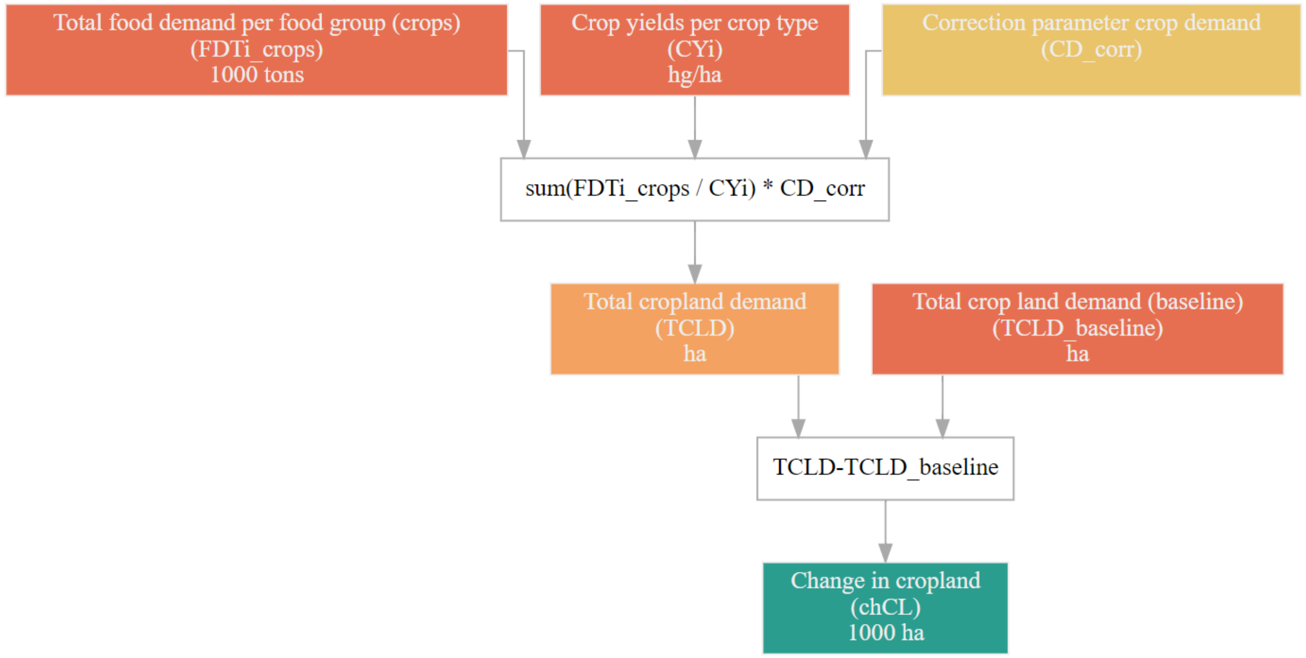
Out[6]:



In [7]:

```
Crop_group2 = ['Cereals - Excluding Beer', 'Fruits - Excluding Wine', 'Oilcrops',
               'Pulses', 'Starchy Roots', 'Sugar Crops', 'Treenuts', 'Vegetables']


chCL_nodes = [
    # this is the value that is computed with the addition of animal feed (so the CRfd part)
    {'type': 'input',
     'id': 'FDTi_crops',
     'name': 'Total food demand per food group (crops)',
     'unit': '1000 tons',
     },
    {'type': 'input',
     'unit': 'hg/ha',
     'id': 'CYi',
     'name': 'Crop yields per crop type',
     },
    # this was TCL2017i
    {'type': 'input',
     'unit': 'ha',
     'id': 'TCLD_baseline',
     'name': 'Total crop land demand (baseline)',
     },
    {'type': 'parameter',
     'unit': '',
     'id': 'CD_corr',
     'name': 'Correction parameter crop demand',
     },
    {'type': 'variable',
     'id': 'TCLD',
     'name': 'Total cropland demand',
     'unit': 'ha',
     'in': ['FDTi_crops', 'CYi', 'CD_corr'],
     'computation': {'name': 'sum(FDTi_crops / CYi) * CD_corr',
                     'formula': lambda X: (X['FDTi_crops'] / X['CYi']).sum() * X['CD_corr'] * 1e7}
     },
    {'type': 'output',
     'id': 'chCL',
     'name': 'Change in cropland',
     'unit': '1000 ha',
     'in': ['TCLD', 'TCLD_baseline'],
     'computation': {'name': 'TCLD-TCLD_baseline',
                     'formula': lambda X: (X['TCLD'] - X['TCLD_baseline']) * 1e-5}
     }
]

chCL_model = GraphModel(chCL_nodes)

chCL_model.draw()
```

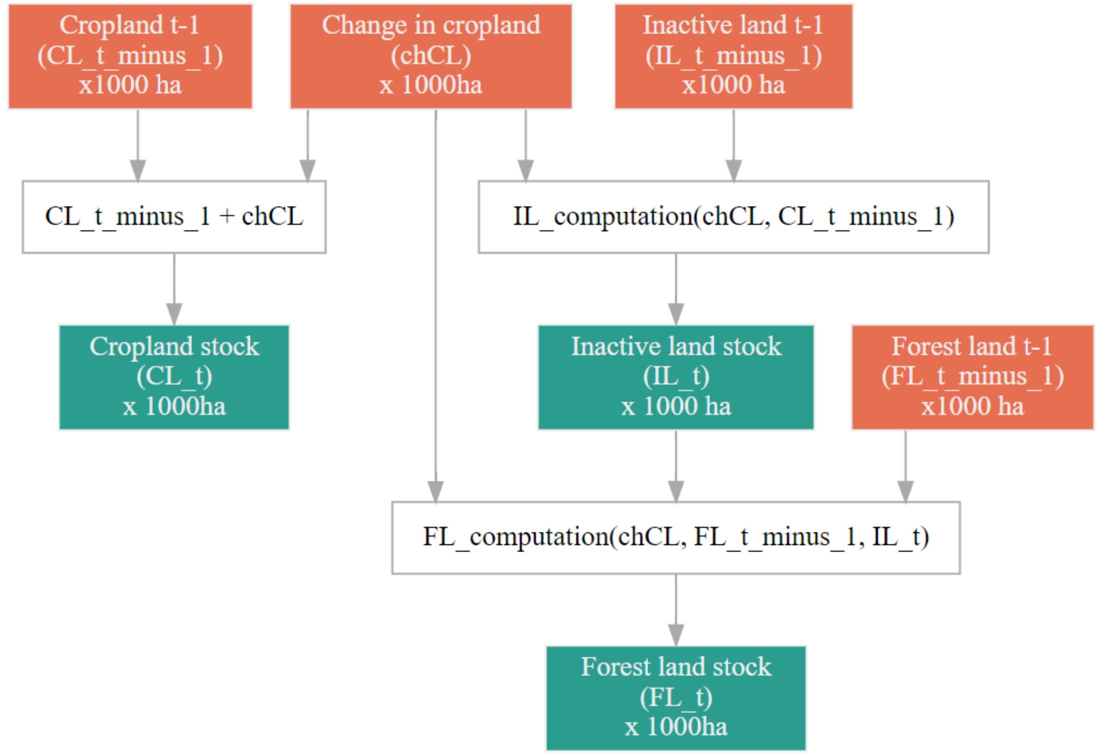
Out[7]:



In [8]:

```
def FL(chCL, FL_t_minus_1, IL_t_minus_1):
    if (chCL > 0) and (IL_t_minus_1 - chCL < 0):
        return FL_t_minus_1 + IL_t_minus_1 - chCL
    else:
        return FL_t_minus_1


def IL(chCL, IL_t_minus_1):
    if (chCL > 0) and (IL_t_minus_1 - chCL < 0):
        return 0
    else:
        return IL_t_minus_1 - chCL


CH_IL_FL_nodes = [
    # from previous part
    {'type': 'input',
     'id': 'chCL',
     'name': 'Change in cropland',
     'unit': 'x 1000ha'
     },
    {'type': 'input',
     'unit': 'x1000 ha',
     'id': 'CL_t_minus_1',
     'name': 'Cropland t-1',
     },
    {'type': 'input',
     'unit': 'x1000 ha',
     'id': 'IL_t_minus_1',
     'name': 'Inactive land t-1',
     },
    {'type': 'input',
     'unit': 'x1000 ha',
     'id': 'FL_t_minus_1',
     'name': 'Forest land t-1',
     },
    {'type': 'output',
     'id': 'CL_t',
     'name': 'Cropland stock',
     'unit': 'x 1000ha',
     'in': ['chCL', 'CL_t_minus_1'],
     'computation': {'name': 'CL_t_minus_1 + chCL',
                     'formula': lambda X: X['chCL'] + X['CL_t_minus_1']}
     },
    {'type': 'output',
     'id': 'IL_t',
     'name': 'Inactive land stock',
     'unit': 'x 1000 ha',
     'in': ['chCL', 'IL_t_minus_1'],
     'computation': {'name': 'IL_computation(chCL, CL_t_minus_1) ',
                     'formula': lambda X: IL(X['chCL'], X['IL_t_minus_1'])}
     },
    {'type': 'output',
     'id': 'FL_t',
     'name': 'Forest land stock',
     'unit': 'x 1000ha',
     'in': ['chCL', 'FL_t_minus_1', 'IL_t'],
     'computation': {'name': 'FL_computation(chCL, FL_t_minus_1, IL_t)',
                     'formula': lambda X: FL(X['chCL'], X['FL_t_minus_1'], X['IL_t'])}
     },
]


model_CH_IL_FL = GraphModel(CH_IL_FL_nodes)


model_CH_IL_FL.draw()
```

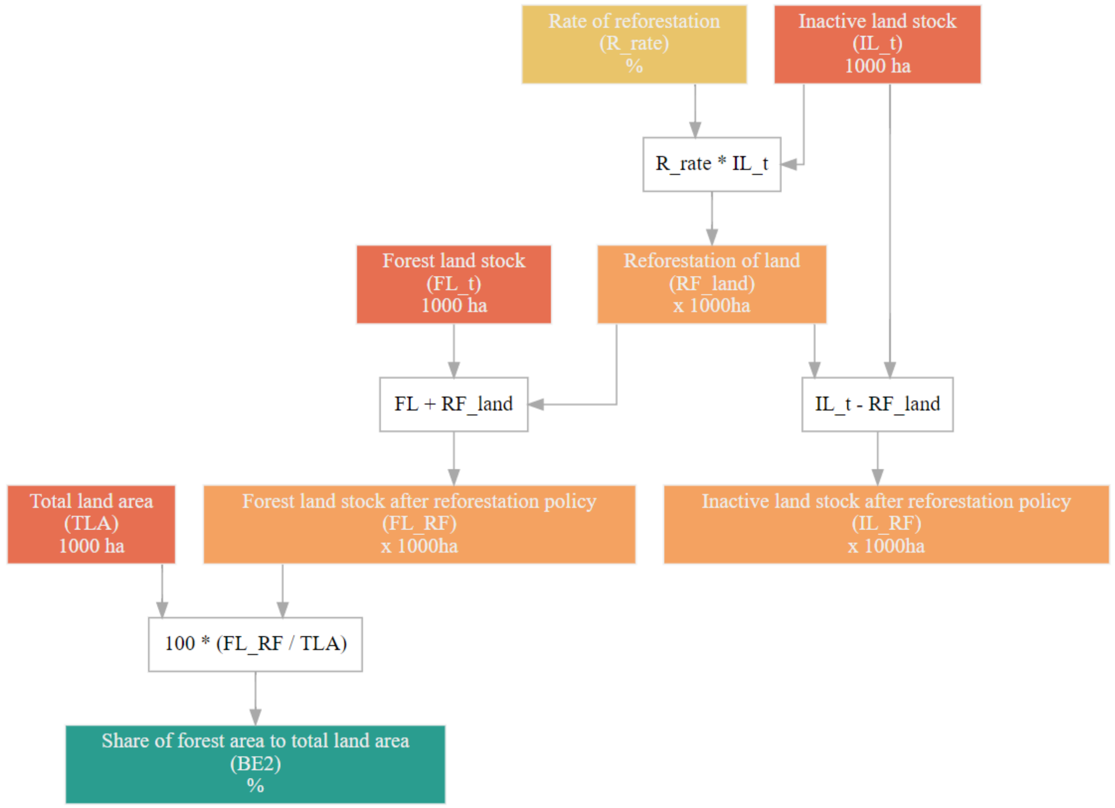
Out[8]:



In [9]:

```
BE2_partial_nodes = [
    {'type': 'input',
     'unit': '1000 ha',
     'id': 'TLA',
     'name': 'Total land area',
     },
    {'type': 'input',
     'unit': '1000 ha',
     'id': 'FL_t',
     'name': 'Forest land stock',
     },
    {'type': 'input',
     'unit': '1000 ha',
     'id': 'IL_t',
     'name': 'Inactive land stock',
     },
    {'type': 'parameter',
     'unit': '%',
     'id': 'R_rate',
     'name': 'Rate of reforestation',
     },
    {'type': 'variable',
     'id': 'RF_land',
     'name': 'Reforestation of land',
     'unit': 'x 1000ha',
     'in': ['R_rate', 'IL_t'],
     'computation': {'name': 'R_rate * IL_t',
                     'formula': lambda X: X['R_rate'] * 1e-2 * X['IL_t']}
     },
    {'type': 'variable',
     'id': 'FL_RF',
     'name': 'Forest land stock after reforestation policy',
     'unit': 'x 1000ha',
     'in': ['RF_land', 'FL_t'],
     'computation': {'name': 'FL + RF_land',
                     'formula': lambda X: X['FL_t'] + X['RF_land']}
     },
    {'type': 'variable',
     'id': 'IL_RF',
     'name': 'Inactive land stock after reforestation policy',
     'unit': 'x 1000ha',
     'in': ['RF_land', 'IL_t'],
     'computation': {'name': 'IL_t - RF_land',
                     'formula': lambda X: X['IL_t'] - X['RF_land']}
     },
    {'type': 'output',
     'id': 'BE2',
     'name': 'Share of forest area to total land area',
     'unit': '%',
     'in': ['TLA', 'FL_RF'],
     'computation': {'name': '100 * (FL_RF / TLA)',
                     'formula': lambda X: 1e2 * X['FL_RF'] / X['TLA']}
     },
]


model_BE2_partial = GraphModel(BE2_partial_nodes)

model_BE2_partial.draw()
```

Out[9]:



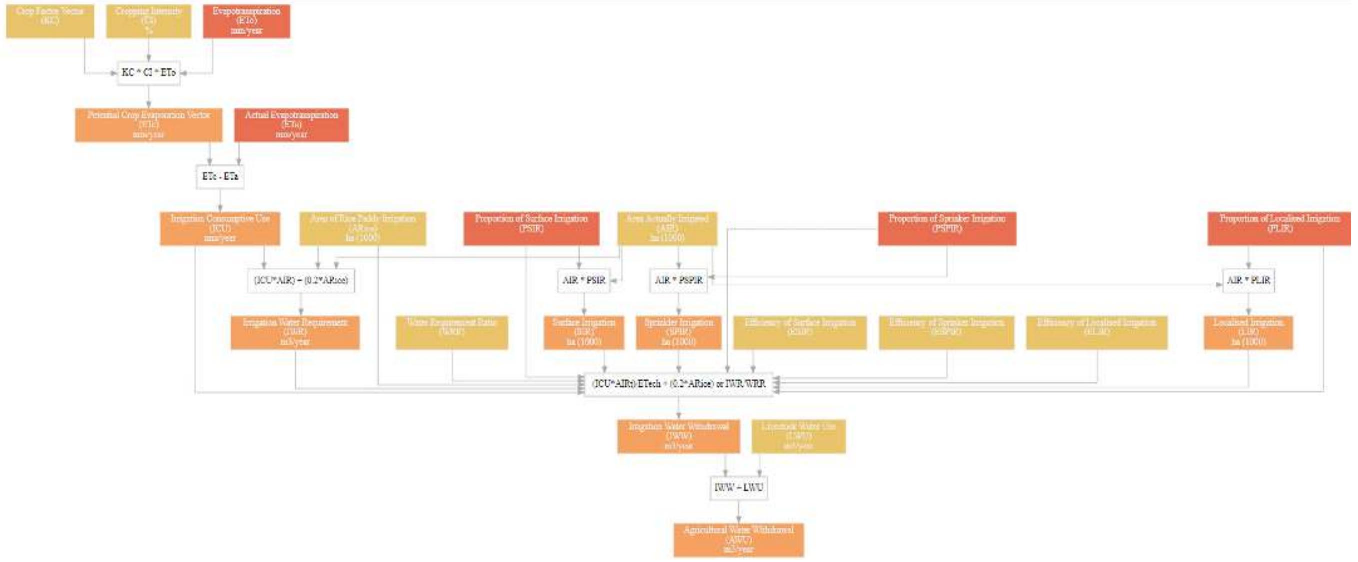
C. Simulation model for water use efficiency

