Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-Created Climate Action

29/08/2024

D6.7 OPEN-ACCESS MODELS FOR CASE-STUDY COUNTRIES

WP6 – Explaining – Policy analysis, capacity development, communication, dissemination, exploitation

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Lead Beneficiary	KTH Royal Institute of Technology			
Responsible Author	Francesco Gardumi	**Email**	gardumi@kth.se	
	KTH	**Phone**	+46702887595	
Contributors	Camilla Lo Giudice (KTH); Fitsum Salehu (AAiT); Salsabila Abdulhalim, Ioannis Tsipouridis (TUM); Lahiru Jayasuriya (RUSL); Borys Dodonov, Anatolii Kravtsev, Igor Piddubnyi (KSE)			
Reviewer(s)	Lorenzo Rinaldi (POLIMI); Ghadaksaz Hesam (Aalto); Anastasios Karamaneas, Natasha Frilingou, Alexandros Nikas (NTUA)			
Keywords	Energy models, OSeMOSYS, OnSSET, CLEWs			

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

This deliverable aims to document the integrated assessment process, concepts, and tools for Ethiopia, Kenya, Sri Lanka, and Ukraine developed in the IAM COMPACT project and to support their use, serving as a reference for policy analysis, capacity development, communication, dissemination and exploitation of open-access models in each national context. These adhere to FAIR data principles, to facilitate the integration and use of the models within the national contexts they are intended for, but also internationally (e.g., by integration of the insights in IPCC reports). The open-access models will also pave the way for reuse in future research and capacity building, both by national researchers and by the IAM community. The final objective is to standardise documentation practices also for extra-EU contexts making the analyses comparable to those carried out in the EU contexts. Moreover, this deliverable aims to contribute to the knowledge base prepared for the IPCC Assessment Reports. By addressing the specific needs for national analyses, the open-access models will provide valuable insights and data that can inform and support the IPCC's comprehensive assessments of global and regional climate change impacts, mitigation strategies, and adaptation measures. Finally, this report can be used by researchers to expand and integrate the reported modelling tools and by stakeholders and policymakers to identify preferable pathways and contribute to the forthcoming NDC update for the case-study countries.

3. Short summary of results (<250 words)

Task 6.5 of IAM COMPACT focuses on building technical and institutional capacity for integrated assessment modelling in four countries: Ethiopia, Kenya, Sri Lanka, and Ukraine. National teams led the capacity development and model creation efforts within and beyond their institutions. Five open-access models were developed to address key policy questions in each country, where such insights have been limited.

In Ethiopia, a geospatial electrification model using OnSSET was created to identify cost-effective ways to provide insights on technically feasible and least-cost pathways for electrifying the remaining part of the population. Additionally, a Climate, Land, Energy, Water systems (CLEWs) model using OSeMOSYS was developed to improve integrated resource management, to be then linked to MicroGridsPy in a future update to support Ethiopia's sustainable development. Kenya's CLEWs model examines renewable energy's role in enhancing climate-resilient food, energy, and water supplies. The development of this model in IAM COMPACT links to a wider interest across several EU- and UK-funded initiatives. In Sri Lanka, a CLEWs model was designed to explore the balance between agricultural and energy development given land constraints, based on literature and stakeholder inputs. For Ukraine, an energy system model was created to guide the Ministry of Energy in developing green post-war reconstruction strategies for electricity infrastructure.

Several models build upon previous modelling efforts, in line with the aim of making use of the existing capacity and expanding it. The key data sources for all models are documented on Zenodo[1], together with the models' executables.

4. Evidence of accomplishment

This report and the data, metadata, and executables of the models described, which are publicly available on IAM COMPACT's Zenodo community, under CC BY 4.0 license.

[1] DOI: 10.5281/zenodo.13505931

Preface

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

NTUA – National Technical University of Athens	EL	
Aalto – Aalto Korkeakoulusaatio SR	FI	
AAU – Aalborg Universitet	DK	
BC3 – Asociacion BC3 Basque Centre for Climate Change – Klima Aldaketa Ikergai	ES	
Bruegel – Bruegel AISBL	BE	
CARTIF – Fundacion CARTIF	ES	
CICERO – Cicero Senter for Klimaforskning Stiftelse	NO	
E3M – E3-Modelling AE	EL	
KTH – Kungliga Tekniska Hoegskolan	SE	
POLIMI – Politecnico di Milano	IT	
UPRC – University of Piraeus Research Center	EL	
UVa – Universidad De Valladolid	ES	
WI – Wuppertal Institut fur Klima, Umwelt, Energie GGMBH	DE	
IIMA – Indian Institute of Management	IN	
THU – Tsinghua University	CN	
USMF – University System of Maryland	US	
AAiT – Addis Ababa University	ET	
KEI – International Civic Organisation Kyiv Economics Institute	UA	
RUSL – Raja Rata University of SriLanka	LK	
TUM – Technical University of Mombasa	KE	
UNIGE – Université de Geneve	CH	
Imperial – Imperial College of Science, Technology and Medicine	UK	

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Executive Summary

This deliverable aims to enhance engagement with the integrated assessment process, providing crucial support to policymakers, stakeholders, and researchers. By focusing on Ethiopia, Kenya, Sri Lanka, and Ukraine as case study countries, the document serves as a reference for future efforts in capacity development, communication, policy analysis, and dissemination within each national context. With the growing concerns around climate change, energy, water and food security, economic growth, and environmental crises, energy models have become essential tools for addressing these complex challenges. Using two open-source models, OnSSET and OSeMOSYS, the document explores ways to improve electrical infrastructure, optimise national energy systems, and address the water, energy, land and water systems conflicts, while supporting economic activities, enhancing population welfare, and ensuring a sustainable development.

The Federal Democratic Republic of **Ethiopia** is the second most populated country in Africa expected to surpass 200 million people by 2050 (Ministry of Planning and Development, 2020). The main challenges include limited access to electricity, water, and sanitation services, together with food insecurity and high vulnerability to climate change. In response, Ethiopia has integrated climate mitigation and adaptation into its national strategies to ensure economic growth, fight against land degradation while ensuring food security and clean energy access. The CLEWs methodology, developed through the modelling tool OSeMOSYS, allows to represent the Climate, Land, Energy and Water nexus, analysing their interactions and mitigating competition among them in future development strategies. This study has allowed to answer important research questions such as which will be the impact of the implementation of the National Determined Contributions (NDC) targets on the climate-land-water-energy system and how water, energy and food security can be improved while supporting the economic activities, population welfare and sustainability. Additionally, due to the low electricity access rate, the OnSSET model has been used for planning the national electrification highlighting the investments needed for the forecasted grid capacity addition required.

Sri Lanka is facing a range of interconnected challenges across critical sectors of its economy, exacerbated by the impacts of climate change. The country's heavy reliance on imported fossil fuels makes it vulnerable to global price fluctuations and supply chain disruptions, which have hindered economic recovery. Despite ambitious targets for expanding renewable energy, the nation struggles with obstacles related to grid integration, cost-effective energy storage, and land availability. A CLEWs model could thus highlight potential conflicts and opportunities for sustainable development, considering the climate-land-energy-water nexus.

Despite having one of the least carbon-intensive power systems in the East African region, **Kenya** faces significant challenges in its efforts to decarbonise and reach net-zero emissions, particularly in the transport and industrial sectors. While the country has a substantial integration of renewable energy sources, it struggles to fully address the emissions targets from these key sectors. By linking the climate, land, energy and water systems, the model aims to inform policy decisions that promote sustainability and mitigate the negative effects of climate change. It serves as a critical tool for policymakers, researchers, and organisations, helping to guide effective climate mitigation, adaptation strategies, and integrated resource management in Kenya.

Finally, the OSeMOSYS model was developed for **Ukraine's** energy system to address challenges posed by the full-scale Russian invasion in early 2022, which resulted in significant damage to the country's energy infrastructure. The analysis was based on data from before 2022 with the final objective of identifying pathways for post-war green reconstruction.

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Introduction

This report constitutes a factsheet for the open-access models of Ethiopia, Sri Lanka, Kenya and Ukraine, developed within the framework of the IAM COMPACT project. It aims to provide a quick overview, through which a technical (with modelling background) audience may be able to understand at a glance the scope and main characteristics of the model enabling a presumptive user to decide whether the above model is usable or not for their purpose. It does not offer any extensive documentation for the model. The extensive documentation is publicly available on I^{2}AM PARIS and is designed to make the model **A**ccessible, **I**nteroperable, **R**eusable (and reproducible). This factsheet provides links to the documentation and guidelines on how it may be used, giving advice on what parts of it are important for which audiences, what part of it shall be used for understanding, or running, or recreating the model. As such, this factsheet can be seen as the starting point for approaching the model, with links to 'all you need to know'. It addresses the **F**indable part of the **FAIR** criteria.

1.1 Aim of the models and target audiences

Deliverable D6.7 "Open-access models for case-study countries" is part of Work Package WP6 "Explaining – Policy analysis, capacity development, communication, dissemination, exploitation", which aims at expanding engagement with the integrated assessment process, concepts, and tools in case-study countries, running technical assistance and capacity development programs, workshops, discussions and finally modelling and policy insights on the country context.

The deliverable provides first an overview of the national models developed by national analysts, their scope and their use, for policy makers, so that they may judge their potential to support different policy-making processes. Secondly, by focusing on the specific requirements for national analyses, the open-access models will offer valuable insights and data to inform and support the IPCC's detailed evaluations of global and regional climate change impacts, mitigation strategies, and adaptation measures. Finally, this report can be utilised by researchers to further develop and integrate the energy models presented, applying them to new contexts or refining them for greater accuracy.

1.2 How to run the models

The models used for the four case studies use OSeMOSYS, for the study of the energy system with the potential link to the land-water-climate nexus (CLEWs), and OnSSET, for supporting electrification planning. According to the FAIR criteria, this section aims at carefully describing how to run these models to be fully Accessible and Reusable.

1.2.1 The OSeMOSYS model

For either a CLEWs model or an energy system model, the modelling process follows, in general the steps defined by Ramos et al. (2022) summarised in the figure below:

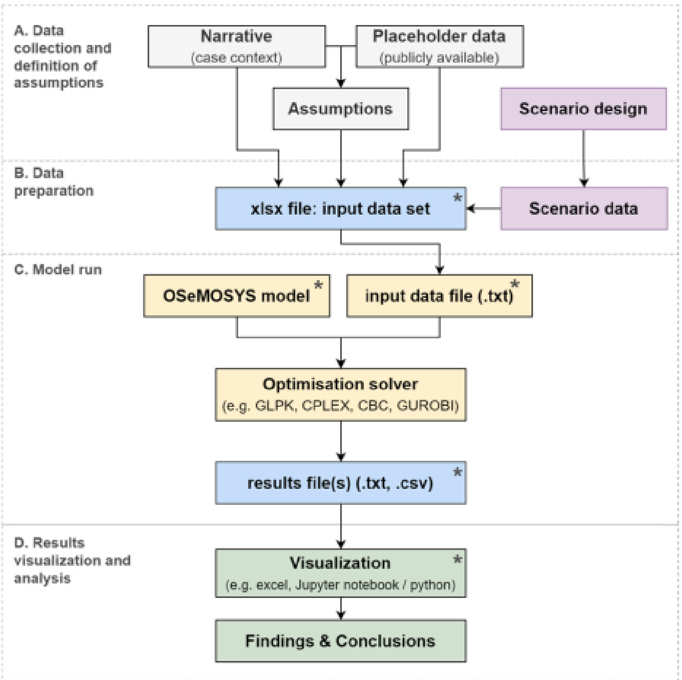

Figure 1 OSeMOSYS modelling workflow (Ramos et al. 2022)

The first step involves understanding the context and needs of the country, and the specific targets required for building the scenarios. For instance, for each case study the *"key data sources"* tables summarize the references used for the data gathering and for the formulation of the key assumptions used in each model. They were subsequently input to the Excel file that can be found on the Zenodo repository[2]. Following the figure workflow, once steps A and B are completed, it is possible to build the model. Thanks to a linear optimisation solver, after running the model, it is possible to get the results in a text file format and a set of .csv files. Finally, using several platforms (such as the OSeMOSYS Cloud, Excel, Jupyter notebook etc.), it is possible to visualize the data to highlight relevant findings and conclusions.

More specifically, all the models developed in IAM COMPACT can be executed by uploading the .zip files shared on Zenodo onto UNDESA's *OSeMOSYS User Interface* and running them there. Instructions on how to upload the models, run them and visualise results are given here.

1.2.2 The OnSSET model

The Ethiopia OnSSET model uses version 1.1 of the OnSSET tool modified for the Global Electrification Platform. In order to run the model, it is first needed to install a version of mini-conda and the required Python environment:

- Go to https://docs.anaconda.com/miniconda/
- Download the right installer accordingly to the system.
- Open the installer and follow the steps to install mini-conda.

After successfully installing mini-conda, open the anaconda prompt and run:

[2] DOI: 10.5281/zenodo.13505931

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conda create -c conda-forge -n onsset_eth python notebook matplotlib seaborn pandas numba openpyxl==3.0.3 numpy==1.18.5

This will download and install the required python packages. Now in the same anaconda prompt, run the following line to activate the environment:

conda activate onsset_eth

For every OnSSET analysis it is needed to open an anaconda prompt, activate the onsset_eth environment and open the GEP generator Jupyter Notebook by running:

jupyter notebook

Finally, open the file GEP_Generator.ipynb and follow the instructions to download the source code of the model. Following the figure below, once also the socio and techno-economic data, together with the GIS input (found in the *et-gis-inputs-v1.csv* file) are gathered, it is possible to extract geospatial data and run the model. Similarly to the OSeMOSYS workflow, it is then possible to visualise the output highlighting relevant findings and conclusions.

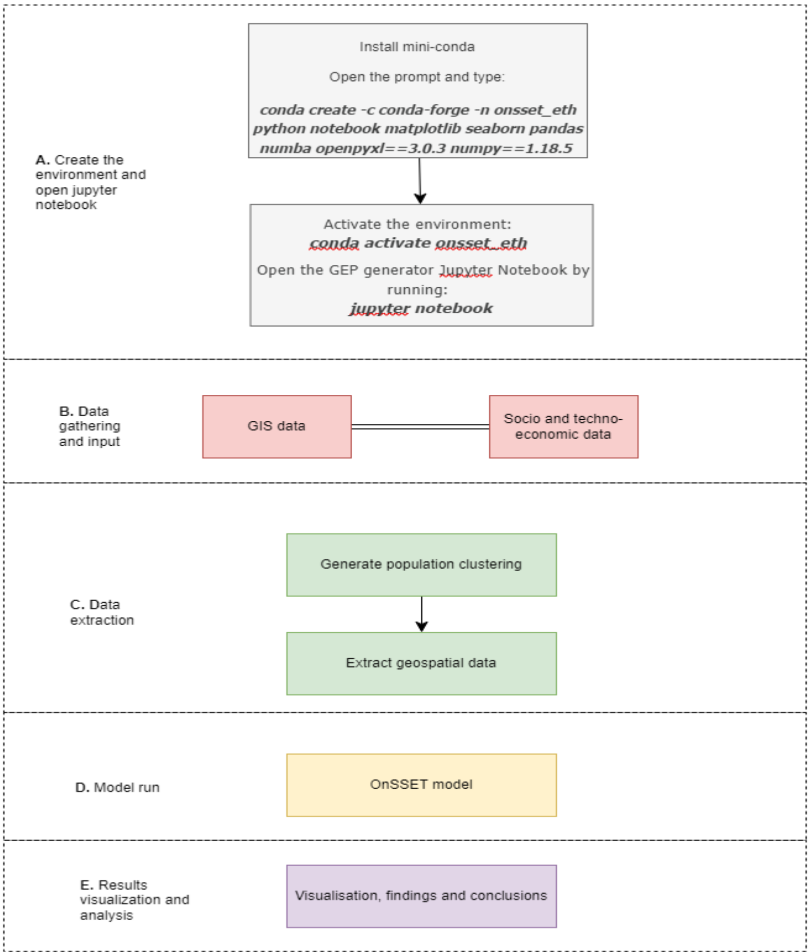

Figure 2 OnSSET modelling workflow

1.3 Limitations

Energy models are considered crucial tools for understanding and planning complex systems. However, it is acknowledged that they have limitations due to simplified assumptions, data quality and availability, uncertainty, and geographical and temporal resolution. For instance, considering the latter, the case studies explore countries, not accounting for possible variations in resource availability and specific energy demand across multiple regions. Regarding time resolution, some models (such as the CLEWs models of Kenya and Ethiopia, which consider only 8 time slices) may not capture the variability in energy supply and demand over shorter timescales, such as hourly variations in renewable energy supply, which can be crucial for understanding grid stability or integrating renewable energy sources.