In [1]:

```
import numpy as np
from graphmodels.graphmodel import GraphModel

__publisher__ = 'Global Green Growth Institute'
__author__ = 'GGPM Team'
__model_lead__ = 'S. Gerrard'
__programmer__ = 'S. Zabrocki'

# all water metrics from FAO data needed to be converted to 10^9 before modelling

# Agricultural Water Use
# for future projections we can assume there will not be a change in type of crops.
IWW_nodes = [{'type': 'parameter', 'unit': '',
              'name': 'Crop Factor Vector', 'id': 'KC'},
             {'type': 'parameter', 'unit': '%',
              'name': 'Cropping Intensity', 'id': 'CI'},
             {'type': 'input', 'unit': 'mm/year',
              'name': 'Evapotranspiration', 'id': 'ETo'},
             {'type': 'variable',
              'name': 'Potential Crop Evaporation Vector',
              'unit': 'mm/year',
              'in': ['KC', 'ETo', 'CI'],
              'computation': {'name': 'KC * CI * ETo', 'formula': lambda X: X['KC'] * X['CI'] * X['ETo']},
              'id': 'ETc'},
             {'type': 'input',
              'unit': 'mm/year',
              'name': 'Actual Evapotranspiration',
              'id': 'ETa'},
             {'type': 'variable',
              'name': 'Irrigation Consumptive Use',
              'unit': 'mm/year',
              'in': ['ETc', 'ETa'],
              'computation': {'name': 'ETc - ETa', 'formula': lambda X: X['ETc'] - X['ETa']},
              'id': 'ICU'},
             {'type': 'parameter',
              'unit': 'ha (1000)',
              'name': 'Area Actually Irrigated',
              'id': 'AIR'},
             {'type': 'parameter',
              'unit': 'ha (1000)',
              'name': 'Area of Rice Paddy Irrigation',
              'id': 'ARice'},
             {'type': 'variable',
              'name': ' Irrigation Water Requirement',
              'unit': 'm3/year',
              'in': ['ICU', 'AIR', 'ARice'],
              'computation': {'name': '(ICU*AIR) + (0.2*ARice) ', 'formula': lambda X: sum((X['ICU'] * X['AIR']) + X['ARice']*0.2)},
              'id': 'IWR'},
             {'type': 'parameter',
              'name': 'Water Requirement Ratio',
              'unit': '',
              'id': 'WRR'},
             # Type of Irrigation Scenario
             {'type': 'input',
              'unit': '',
              'name': 'Proportion of Surface Irrigation',
              'id': 'PSIR'},
             {'type': 'input',
              'unit': '',
              'name': 'Proportion of Sprinker Irrigation',
              'id': 'PSPIR'},
             {'type': 'input',
              'unit': '',
              'name': 'Proportion of Localised Irrigation',
              'id': 'PLIR'},
             {'type': 'parameter',
              'unit': '',
              'name': 'Efficiency of Surface Irrigation',
              'id': 'ESIR'},

             {'type': 'parameter',
              'unit': '',
              'name': 'Efficiency of Sprinker Irrigation',
              'id': 'ESPIR'},
             {'type': 'parameter',
              'unit': '',
              'name': 'Efficiency of Localised Irrigation',
              'id': 'ELIR'},
             {'type': 'variable',
              'name': 'Surface Irrigation',
              'unit': 'ha (1000)',
              'in': ['AIR', 'PSIR'],
              'computation': {'name': 'AIR * PSIR', 'formula': lambda X: (X['AIR'] * X['PSIR'])},
              'id': 'SIR'},
             {'type': 'variable',
              'name': 'Sprinkler Irrigation',
              'unit': 'ha (1000)',
              'in': ['AIR', 'PSPIR'],
              'computation': {'name': 'AIR * PSPIR', 'formula': lambda X: (X['AIR'] * X['PSPIR'])},
              'id': 'SPIR'},
             {'type': 'variable',
              'name': 'Localised Irrigation',
              'unit': 'ha (1000)',
              'in': ['AIR', 'PLIR'],
              'computation': {'name': 'AIR * PLIR', 'formula': lambda X: (X['AIR'] * X['PLIR'])},
              'id': 'LIR'},
             # Irrigation Water Withdrawal
             # to improve
             {'type': 'variable',
              'name': ' Irrigation Water Withdrawal',
              'unit': 'm3/year',
              'in': ['ICU', 'SIR', 'SPIR', 'LIR', 'ARice', 'ESIR', 'ESPIR', 'ELIR', 'IWR', 'WRR', 'PSIR', 'PSPIR', 'PLIR'],
              'computation': {'name': '(ICU*AIRt)/ETech + (0.2*ARice) or IWR/WRR', 'formula': lambda X: sum((X['ICU'] * X['SIR']/X['ESIR']) \
                                                                                                + (X['ICU'] * X['SPIR']/X['ESPIR']) \
                                                                                                + (X['ICU'] * X['LIR']/X['ELIR']) \
                                                                                                + X['ARice']*0.2) \
                                                                                                if (X['PSIR']+X['PSPIR']+X['PLIR']) > 0 and (X['PSIR']+X['PSPIR']+X['PLIR']) <= 1 \
                                                                                                else X['IWR']/X['WRR']},
```

```
              'id': 'IWW'},
             {'type': 'parameter',
              'name': 'Livestock Water Use',
              'unit': 'm3/year',
              'id': 'LWU'},
             {'type': 'variable',
              'name': 'Agricultural Water Withdrawal',
              'unit': 'm3/year',
              'in': ['IWW', 'LWU'],
              'computation': {'name': 'IWW + LWU', 'formula': lambda x: x['IWW'] + x['LWU']},
              'id': 'AWU'},
             ]

GraphModel(IWW_nodes).draw()
```

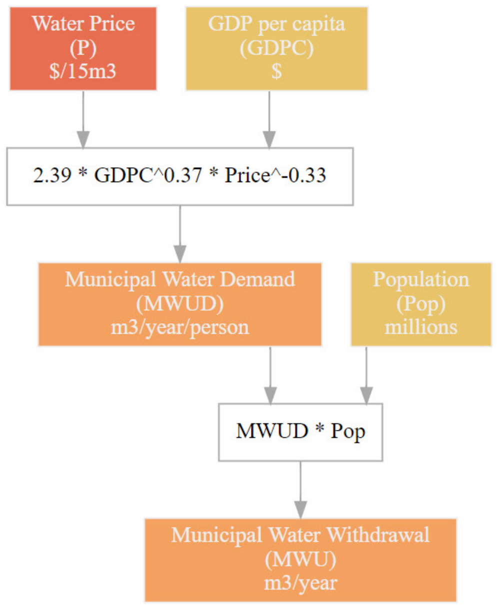
Out[1]:



In [2]:

```
# Municipal Water Use
MWU_nodes = [{'type': 'input',
              'name': 'Water Price',
              'unit': '$/15m3',
              'id': 'P'},
             {'type': 'parameter',
              'name': 'GDP per capita',
              'unit': '$',
              'id': 'GDPC'},
             {'type': 'variable',
              'name': 'Municipal Water Demand',
              'unit': 'm3/year/person',
              'in': ['P', 'GDPC'],
              'computation': {'name': '2.39 * GDPC^0.37 * Price^-0.33 ', 'formula': lambda x: 2.39 * x['GDPC']**0.37 * x['P']**-0.33},
              'id': 'MWUD'},
             {'type': 'parameter',
              'name': 'Population',
              'unit': 'millions',
              'id': 'Pop'},
             {'type': 'variable',
              'name': 'Municipal Water Withdrawal',
              'unit': 'm3/year',
              'in': ['Pop', 'MWUD'],
              'computation': {'name': 'MWUD * Pop ', 'formula': lambda x: x['MWUD'] * x['Pop']},
              'id': 'MWU'},
             ]

GraphModel(MWU_nodes).draw()
```