Moreover, static models like OnSSET lacks a time evolution and provide a snapshot of an energy system in a single year, often assuming that system parameters and conditions are fixed. Data gathering might also present a significant limitation, especially if it is not possible to access updated databases or if the data are not open source. The accuracy of energy models heavily depends on the quality and availability of them, but they are often outdated, incomplete, or inaccurate, particularly in regions with limited data collection (such as in the water sector in Ethiopia). Additionally, aggregating data from different sources or over different time periods can introduce errors or inconsistencies, reducing the reliability of model outputs.

Finally, all models also rely on specific assumptions made by the modeler. These assumptions can limit the accuracy of predictions, as they might not fully capture the complexities of real-world systems for instance, future energy demand or commodity prices considered in these case studies do not consider market imperfections or variability.

Overall, energy planners use mathematical and computational models to analyse energy systems and their behaviour under various scenarios and assumptions. These tools are crucial for assessing interactions, trade-offs, and strategies to put into practice. However, it is always important to keep in mind that they represent a simplified version of a highly complex system and should therefore be considered as a tool that provides help and support in achieving policy objectives. The outcomes should always be cross-checked with the specific assumptions made to critically analyse the results.

2 Model factsheet: Ethiopia - CLEWs

2.1 Context and needs

The Federal Democratic Republic of Ethiopia, located in the Greater Horn of Eastern Africa, is the second most populated country in Africa, with 123 million people in 2022 (World Bank, 2022) expected to surpass 200 million by 2050 (Ministry of Planning and Development, 2020). Despite an average economic growth of 7.3% over the past five years (World Bank, 2022), the country remains one of the least developed, with a low per capita income of $1,218 and a human development index of 0.38 (Ministry of Planning and Development, 2020) with 0.55 and 0.7 considered respectively medium and high values accordingly to the UNDP reports (United Nations, n.d.).

Significant challenges persist, including limited access to modern energy, water, and sanitation services, particularly in rural areas where 78% of the population resides (World Bank, 2022). Only 51% have access to electricity, 7% to clean cooking, and basic sanitation is available to less than 10% of the population (IEA et al., 2022). Food insecurity is also severe, with 15.8 million people projected to face hunger in 2024 (United Nations, 2024). Ethiopia is highly vulnerable to climate change (Ministry of Agriculture and Forestry, 2015), despite contributing less than 0.1% of global emissions (Ethiopia's Long Term Low Emission and Climate Resilient Development Strategy (2020-2050), 2023). Climate-related challenges like droughts, floods, and soil erosion threaten the country, where 85% of farmers rely on rain-fed agriculture (Ministry of Agriculture and Forestry, 2015). GHG emissions have nearly doubled in the past 20 years, driven by economic growth and population increase, with agriculture and deforestation accounting for over 85% of these emissions (USAID, 2022).

In response, Ethiopia has integrated climate mitigation and adaptation into its national strategies. The Climate Resilient Green Economy (CRGE) strategy, launched in 2011 and subsequently updated in 2015 and divided into CRGE Water & Energy and CRGE Agriculture & Forestry (Ministry of Agriculture and Forestry, 2015; Ministry of Water and Energy, 2015), considers irrigation development as a crucial adaptation response to climate change and deforestation risk. On the other hand, the ten-year development plan (10YDP) focuses on economic growth, fighting land degradation, reducing pollution, and promoting green urban development. Moreover, Ethiopia's updated Nationally Determined Contribution (NDC) targets a 69% reduction in emissions by 2030 compared to a business-as-usual scenario, requiring significant international financial support.

2.1.1 Aim of the model and target audiences

The Ethiopia CLEWs model is designed to provide a comprehensive understanding of the interconnections between climate, land, energy, and water resources in the country. By modelling these sectors together, the tool aims to offer critical insights for policymakers on how to optimize resource use while minimizing environmental impacts and ensuring sustainable development. The model helps identify potential conflicts and synergies among sectors, particularly under the pressures of climate change, enabling more informed decision-making. Target audiences for the Ethiopia CLEWs model include government agencies responsible for resource management and policy formulation, researchers analysing sustainability pathways, non-governmental organisations focused on environmental conservation and development, and international bodies supporting climate resilience and sustainable resource use.

2.1.2 Brief history on model development

This CLEWs model of Ethiopia was created through a Master thesis project under the supervision of Dr. Francesco Gardumi, as part of IAM COMPACT. It builds on, expands, updates, and corrects a previous model build by Pegah Atarian under the supervision of Dr. Francesco Gardumi (https://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1820331&dswid=5435). Specific contributions of IAM COMPACT to the existing model are:

- Analysis of the Impact of Nationally Determined Contributions (NDC) Targets on the Climate, Land, Water,

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- Analysis of the impact of climate-change projections
- Improvement of the water, energy and food security while supporting the economic activities, population welfare and environment
- Livestock sector modelling

It is important to note that the creation of this model and the introduction of the CLEWs modelling practice in Ethiopia are not the first of their kind. Previous efforts have been recorded, in the framework of technical assistance programs offered by UNDESA to the government. The effort of IAM COMPACT comes in the wake of those previous actions and aims at recreating and perfecting the modelling effort, documenting in with the latest standards of open science (Open Science, 2024) and packaging it for a different target audience, an academic one.

2.2 Model scope and structure

Table 1. Model scope and structure - Ethiopia

	Scope	Detail
Sectoral coverage	Climate, Water, Land and Energy	It is a comprehensive analysis of the climate, land, energy and water (CLEW) nexus to mitigate heightened competition among them in future development strategies. The interactions among these sectors were modelled through commodities and technologies in OSeMOSYS.
Type of analysis	Cost-optimisation; Long-term planning	All the scenarios represent cost-optimal solutions since the objective function consist of the minimisation of the Net Present Value. Additionally, all of them are subjected to specific constrains (such as GHG emissions, resource availability etc.) with the final aim of reaching specific targets set by the government while respecting environmental goals. Finally, the long-term planning is set on a 30-year time period.
Modelling tool used	OSeMOSYS	OSeMOSYS is an Open-Source Energy Modelling System created to aid in the formation of energy strategies at local, national, and multi-regional levels. CLEWs is a methodology that enables the representation of the Climate, Land, Energy and Water systems nexus. Link to OSeMOSYS documentation: https://osemosys.readthedocs.io/en/latest/manual/Introduction.html Link to CLEWs documentation: https://iopscience.iop.org/article/10.1088/1748-9326/abd34f/meta l
Open source code	Yes	https://github.com/OSeMOSYS/CLEWs
Open access data	Yes	License and link to repository
Documentation	Yes	
Previous use	No	
Institution(s) that created model	KTH Royal Institute of Technology	

Institution(s) that maintain model	KTH Royal Institute of Technology and Addis Ababa University	
Geographical coverage	Ethiopia	
Geographical resolution	National	
Time domain	2020-2050	
Time resolution	Intra-annual time steps	The model is divided into 8 time-slices, dividing the year into 4 seasons and 2 day-types each (day and night). The seasons are divided as: March-May, June-September, October-November and December-February.
Deterministic	Yes	
Dynamic	Yes	Year-by-year capacity expansion, with intra-annual operation.
Mathematical formulation	Linear programming	Constrained optimisation, where the objective function is the minimisation of the total net present cost of the whole land-energy-water system for all the years, with perfect foresight. Key constraints are availability of energy, land and water resources, demands for energy, food and water (which must be met), techno-economic constraints of technologies and policy constraints.
Rationale	Optimisation	See above
Technology richness	Bottom-up	The total amount of modelled technologies is 84 and they can be divided in these main groups: conversion (such as power plants), supply (fossil fuel resources), land (crops), water supply and transmission and distribution. Then each technology receives as an input and has as an output a commodity (such as electricity, land, fossil fuel etc.). The total number of commodities is 43.
Solver(s) used	CBC	Free and open source: https://github.com/coin-or/Cbc
Solution	1 minute	• OSeMOSYS UI: 4.6 • RAM: 32 GB • Processor: 13th Gen Intel(R) Core (TM) i7-1370P 1.90 GHz

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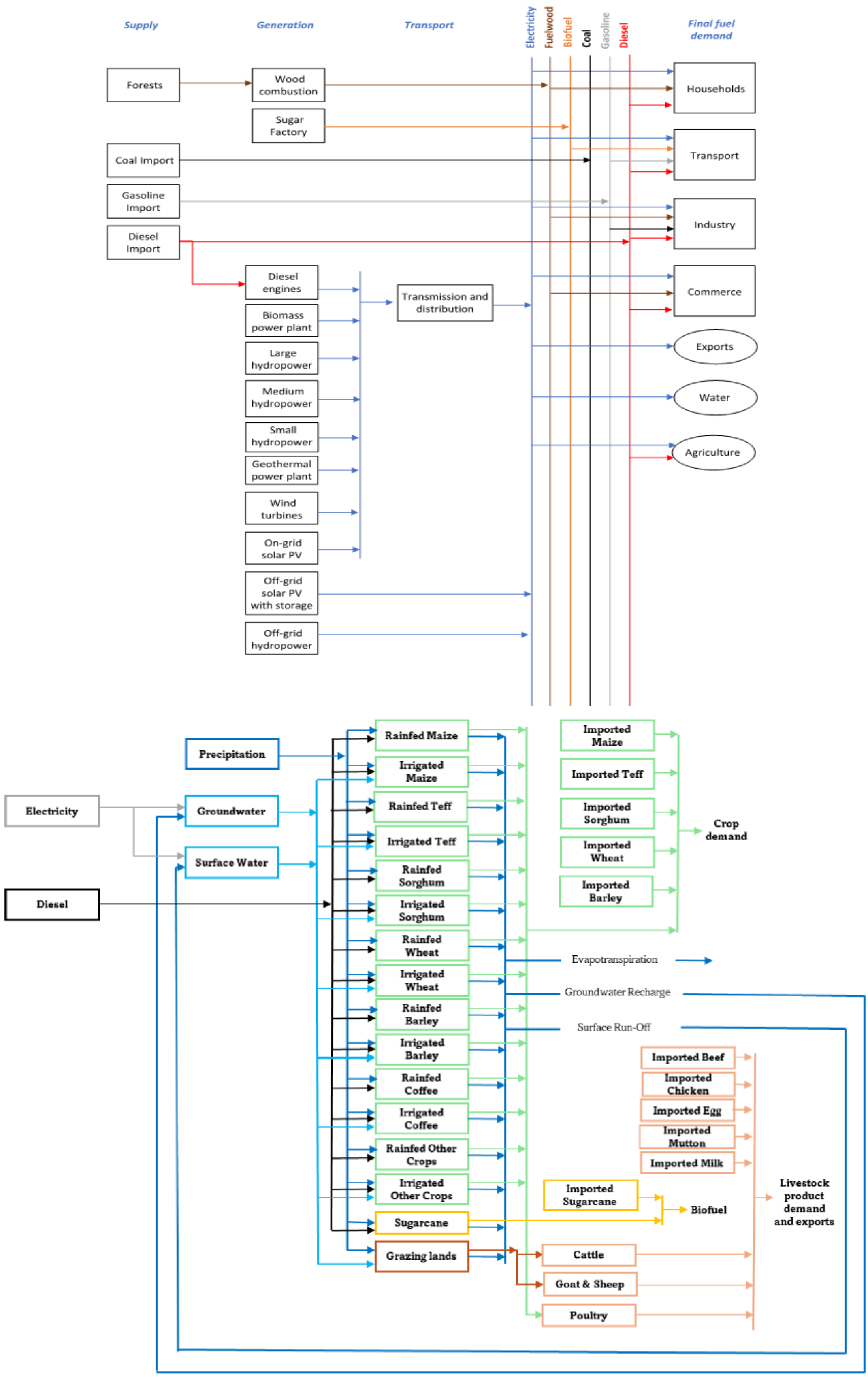

Figure 3 CLEW Reference system - Ethiopia

2.2.1 Key data sources

Table 2. Key data sources - Ethiopia.

Dataset	Source	Open access
Population growth	World Bank, 2022; https://data.worldbank.org/country/ethiopia	Y
Forest growth and statistics	Global Forest Watch; https://www.globalforestwatch.org/dashboards/country/ETH/?category=forest-change	Y
Forest cover; increase in above-ground biomass	LT-LEDS; https://unfccc.int/sites/default/files/resource/ETHIOPIA_%	Y
Crops	FAOSTAT; https://www.fao.org/countryprofiles/index/en/?iso3=ETH	Y
Livestock	Central Statistics Agency, 2021; https://www.statsethiopia.gov.et/wp-content/uploads/2021/05/2013.LIVESTOCK-REPORT.FINAL_.pdf	Y
Energy demand, emission activity ratio	UNSD – Energy balances; https://unstats.un.org/unsd/energystats/pubs/balance/	Y
Energy demand; electricity generation by source	IEA, 2021; https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=%5Bobject%20Object%5D&energy=Balances&year=2021	Y
Fossil fuels reserves	Energy projections for African countries, 2019; https://www.researchgate.net/profile/Ioannis-Pappis/publication/337154878_Energy_projections_for_African_countries/links/5dc847e3a6fdcc57503dd5c1/Energy-projections-for-African-countries.pdf doi:10.2760/678700	Y
Emission activity ratio	IPCC Guidelines for National GHG Inventories, 2006; https://www.osti.gov/etdeweb/biblio/20880391	Y
CO2 equivalent estimation	GHG Protocol, 2016; https://ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf	Y
Wood energy content	The Ethiopian energy sector and its implications for the SDGs and modelling, 2022; https://doi.org/10.1016/j.rset.2022.100018	Y
Fossil fuel price	National Bank of Ethiopia, 2023; https://nbe.gov.et/publications-statistics/statistics/annual-report/	Y
Coal price	IRENA, 2018; https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Planning_West_Africa_2018.pdf?rev=3a0ff05c815f46caa8ed40441caef5a6	Y
Price projections; RES Technical data	IRENA, 2021; https://www.irena.org/publications/2021/Apr/Planning-and-prospects-for-renewable-power-Eastern-and-Southern-Africa	Y
Water	AQUASTAT, 2016; https://www.fao.org/aquastat/en/countries-and-basins/country-profiles/country/ETH	Y
Installed power plants	Ethiopian Electric Power; https://www.eep.com.et/?page_id=1033	Y

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2.3 Preliminary results and main insights

The results of the CLEW system analysis in Ethiopia indicate significant competition for land and resources, particularly when considering the effects of climate change. Although current trends can meet the increasing demand for energy and food, they come at a high cost, including extensive deforestation and increased emissions.

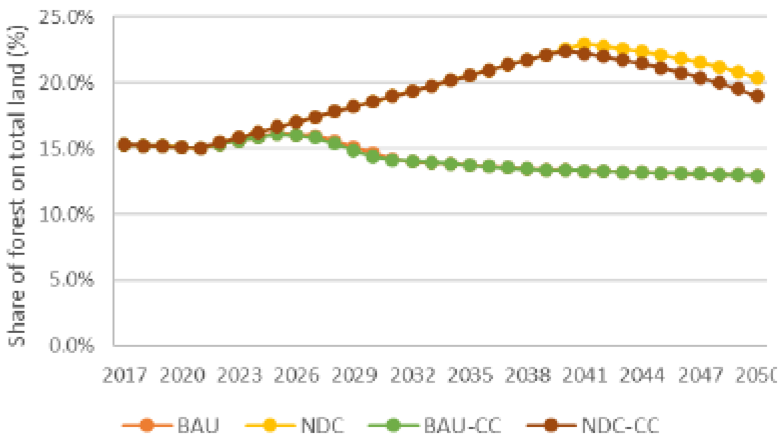

Figure 4 Forest share by scenario - Ethiopia

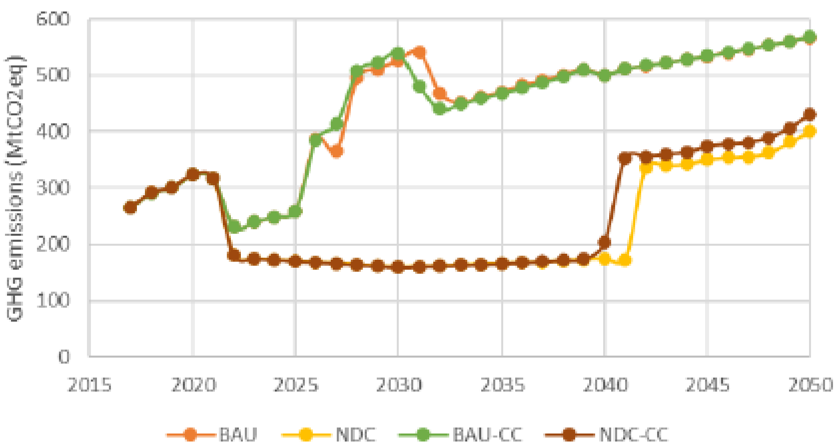

Figure 5 Annual GHG emissions by scenario - Ethiopia

When NDC (Nationally Determined Contributions) policies are implemented, the rising demand for electricity requires greater installed capacity, which helps lower emissions due to a 100% renewable energy share and the electrification of the residential and transport sectors. This shift also reduces biomass use and its associated environmental impacts. However, efforts to increase crop production hinder the ability to achieve afforestation targets due to limited available land.