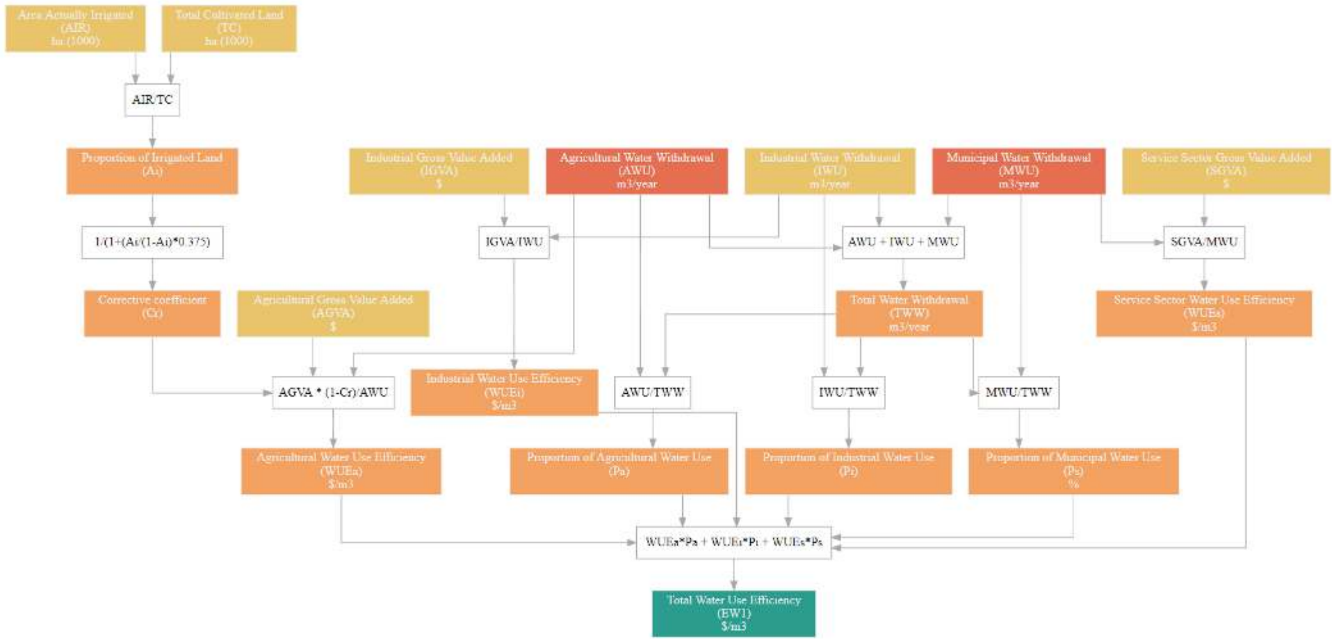
Out[2]:



In [3]:

```
EW1_nodes = [
    # Industrial Water Use
    {'type': 'parameter',
     'name': 'Industrial Water Withdrawal',
     'unit': 'm3/year',
     'id': 'IWU'},
    {'type': 'parameter',
     'unit': 'ha (1000)',
     'name': 'Area Actually Irrigated',
     'id': 'AIR'},
    {'type': 'input',
        'name': 'Municipal Water Withdrawal',
        'unit': 'm3/year',
        'id': 'MWU'},
    {'type': 'input',
     'name': 'Agricultural Water Withdrawal',
     'unit': 'm3/year',
     'id': 'AWU'},

    # Total Water Withdrawal
    {'type': 'variable',
        'name': 'Total Water Withdrawal',
        'unit': 'm3/year',
        'in': ['MWU', 'AWU', 'IWU'],
        'computation': {'name': 'AWU + IWU + MWU', 'formula': lambda x: x['AWU'] + x['IWU'] + x['MWU']},
        'id': 'TWW'},

    # Agricultural Water Use Efficiency
    {'type': 'parameter',
        'unit': 'ha (1000)',
        'name': 'Total Cultivated Land',
        'id': 'TC'},
    {'type': 'variable',
        'name': 'Proportion of Irrigated Land',
        'unit': '',
        'in': ['AIR', 'TC'],
        'computation': {'name': 'AIR/TC', 'formula': lambda x: x['AIR'] / x['TC']},
        'id': 'Ai'},
    {'type': 'variable',
     'name': 'Corrective coefficient',
     'unit': '',
     'in': ['Ai'],
     'computation': {'name': '1/(1+(Ai/(1-Ai)*0.375)', 'formula': lambda x: 1/(1 + (x['Ai']/(1-x['Ai'])*0.375))},
     'id': 'Cr'},
    {'type': 'parameter',
     'name': 'Agricultural Gross Value Added',
     'unit': '$',
     'id': 'AGVA'},
    {'type': 'variable',
     'name': 'Agricultural Water Use Efficiency',
     'unit': '$/m3',
     'in': ['AGVA', 'Cr', "AWU"],
     'computation': {'name': 'AGVA * (1-Cr)/AWU', 'formula': lambda x: x['AGVA'] * (1-x['Cr'])/x['AWU']},
     'id': 'WUEa'},
    # Industrial Water Use Efficiency
    {'type': 'parameter',
     'name': 'Industrial Gross Value Added',
     'unit': '$',
     'id': 'IGVA'},
    {'type': 'variable',
     'name': 'Industrial Water Use Efficiency',
     'unit': '$/m3',
     'in': ['IGVA', 'IWU'],
     'computation': {'name': 'IGVA/IWU', 'formula': lambda x: x['IGVA'] / x['IWU']},
     'id': 'WUEi'},
    # Municipal/Service sector water use efficiency
    {'type': 'parameter',
     'name': 'Service Sector Gross Value Added',
     'unit': '$',
     'id': 'SGVA'},
    {'type': 'variable',
     'name': 'Service Sector Water Use Efficiency',
     'unit': '$/m3',
     'in': ['SGVA', 'MWU'],
     'computation': {'name': 'SGVA/MWU', 'formula': lambda x: x['SGVA'] / x['MWU']},
     'id': 'WUEs'},
    # EW1 calculation
    {'type': 'variable',
     'name': 'Proportion of Agricultural Water Use',
     'unit': '',
     'in': ['AWU', 'TWW'],
     'computation': {'name': 'AWU/TWW', 'formula': lambda x: x['AWU'] / x['TWW']},
     'id': 'Pa'},
    {'type': 'variable',
     'name': 'Proportion of Industrial Water Use',
     'unit': '',
     'in': ['IWU', 'TWW'],
     'computation': {'name': 'IWU/TWW', 'formula': lambda x: x['IWU'] / x['TWW']},
     'id': 'Pi'},
    {'type': 'variable',
        'name': 'Proportion of Municipal Water Use',
        'unit': '%',
        'in': ['MWU', 'TWW'],
        'computation': {'name': 'MWU/TWW', 'formula': lambda x: x['MWU'] / x['TWW']},
        'id': 'Ps'},
    {'type': 'output',
     'name': 'Total Water Use Efficiency',
     'unit': '$/m3',
     'in': ['WUEa', 'Pa', 'WUEi', 'Pi', 'WUEs', 'Ps'],
     'computation': {'name': 'WUEa*Pa + WUEi*Pi + WUEs*Ps', 'formula': lambda x: x['WUEa'] * x['Pa'] + x['WUEi'] * x['Pi'] + x['WUEs'] * x['Ps']},
     'id': 'EW1'}

]
GraphModel(EW1_nodes).draw()
```

Out[3]:



In [4]:

```
EW2_nodes = [
    {'type': 'input',
     'unit': 'mm/year',
        'name': 'Precipitation',
     'id': 'P'},
    {'type': 'input',
     'unit': 'mm/year',
        'name': 'Evapotranspiration',
     'id': 'ET'},
    {'type': 'input',
     'unit': 'ha',
        'name': 'Catchment Size',
     'id': 'A'},
    {'type': 'variable',
     'name': 'Change in Surface Water Storage',
     'unit': 'mm/year',
     'in': ['P', 'ET', 'A'],
     'computation': {'name': '(P - ET)*A', 'formula': lambda X: (X['P'] - X['ET']) * X['A']},
     'id': 'S'},
    {'type': 'parameter',
        'unit': 'm3/year',
        'name': 'Surface Water',
     'id': 'SW'},
    {'type': 'parameter',
        'unit': 'm3/year',
        'name': 'Groundwater Water',
     'id': 'GW'},
    {'type': 'parameter',
        'unit': 'm3/year',
        'name': 'Overlap (Surface - Groundwater)',
     'id': 'Overlap'},
    {'type': 'variable',
     'name': 'Internal Renewable Water Resources',
     'unit': 'm3/year',
     'in': ['SW', 'GW', 'Overlap', 'S'],
     'computation': {'name': 'GW + (SW + S) - Overlap', 'formula': lambda X: X['GW'] + (X['SW'] - X['S']) - X['Overlap']},
     'id': 'IRWR'}.
    {'type': 'parameter',
        'unit': 'm3/year',
        'name': 'External Renewable Water Resources',
     'id': 'ERWR'},
    {'type': 'variable',
     'name': 'Total Renewable Freshwater',
     'unit': 'm3/year',
     'in': ['IRWR', 'ERWR'],
     'computation': {'name': 'IRWR + ERWR', 'formula': lambda X: X['IRWR'] + X['ERWR']}, 'id': 'TRF'},
    # Non conventional water
    {'type': 'parameter',
     'unit': 'm3/year',
        'name': 'Desalination Water',
     'id': 'DW'},
    {'type': 'parameter',
        'unit': 'm3/year',
        'name': 'Treated Wastewater',
        'id': 'TW'},
    {'type': 'variable',
     'name': 'Total Non Conventional Water',
     'unit': 'm3/year',
     'in': ['DW', 'TW'],
     'computation': {'name': 'DW + TW', 'formula': lambda X: X['DW'] + X['TW']}, 'id': 'TNCW'},
    {'type': 'variable',
        'name': 'Total Freshwater Available',
        'unit': 'm3/year',
        'in': ['TRF', 'TNCW'],
        'computation': {'name': 'TRF + TNCW', 'formula': lambda X: X['TRF'] + X['TNCW']}, 'id': 'TFA'},
```

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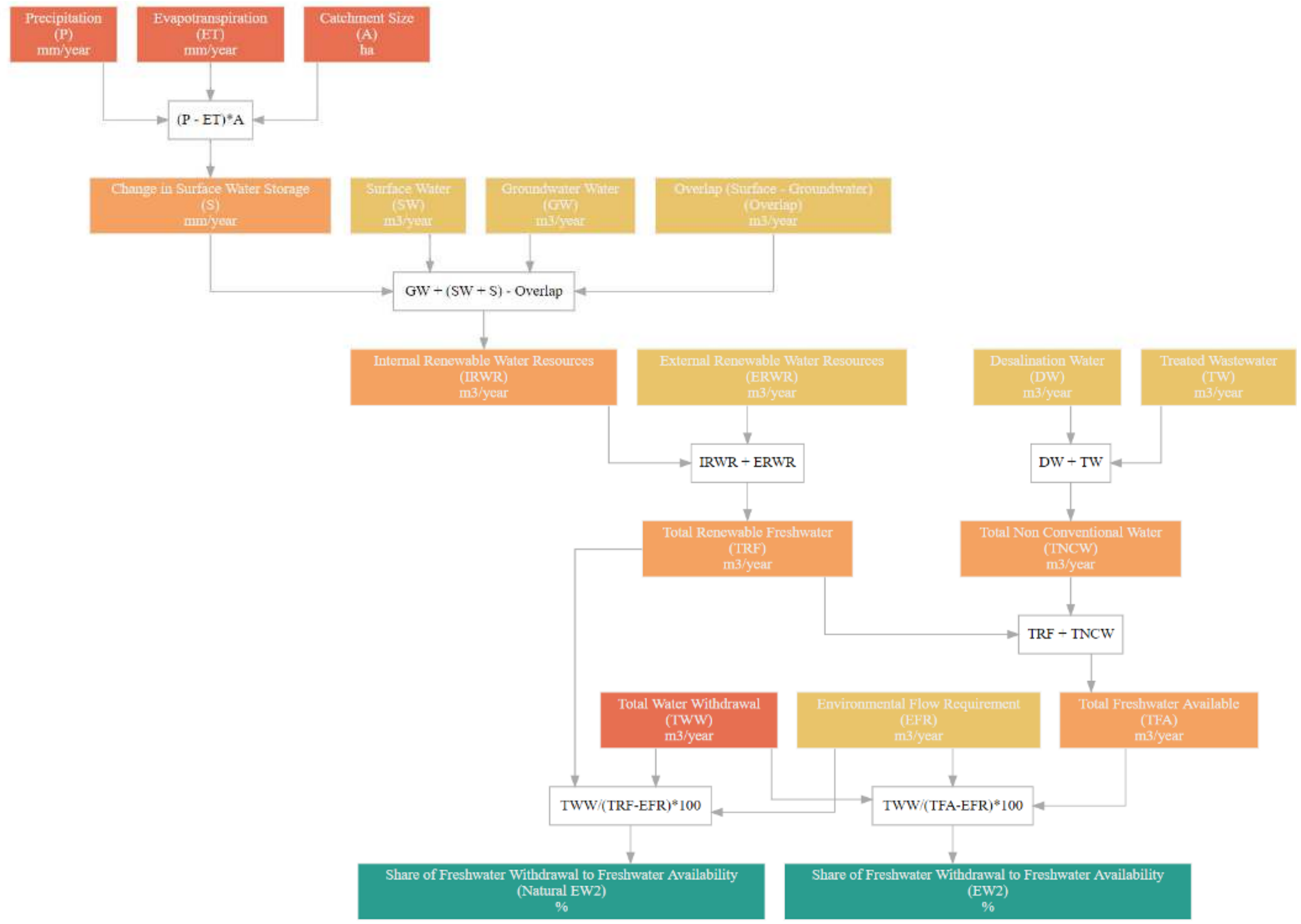
```
    # calculation of EW 2
    {'type': 'input',
        'unit': 'm3/year',
        'name': 'Total Water Withdrawal',
     'id': 'TWW'},
    {'type': 'parameter',
     'unit': 'm3/year',
        'name': 'Environmental Flow Requirement',
     'id': 'EFR'},
    # inclusion of both natural and non-conventional water sources
    {'type': 'output',
     'name': 'Share of Freshwater Withdrawal to Freshwater Availability',
     'unit': '%',
     'in': ['TFA', 'TWW', 'EFR'],
     'computation': {'name': 'TWW/(TFA-EFR)*100', 'formula': lambda X: X['TWW'] / (X['TFA'] - X['EFR']) * 100}, 'id': 'EW2'},
    # only natural water sources
    {'type': 'output',
     'name': 'Share of Freshwater Withdrawal to Freshwater Availability',
     'unit': '%',
     'in': ['TRF', 'TWW', 'EFR'],
     'computation': {'name': 'TWW/(TRF-EFR)*100', 'formula': lambda X: X['TWW'] / (X['TRF'] - X['EFR']) * 100}, 'id': 'Natural EW2'},
]

GraphModel(EW2_nodes).draw()
```

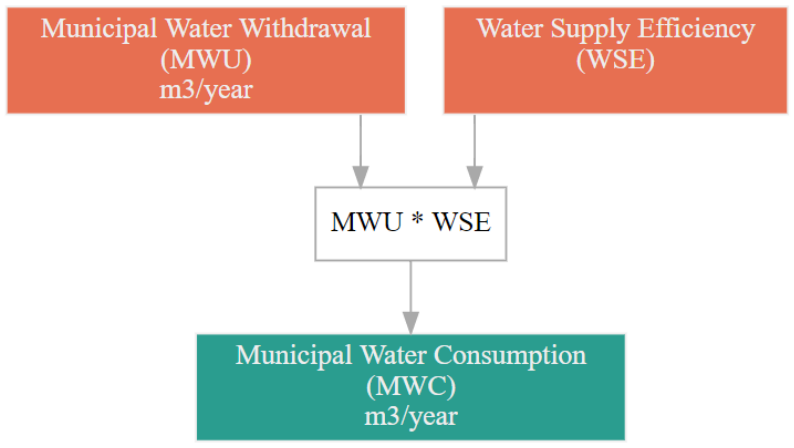
Out[4]:



In [5]:

```
MWC_nodes = [
    {'type': 'input',
     'name': 'Municipal Water Withdrawal',
     'unit': 'm3/year',
     'id': 'MWU'},
    {'type': 'input',
     'name': 'Water Supply Efficiency',
     'unit': '',
     'id': 'WSE'},
    {'type': 'output',
        'name': 'Municipal Water Consumption',
        'unit': 'm3/year',
        'in': ['MWU', 'WSE'],
        'id': 'MWC',
        'computation': {'name': 'MWU * WSE', 'formula': lambda X: X['MWU'] * X['WSE']}},
]


GraphModel(MWC_nodes).draw()
```

Out[5]:

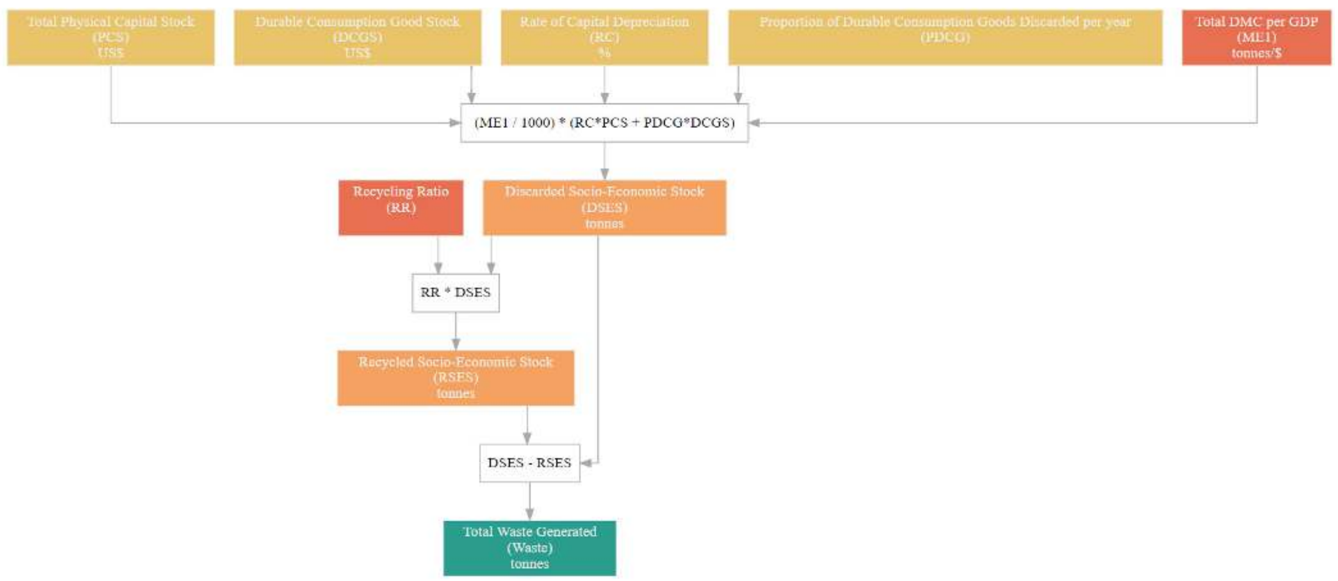


D. Simulation model for material use efficiency

In [1]:

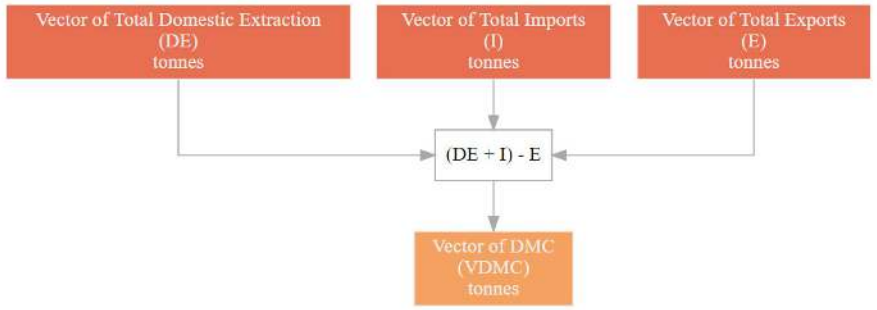
```
import numpy as np
from graphmodels.graphmodel import GraphModel

__publisher__ = 'Global Green Growth Institute'
__author__ = 'GGPM Team'
__model_lead__ = 'S. Gerrard'
__programmer__ = 'S. Zabrocki'

# Waste Generation Component
Waste_nodes = [{'type': 'parameter',
                'name': 'Total Physical Capital Stock',
                'unit': 'US$',
                'id': 'PCS'},

               {'type': 'parameter',
                'name': 'Durable Consumption Good Stock',
                'unit': 'US$',
                'id': 'DCGS'},

               {'type': 'parameter',
                'name': 'Rate of Capital Depreciation',
                'unit': '%',
                'id': 'RC'},

               {'type': 'parameter',
                'name': 'Proportion of Durable Consumption Goods Discarded per year',
                'unit': '',
                'id': 'PDCG'},

               {'type': 'variable',
                'name': 'Discarded Socio-Economic Stock',
                'unit': 'tonnes',
                'in': ['ME1', 'PCS', 'DCGS', 'RC', 'PDCG'],
                'computation': {'name': '(ME1 / 1000) * (RC*PCS + PDCG*DCGS)', 'formula': lambda X: (X['ME1'] / 1000)*(X['RC']*X['PCS'] + X['PDCG']*X['DCGS'])}, 'id': 'DSES'},

               {'type': 'input',
                'name': 'Recycling Ratio',
                'unit': '',
                'id': 'RR'},
               {'type': 'variable',
                'name': 'Recycled Socio-Economic Stock',
                'unit': 'tonnes',
                'in': ['DSES', 'RR'],
                'id': 'RSES',
                'computation': {'name': 'RR * DSES', 'formula': lambda X: X['DSES'] * X['RR']}, },
               {'type': 'output',
                'name': 'Total Waste Generated',
                'unit': 'tonnes',
                'in': ['DSES', 'RSES'],
                'id': 'Waste',
                'computation': {'name': 'DSES - RSES', 'formula': lambda X: X['DSES'] - X['RSES']}},
               {'type': 'input',
                'name': 'Total DMC per GDP',
                'unit': 'tonnes/$',
                'id': 'ME1', },
               ]
GraphModel(Waste_nodes).draw()
```

Out[1]:



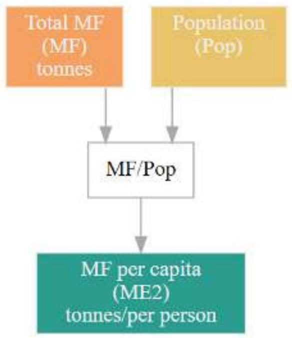
In [2]:
```
VDMC = [{'type': 'input',
         'name': 'Vector of Total Domestic Extraction',
         'unit': 'tonnes',
         'id': 'DE'},
        {'type': 'input',
         'name': 'Vector of Total Imports',
         'unit': 'tonnes',
         'id': 'I'},
        {'type': 'input',
         'name': 'Vector of Total Exports',
         'unit': 'tonnes',
         'id': 'E'},
        # Calculation of ME 1
        {'type': 'variable',
         'name': 'Vector of DMC',
         'unit': 'tonnes',
         'in': ['DE', 'I', 'E'],
         'computation': {'name': '(DE + I) - E', 'formula': lambda X: (X['DE'] + X['I']) - X['E']}, 'id': 'VDMC'},
        ]

GraphModel(VDMC).draw()
```

Out[2]:



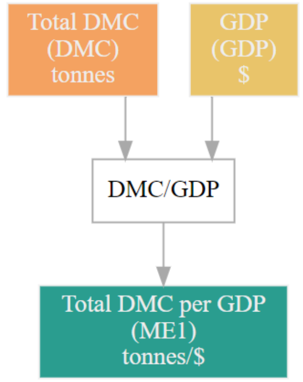
In [3]:
```
ME2_nodes = [{'type': 'variable',
              'name': 'Total MF',
              'unit': 'tonnes',
              'id': 'MF'},
             {'type': 'parameter',
              'name': 'Population',
              'unit': '',
              'id': 'Pop'},
             {'type': 'output',
              'name': 'MF per capita',
              'unit': 'tonnes/per person',
              'in': ['Pop', 'MF'],
              'id': 'ME2',
              'computation': {'name': 'MF/Pop', 'formula': lambda X: X['MF'] / X['Pop']}, }
             ]

GraphModel(ME2_nodes).draw()
```

Out[3]:



In [4]:
```
ME2_nodes = [
    {'type': 'variable',
     'name': 'Total DMC',
     'unit': 'tonnes',
     'id': 'DMC'},
    {'type': 'parameter',
     'name': 'GDP',
     'unit': '$',
     'id': 'GDP'},

    {'type': 'output',
     'name': 'Total DMC per GDP',
     'unit': 'tonnes/$',
     'in': ['DMC', 'GDP'],
     'id': 'ME1',
     'computation': {'name': 'DMC/GDP', 'formula': lambda X: X['DMC'] / X['GDP']*1000}, },
]
GraphModel(ME2_nodes).draw()
```

Out[4]:



In [5]:
```
JE_nodes = [
    {'type': 'variable',
     'name': 'Vector of DMC',
     'unit': 'tonnes',
     'id': 'VDMC'},
    {'type': 'variable',
     'name': 'Total DMC',
     'unit': 'tonnes',
     'in': ['VDMC'],
     'computation': {'name': '(DE + I) - E', 'formula': lambda X: sum(X['VDMC'])}, 'id': 'DMC'},
    # Calculation of ME 2
    # Resource Efficiency Improvement Scenario
    {'type': 'input',
        'name': 'Material Efficiency Improvement',
        'unit': '%',
        'id': 'MI'},
    {'type': 'variable',
        'name': 'Resources Saved',
        'unit': 'tonnes',
        'in': ['MI', 'DMC'],
        'id': 'RS',
     'computation': {'name': 'MI*DMC', 'formula': lambda X: X['MI'] * X['DMC 1'], }},
    # Calculate share of each material in DMC
    {'type': 'variable',
        'name': 'Share of Materials',
        'unit': '',
     'in': ['VDMC', 'DMC'],
     'computation': {'name': 'VDMC / DMC', 'formula': lambda X: X['VDMC'] / X['DMC']}, 'id': 'MS'},

    {'type': 'parameter',
        'name': 'Vector of Lastest Average Prices of Commodities',
        'unit': '$',
        'id': 'AP'},

    {'type': 'parameter',
        'name': 'Vector of Export Weights (to Total Commodities)',
        'unit': '',
        'id': 'EX'},

    {'type': 'variable',
     'name': 'Cost per unit of Materials',
     'unit': '$',
     'in': ['AP', 'EX'],
     'computation': {'name': 'AP * EX', 'formula': lambda X: X['AP'] * X['EX']}, 'id': 'CM'},

    {'type': 'variable',
        'name': 'Total Price per unit of Materials',
        'unit': '$',
     'in': ['CM', 'MS'],
     'computation': {'name': 'MS * CM', 'formula': lambda X: X['MS'] * X['CM']}, 'id': 'PM'},

    {'type': 'variable',
        'name': 'Monetary Savings',
        'unit': '$',
     'in': ['PM', 'RS'],
     'computation': {'name': 'PM * RS', 'formula': lambda X: X['PM'].sum() * X['RS']}, 'id': 'TMS'},

    {'type': 'parameter',
        'name': 'Average Wage',
        'unit': '$',
        'id': 'AW'},

    {'type': 'output',
        'name': 'Job Equivalents',
        'unit': '',
     'in': ['AW', 'TMS'],
     'computation': {'name': 'TMS/AW', 'formula': lambda X: X['TMS'] / X['AW']}, 'id': 'JE'},

    {'type': 'variable',
        'name': 'Total DMC',
        'unit': 'tonnes',
        'in': ['VDMC'],
     'computation': {'name': '(DE + I) - E', 'formula': lambda X: sum(X['VDMC'])}, 'id': 'DMC'},
]

GraphModel(JE_nodes).draw()
```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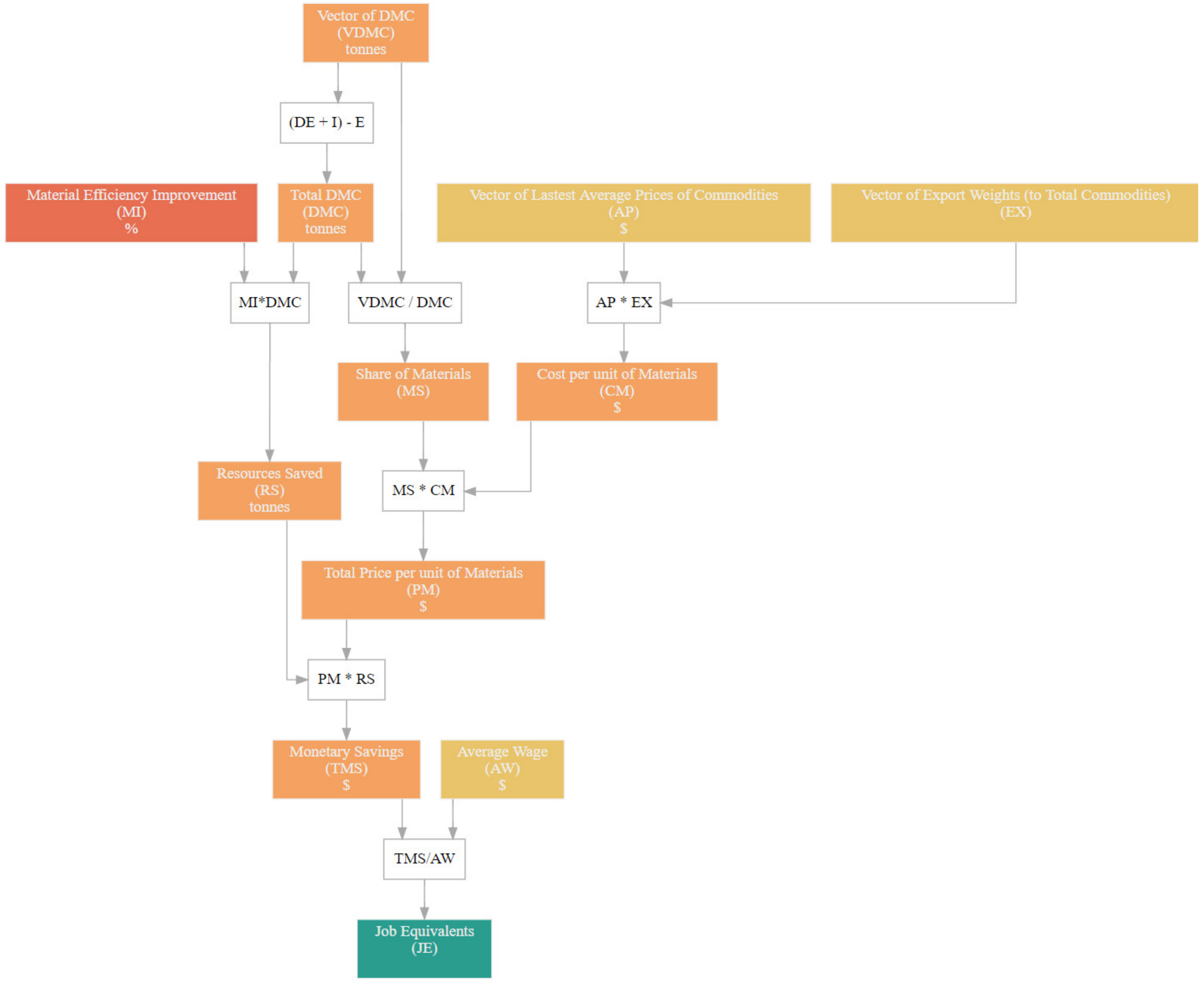
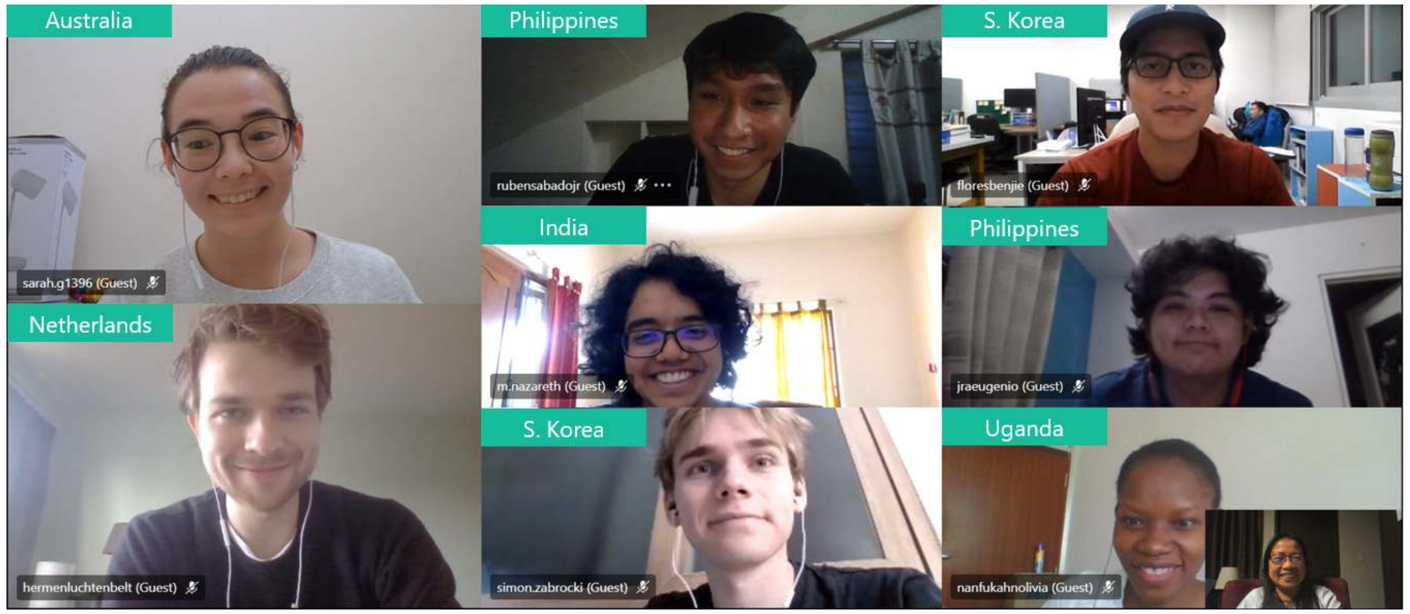
Out[5]:



APPENDIX 5

THE GGPM TEAM



The GGPM team members during one of the online meetings from their respective work locations. From left to right and, from top to bottom: Sarah Gerrard, Hermen Gerrit Hendrik Luchtenbelt, Ruben Sabado, Jr., Michelle Nazareth, Simon Zabrocki, Benjemar Hope Flores, Jeremiah Ross Eugenio, Olivia Nanfuka, and Lilibeth Acosta.

Lilibeth Acosta is a Specialist in GGGI's Climate Action and Inclusive Development Division and Program Manager for the Green Growth Performance Measurement. Lilibeth has over 15 years of experience in indicator development, integrated assessment and scenario modelling of climate change vulnerability and adaptation as well as sustainable development in the fields of ecosystem and biodiversity, agriculture and land use, and renewable energy. She worked as development specialist in the National Economic Development Authority in the Philippines, senior scientist in the Potsdam Institute for Climate Impact Research in Germany, and researcher in Environmental Science departments in the universities in Japan, Belgium, UK and the Philippines. Before joining GGGI, she worked as consultant in the ADB, UNCCD and UNCTAD. She holds a PhD in Agricultural Policy from University of Bonn (Germany), MPhil in Economics and Politics of Development from University of Cambridge (England), and BSc in Agricultural Economics from the University of the Philippines.

Jeremiah Ross Eugenio is a GGPM researcher and member of the publication team of Sarena Grace Quiñones, who is coordinating editorial, layout, and research support to the GGPM. He has been part of Sarena's team since October 2019. His tasks include literature review and preparation of references in Mendeley software, encoding of results from the online survey and reviews of online tools and literature, preparation of graphics for and analysis of these results, and provide research support to the modelling team of the Green Growth Index and Simulation Tool. He earned his Bachelor of Science degree in Agricultural Economics with major in marketing and prices from the University of the Philippines in Los Baños. He participated in various seminars that are relevant to the Index and Tool including farm tourism in the Philippines, assessment of neighborhood and spillover effects of technical efficiency of irrigated rice farms, and responding to food security and inclusiveness concern in the ASEAN region.

Sarah Gerrard is a GGPM consultant for the 2020 Green Growth Index and Simulation Tool. Her work in GGPM has focused on results analysis for the 2020 Green Growth Index, in particular a subregional analysis of green growth dimensions as well as assessing top country performance. She has also contributed as a leading author to the publication of the 2020 Green Growth Technical Report. Sarah has further been working on the GGPM Simulation Tool, supporting the development of the efficient and sustainable resource use and green economic opportunities models. Before joining GGGI, she has previously worked in sustainable urban development by interning at the United Nations Economic and Social Commission for Asia and the Pacific (UN ESCAP). Sarah holds a Master of Environmental Science with a specialization in land and water management and a BSc in Environmental Science and Natural Resource Management, both from the University of Western Australia.

Hermen Luchtenbelt is a GGPM research consultant for the 2020 Green Growth Index and Simulation Tool. He joined the GGPM as an intern in May 2020 and as a consultant in November 2020. His main contributions to the simulation tool were with models related to natural capital protection, land-use, and greenhouse gas emissions. Other tasks included preparing the spatial maps in the 2020 Green Growth Technical Report. Before joining GGGI, he did field work at the Osotua foundation and supported in the development of a showcase for cattle, culture, and wildlife interactions in the Masai Mara. Hermen has a MSc in climate studies specialized in biogeochemical cycles and a MSc in Environmental Economics and Natural Resource Management at Wageningen University in the Netherlands. Before that he completed his BSc in Economics and Governance, specialized in Agricultural Economics at the same university.

Olivia Nanfuka joined GGPM team as intern in May 2020 and as consultant in the GGGI Country Office in Uganda in November 2020. She is contributing to the development of the Simulation Tool, particularly the models related to efficient and sustainable energy use. Her key areas of interest include improving access to modern energy; clean cooking energy and reliable electricity for rural communities (bio-energy, hydro and solar energy), energy efficiency and management, renewable energy policy, energy economics, savings and energy yield assessments. Before joining GGGI, she had experience working as Health and Safety Assistant in the JUAJAMII start-up company in Algeria as well as sustainability and policy intern in the Atacama Consulting, shift superintendent in the Bwendero Dairy Farm Limited Distillers, and teaching assistant in the Ndejje University in Uganda. She completed her BSc Chemical Engineering in the Ndejje University in Uganda and MSc Energy Engineering in Pan African University Institute for Water and Energy Science in Algeria.

Michelle Nazareth is a GGPM consultant for the 2020 Green Growth Index and Simulation Tool, contributing to the analysis of the results for the 2020 Green Growth Index and supporting the development of the models related to social inclusion. She also contributed to an article on social inclusion that was submitted by GGGI to an international journal. She worked as intern in the Environmental Synergies in Development and graduate research consultant in the United Nations Office for the Coordination of Humanitarian Affairs. She completed her Bachelor of Arts (Triple Major) in Economics, Sociology and Psychology in the Christ University in India and Master of Science in Development Management in the London School of Economics and Political Science.

Ruben Sabado, Jr. is a GGPM researcher and member of the publication team of Sarena Grace Quiñones, who is coordinating editorial, layout, and research support to the GGPM. He has been part of Sarena's team since July 2020. His tasks include literature review and preparation of references in Mendeley software, encoding of results from the online survey and reviews of online tools and literature, preparation of graphics for and analysis of these results, and provide research support to the modelling team of the Simulation Tool. He earned his Bachelor of Science degree in Agricultural Economics with major in marketing and prices from the University of the Philippines in Los Baños. He attended various seminars that are related to the Green Growth Index and Simulation tool such as the Philippine Rice Information System (PRISM) and success stories of the Farmer-Scientists RDE Training Program (FSTP).

Simon Zabrocki joined GGGI as programmer and modeler consultant in July 2020, with main tasks of developing an automated collection and processing of data for the Green Growth Index computation, designing user-friendly dashboards to allow policy makers exploring and analyzing Green Growth data and scores, and contributing to a policy simulation tool development by implementing and integrating models and policy scenarios. Before joining GGGI, he worked as data scientist in HawaDawa company on air quality management in Germany and in Sanofi, Biologics Development R&D in the United States, Python developer for an applicant tracking system in Manatal in Thailand, and teacher in Bac Ninh high School for gifted students in Vietnam. He earned his Bachelor in Engineering and Master of Science in Applied Mathematics in École Polytechnique in France, and Master Mathematics for Data Science in the Technische Universität München in Germany.

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