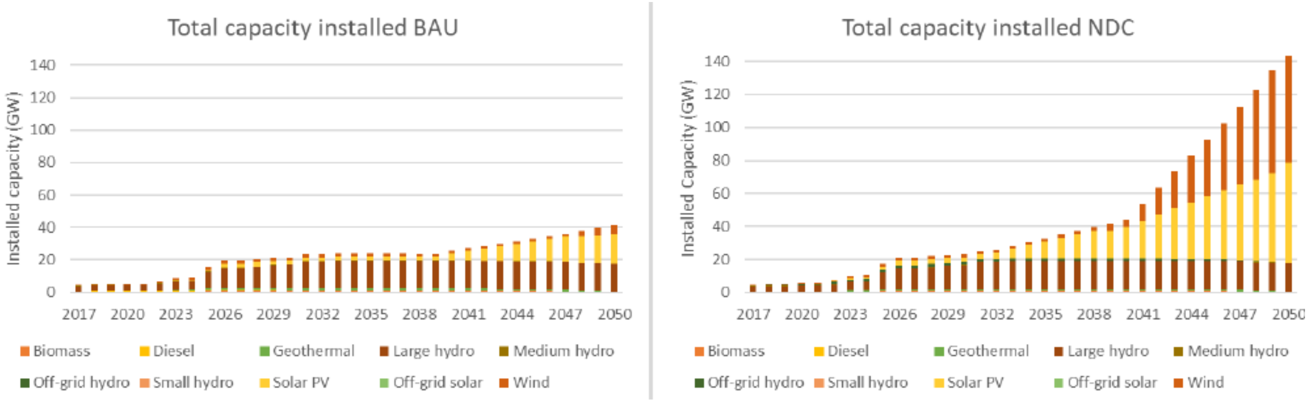

Figure 6 Total installed capacity in BAU and NDC scenarios - Ethiopia

While in a BAU scenario hydro power plants are still forecasted to account for the highest share for electricity production, in NDC, solar PV and Wind reach high shares, suggesting that it would be beneficial for the country to start making early investment considering the future increase in the electricity demand.

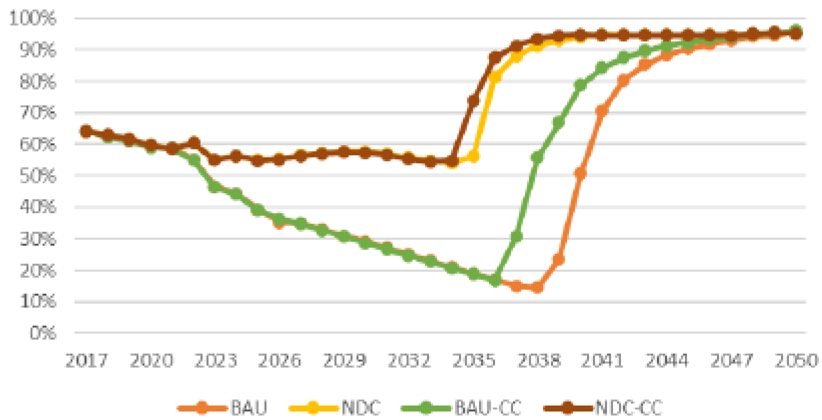

Figure 7 Share of irrigation on eater withdrawal - Ethiopia

Finally, this model has considered climate change impacts through a variation in precipitation and crop yield. For the case study of Ethiopia, precipitations are expected to increase accordingly to the EPCC (2015) forecasts, whereas crop yields are expected to decrease considering the negative effects related to droughts, flooding and extreme atmospheric phenomena (Rettie et al. 2022; Tirfi and Oyekale 2022; Murken et al. 2020; Tomalka et al 2020; Mohamed 2017; ECFF 2017; Alemayehu et al. 2018; and Zewudie et al. 2021). Because of that, the increased precipitation is still not enough for mitigating the lower crop production caused by the climate change impacts and hence, higher irrigation is needed in order to meet the crop demand. Consequently, Ethiopia's water resources face significant challenges, as future demands are expected to come close to the limits of their renewable availability. Therefore, effective water management, careful monitoring of water use, and precise mapping of the country's currently unknown groundwater potential are essential.

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3 Model factsheet: Ethiopia – OnSSET

3.1 Context and need

The electricity access rate in 2022 was about 55%, with a huge disparity between urban and rural population at 94% and 43% respectively (World Bank Open Data, 2022). It has also one of the lowest average annual electricity consumption per capita in the world estimated at about 77 kWh (Worlddata: The World in Numbers, 2020).

As boldly outlined in the National Electrification Program (NEP 2.0) which was launched in 2019, the first and foremost policy objectives were to enhance the electricity access and fulfil the goal of electrification for all by 2025, whereby 65% is through the national grid and the remaining 35% with off-grid solutions (Ministry of Water, Irrigation, and Energy, 2019). Now, Ethiopia strongly depends on hydropower with the share of around 92% of the installed electricity capacity (which roughly accounts less than 3% of the total energy supply) and, therefore, it is sensitive to climate change and particularly to the availability of water. Furthermore, the household expenditure as a percentage showed that 96% of the population depends on traditional biomass, particularly firewood, for cooking, which highly contributed to indoor pollution hence health complications and environmental pollution as well. Other major challenges of the sector are power transmission and distribution networks losses, limited diversity of the generation portfolio, etc.

Hence, the OnSSET spatial electrification tool help to enhance the electricity access rates and reduce the common traditional biomass reliance in the country

3.1.1 Aim of the model and target audiences

The aim of the model is to give eye-opener insights for policy/decision makers to test existing and support upcoming electrification planning for an optimal electricity infrastructure investment (least cost electrification), highlighting prioritisation by assessing spatially explicitly electricity demand, renewable energy resources and their potential positive impacts. Moreover, it also helps building up on existing knowledge and useful resource for academia and modelling community/analysts for electrification analysis and gives an idea of the sub-sector development for various stakeholders such as investors and other private sector players. This enables for assisting with electrification planning for more people accessing electricity in a sustainable manner. This would not only lead to an enhancement of the quality of life of those in the community but also lower the negative environmental impact and improve people’s welfare due to the reduction of the usage of polluting traditional biomass fuels.

3.1.2 Brief history on model development

This OnSSET spatial electrification model was first developed through UK aid FCDO funding under the Energy and Economic Growth program for cost-optimal electricity supply, in the “energy system development pathways” project in collaboration with KTH. However, now in IAM COMPACT, the current OnSSET is updated using actual ground-level electricity infrastructure data (compared to data built on other data and modelled) and recalibrated using up-to-date socio-economic data. In Ethiopia, meagre is done on integrating geospatial models in national electrification planning. Optimal mix of electrification and spatial dependency (Mentis et al., 2016) and grid expansion suitability analysis (factors such as terrain characteristics and distance from infrastructure) and grid extension cost (Temesgen et al., 2024) are from the very limited works in the country.

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3.2 Model scope and structure

Table 3 Electrification model scope and structure – Ethiopia

	Scope	Detail
Sectoral coverage	Spatially explicit electrification	Covering grid, mini-grid and standalone electricity access technologies.
Type of analysis	Least cost optimisation.	Where the objective function is the levelised cost of energy (LCoE)
Modelling tool used	OnSSET	Open Source Spatial Electrification Tool (http://www.onsset.org)
Open source code	Yes	Link, with MIT license
Open access data	Yes	License and link to repository
Documentation	Yes	Link License and link to documentation
Previous use	Update on existing model	Update electricity infrastructure (digitised utility data, as compared to previously modelled data), model recalibration (socio-economic data) from previous work available at link 1, link 2.
Institution(s) that created model	Addis Ababa Institute of Technology	
Institution(s) that maintain model	Addis Ababa Institute of Technology	
Geographical coverage	Ethiopia	
Geographical resolution	National	
Time domain	Year(s) modelled	2024 - 2035
Time resolution	Modelling time steps	2024 – 2028 - 2035
Deterministic	Yes	
Dynamic	No	Static – i.e. giving a snapshot at the target year
Mathematical formulation	Linear program	LCoE minimisation for every settlement (grid cell) based on local spatial electricity infrastructure, demand, resource potential and other peculiar characteristics.
Rationale	Geospatial optimisation	For every cell, choice of the electrification option (among a set of given options) with the lowest LCoE.
Technology richness	Mixed (Top-down and bottom-up)	For the electricity demand from bottom-up ESMAP's Mutli-tier Framework tier demand, or from socio-economic parameters (GDP, poverty, etc.)
Solver(s) used	None	
Solution	31.7 minutes	• Processor: Intel(R) Core(TM) i7-10610U CPU @ 1.80GHz • RAM: 16GB

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1. Key data sources

Table 4 Key data sources – Ethiopia electrification model

Dataset	Source	Open access
Population clusters (vector polygon)	https://wopr.worldpop.org/	Y
Land cover (raster)	https://www.diva-gis.org/gdata	Y
Night time light (raster)	https://eogdata.mines.edu/products/vnl/#annual_v2	Y
Administrative boundaries (vector polygon)	https://gadm.org/download_country.html	Y
Annual GHG	https://globalsolaratlas.info/	Y
Wind speed at 50m	https://globalwindatlas.info/	Y
Roads infrastructure network	OpenStreetMap https://www.openstreetmap.org	Y
Digital elevation model (raster)	DIVA-GIS https://diva-gis.org/	Y
HV infrastructure network (vector line)	OpenStreetMap https://www.openstreetmap.org	Y
MV (overhead and underground) infrastructure network (vector line)	Actual digitised data from utility (EEU)	N
Substations, transformers, diesel stations infrastructure (vector points)	EEU	N
Travel time (raster)	Malaria atlas https://data.malariaatlas.org/maps	Y
Small-scale hydro resource	https://energydata.info/dataset/small-and-mini-hydropower-potential-in-sub-saharan-africa/resource/	Y
Population	https://population.un.org/wpp/	Y
Electricity demand Capital costs (HV lines, mini-grids, and standalone infrastructure) Discount rate	World Bank Group, Ethiopia GEP, https://energydata.info/ , CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/)	Y

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3.3 Preliminary results and main insights

The current electrification status of population settlements is shown in yellow for un-electrified areas and blue for electrified areas. OnSSET uses these population clusters and their geospatial proximity to electricity infrastructures, as well as local energy demand and resources, to plan effective electrification strategies. These strategies include a mix of grid extensions, mini-grids, and standalone systems based on the current baseline scenario.

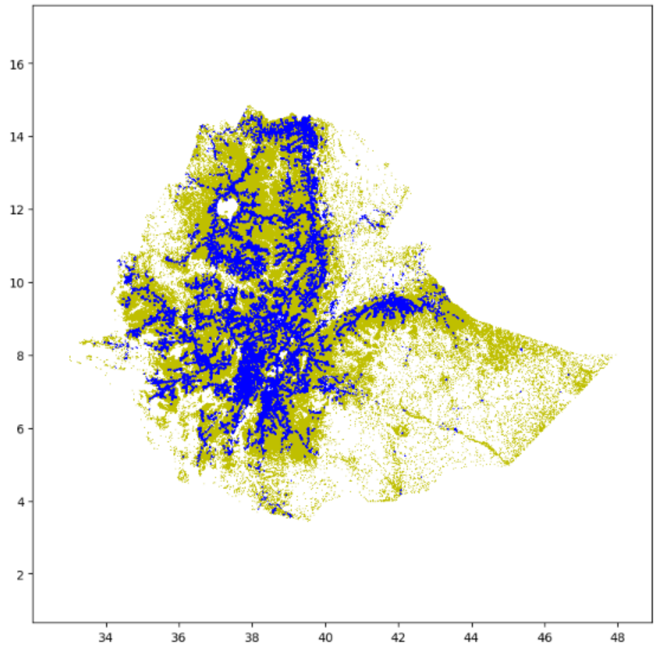

Figure 8 Electricity access rate (settlements) at the modelling start year (2024).

The optimal electrification mix consisting of grid connection, off-grid and standalone systems, up to the modelling period of 2035 highlights that:

- Population connected to the grid in 2035 is nearly 102 mil people;
- Newly connected are about 25 mil within this time horizon;
- Grid capacity addition required to achieve the electrification rate is 974 MW;
- Standalone and mini-grid PV are 669 MW and 279 MW respectively.

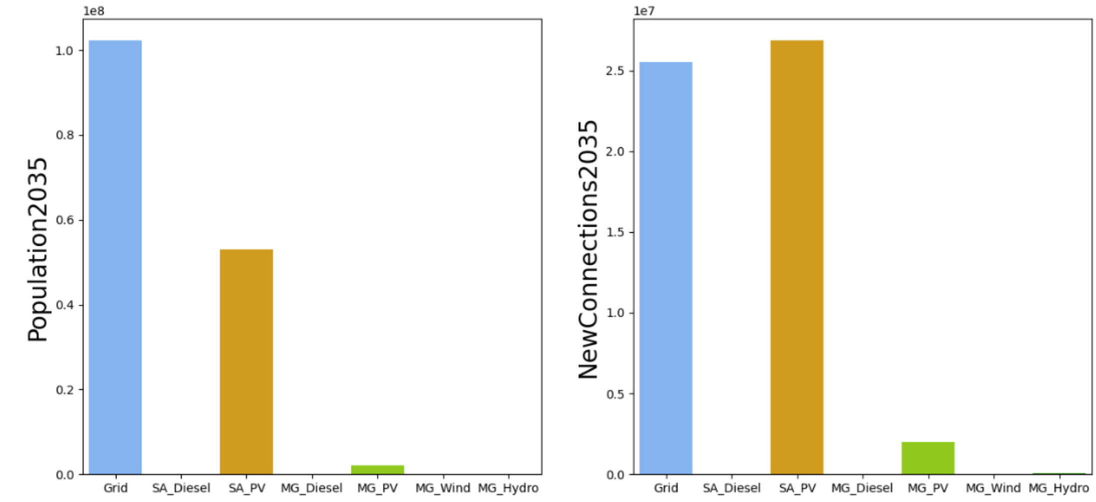

Figure 9 Population electrification by technology (left) and newly connected (right) in 2035.

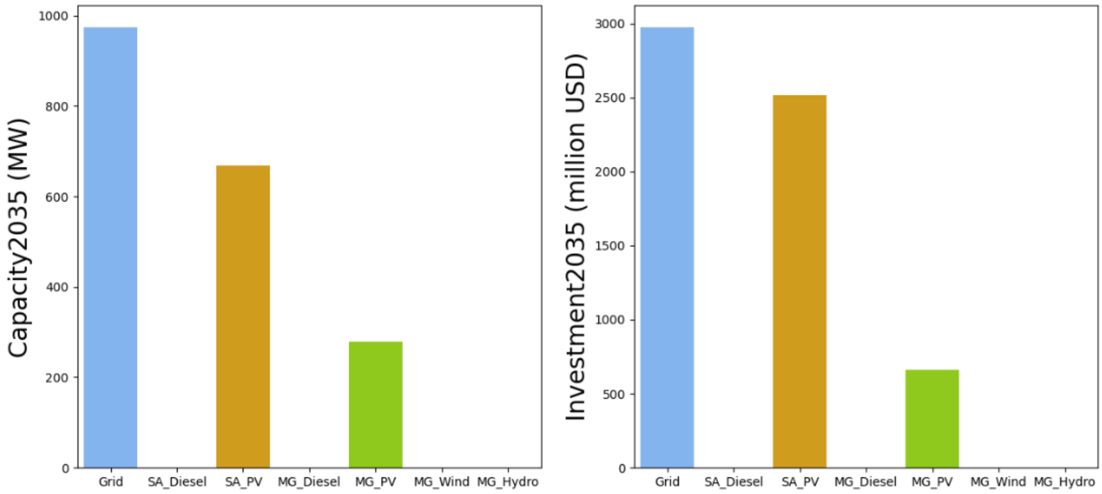

Figure 10 Installed capacity by technology (left) and investments needed (right) in 2035.

The spatial electrification analysis, based on minimizing the Levelised Cost of Electricity (LCoE), indicates that standalone photovoltaic (PV) systems will continue to play a significant role in achieving universal electrification, particularly for settlements located far from the grid with low demand tiers. These preliminary results suggest that while the national target of achieving universal electrification by 2025, as outlined in NEP 2.0, is highly ambitious, they also reinforce the NEP's argument that off-grid and standalone solutions will be essential in reaching this goal.

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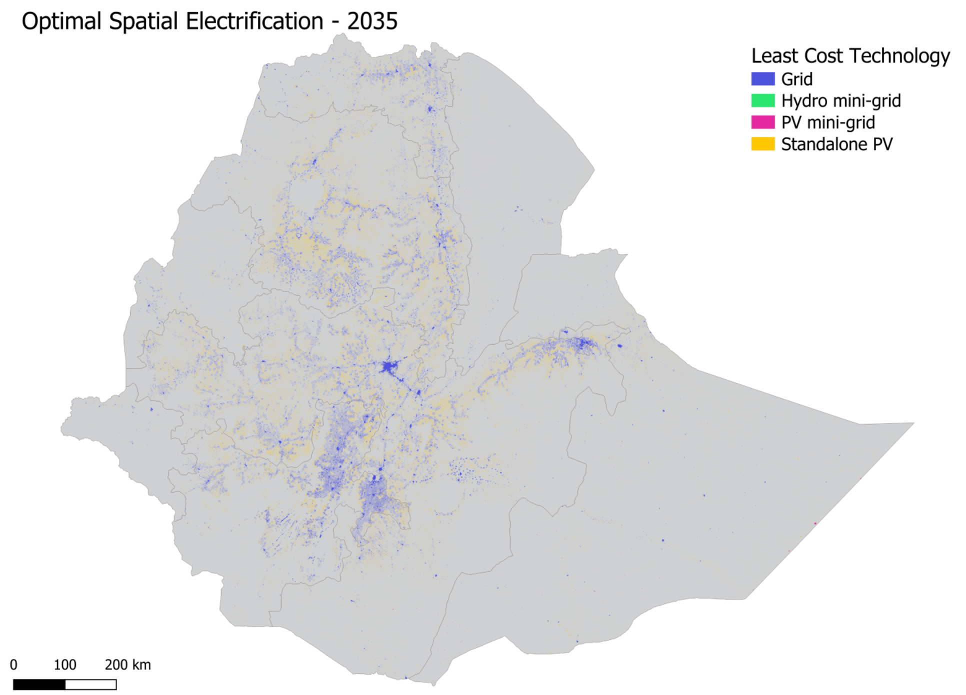

Figure 11 Spatial electrification visual in 2035 through grid, mini-grid and standalone technologies.

4 Model factsheet: Sri Lanka - CLEWs

4.1 Context and needs

Sri Lanka is an island nation in the Indian Ocean classified as a lower-middle-income country by the World Bank with a per capita GDP reaching $3474 by mid-2022 (Central Bank of Sri Lanka (2023). The country's population of 22 million resides within a relatively small land area of 65,610 sq.km resulting in a high population density of ~354 persons per sq.km, ranking 40th in the world (Central Bank of Sri Lanka, 2022). These demographic characteristics, coupled with the country's geographic location and economic structure contributes to its increased vulnerability to the impacts of climate change. Sri Lanka has experienced the increasing frequency and intensity of extreme weather conditions. The country has been grappling with significant challenges in recent years. This is including prolonged effects of the COVID-19 pandemic, and a severe economic crisis marked by high inflation rates (69.7% in September 2022) skyrocketing retail prices of essential goods and shortage of fuel (Central Bank of Sri Lanka (2023b). This economic crisis has had cascading impacts on energy security, industrial productivity, decline in quality of life and the overall development progress of the country including the set targets of GHG mitigation. With extended support from the International Monetary Fund (IMF), Sri Lanka is taking steps towards recovery. However, the IMF funds come with certain conditions such as import restrictions, governance reforms particularly in the energy sector and revised tax structures (IMF, 2023).

The extensive dependence on imported fossil fuels (43% of primary energy supply) for power generation, transportation, industry, and building energy needs (SLSEA, 2020) in Sri Lanka makes the country vulnerable to global price shocks and supply chain disruptions. This has been a significant challenge to the country's economic recovery. There are ambitious renewable energy expansion targets set as a crucial measure for reducing greenhouse gas emissions (GHG) and fossil fuel dependency such as delivering 70% of electricity from renewable energy source by 2030 (Ministry of Environment, 2021). The set targets are profound in the power generation sector but face hurdles in terms of grid integration, the availability of cost-effective energy storage solutions, and land availability concerns.

The transport sector has been subjected to the least level of GHG reduction efforts so far. The sector is dominated by private vehicles year on year while suffering from a decline in public transport usage and increasing congestion, leading to higher emissions and reduced air quality. Rapid urbanisation and the widespread use of informal construction methods in the building sector pose challenges for sustainable development and resource management. The forestry sector is grappling with deforestation and forest degradation, impacting biodiversity and carbon sequestration. The agricultural sector, a significant contributor to GDP and employment in Sri Lanka, is grappling with low productivity due to outdated farming practices and the increasing frequency of climate change-induced extreme weather events like droughts and floods (Ministry of Environment, 2021; Ministry of Mahaweli Development and Environment, 2016).

These multifaceted challenges underscore the need for a CLEWs model that can comprehensively assess the interactions between climate, land use, energy, and water systems in Sri Lanka to inform effective and sustainable policymaking.

4.1.1 Aim of the model and target audience

A Sri Lankan CLEWs model is being developed to gain detailed insight into the complex interactions among the climate, land-use, energy, and water systems. The model would show existing or potential conflicts and opportunities for attaining sustainable development when interdependencies across different sectors are assessed. As a key tool to project the impacts of climate change, pinpoint vulnerable areas for policymakers and stakeholders, it aims to inform the development of policies and strategies for sustainable development, economic growth, and climate resilience. The final goal is to enable decision making via evidence-based modelling which has been lacking in Sri Lanka's context, as the tool could be utilised by policymakers at different ministries and institutions to gain insights that could inform their policies and measures, account for the impacts across multiple sectors, and ensure sustainable development and efficient resource management.

Researchers and academics would find the model useful in research studies relevant to climate change, energy, water, and land use interactions, and could use it for exploratory scenarios of Sri Lanka's future. The model could also provide insights to international organisations, aligning local policies with global frameworks (e.g., Pais Agreement); the private sector by developing adaptive strategies, and identifying vulnerabilities and risks; and civil society by enhancing public engagement and supporting participatory governance as it allows for greater transparency in how data is used and interpreted, and interested parties can freely access all information, and test the model.

4.1.2 Brief history on model development

The CLEWs model for Sri Lanka is an advancement of the work done during the CLEWs Training Programme by UNDP and UNDESA South Asia Region in 2020 (Jayasuriya et al., 2023). During the programme more of an abstract representation of energy, land, and water systems and preliminary data validation were used. For IAM COMPACT, the CLEWs model has been redeveloped from scratch, bringing additional details in the power generation sector. This includes modelling of all individual major power stations and validation of data from the up-to-date publications available from the government. Where possible, parameter definitions such as availability factor, capacity factor and specified demand profiles will now include detailed analysis of historic data published by the government and utility companies. Energy storage modelling and potential soft linking to macro-economic models are envisaged during IAM COMPACT.

4.2 Model scope and structure

Table 5 Model scope and structure - Sri Lanka

	Scope	Detail
Sectoral coverage	Climate, Water, Land and Energy	**Energy**: Cover all fossil fuel supply chains for residential, commercial, industrial and transport sectors. This includes the crude oil refinery and refined petroleum imports. Electricity supply technologies and expansion candidates are modelled in detail including reserve, and changes in transmission and distribution losses over the years. Electricity demand for water pumping in irrigation and public water supplies are modelled. **Land-use**: Six major land-use types are considered; Agriculture, Water, Built-upland, Forest, Grass-land, and Barren Land. Agriculture land is further details into major crops, Rice Paddy, Coconut, Tea, Rubber, and Maize. Each crop land area is characterised by the crop yield (High, Intermediate, and Lows) and water source (irrigated, rain-fed). Land-use for power generation plants are factorised as a demand for built-up land in the model. **Water**: The core water balance is modelled for different land-use types; precipitation, evapotranspiration, ground-water recharge and surface run-off. Water demand for cooling thermal power stations is covered. **Climate**: details to be included.

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Type of analysis	Cost-optimisation; Long-term planning	The objective function aims to minimize the net present value (NPV) of all costs incurred across the interconnected climate, land, energy, and water systems over the analysis period. This encompasses costs related to resource extraction, infrastructure development, technology deployment, environmental mitigation, and more.
Modelling tool used	OSeMOSYS	CLEWs stands for Climate, Land, Energy, and Water systems and is the methodology implemented by the OSeMOSYS tool. This approach is designed to help decision-makers understand and analyse the complex interactions between these four critical systems. It helps assess the impacts of policy and investment decisions made in one sector (e.g., land use) on the other sectors (e.g., water supply). Link to OSeMOSYS documentation: https://osemosys.readthedocs.io/en/latest/manual/Introduction.html Link to CLEWs documentation: https://iopscience.iop.org/article/10.1088/1748-9326/abd34f/meta
Open source code	Yes	https://github.com/OSeMOSYS/CLEWs
Open access data	Yes	License and link to repository
Documentation	Yes	License and link to documentation
Previous use	Building on existing model	(Jayasuriya et al., 2023)
Institution(s) that created model	Rajarata University of Sri Lanka	
Institution(s) that maintain model	Rajarata University of Sri Lanka	
Geographical coverage	Sri Lanka	
Geographical resolution	National	
Time domain	2020 - 2050	
Time resolution	Intra-annual time steps	Three seasons in a year: Dry, High Wind and Wet. The seasons have been typically continuous, and it is the same used in most national scale analysis such as the analysis conducted by the Ceylon Electricity Board for their Long-Term Generation Expansion Plan (CEB, 2023b) . However, the seasonality is vulnerable to climate

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		change. Two-day types: Weekdays, Weekends Intraday: Peak, Off-peak and Day Peak. In total, 18-time slices will represent a year.
Deterministic	Yes	
Dynamic	Yes	Year-by-year capacity expansion, with intra-annual operation
Mathematical formulation	Linear programming	Constrained optimisation, where the objective function is the minimisation of the total net present cost of the whole land-energy-water system for all the years, with perfect foresight. Key constraints are availability of energy, land and water resources, demands for energy, food and water (which must be met), techno-economic constraints of technologies and policy constraints.
Rationale	Optimisation	see above
Technology richness	Bottom-up	Therefore, the model incorporates bottom-up elements, particularly in its detailed representation of the energy sector, agriculture and water resource. For each of them, has been considered factors like technology costs, efficiencies, capacities, and resource availability to determine the optimal technology mix to meet demand. The total amount of modelled technologies is 149 and they can be divided in these main groups: conversion (such as power plants), supply (fossil fuel resources), land (crops), water supply and transmission and distribution. Then each technology receives as an input and has as an output a commodity (such as electricity, land, fossil fuel etc.). The total number of commodities is 63.
Solver used	CBC	Free and open source: https://github.com/coin-or/Cbc
Solution	Total time (CPU second): 20.45	• OSeMOSYS UI: 4.9 • RAM: 16 GB • Processor: Intel(R) CoreÜM) i7-8550U CPU @ 1.80GHZ (8 cpus), 2.0 GHz

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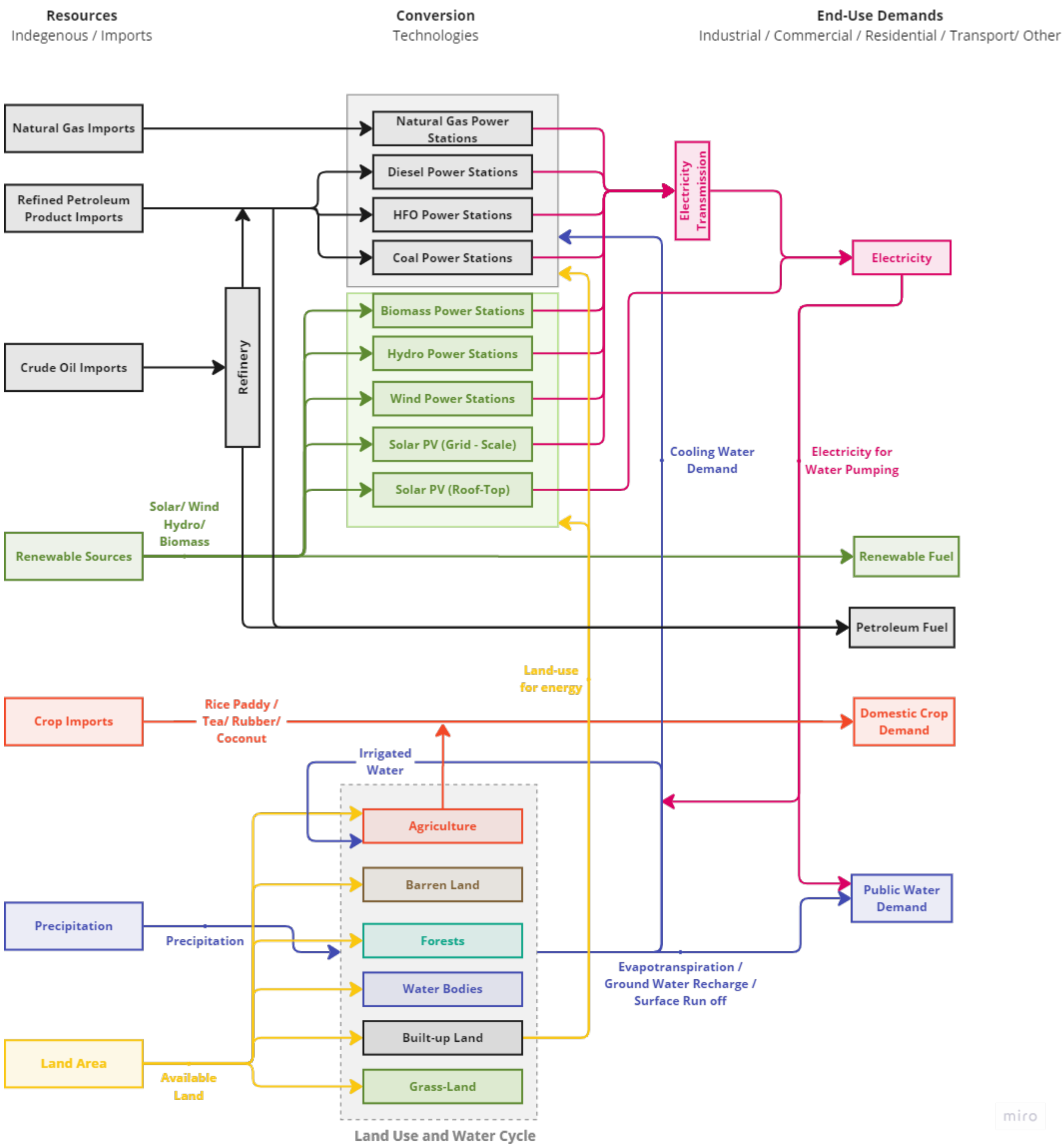

Figure 12 CLEWs Reference system – Sri Lanka[3]

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[3] A detailed version of the reference system is available here.

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4.2.1 Key data sources

Table 6 Key data sources – Sri Lanka

Dataset	Source	Open access
Power generation expansion data, Annual energy demand projections Power generator data - existing (efficiencies, capital costs, variable costs, fixed costs) time definitions (seasons etc.)	https://ceb.lk/front_img/img_reports/1677040471CEB_LTGEP_2023-2042_DL-LINK-.pdf JICA. (2018). Project on Electricity Sector Master Plan Study in Democratic Socialist Republic of Sri Lanka. http://www.osti.gov/bridge https://www.nrel.gov/docs/fy17osti/67645.pdf	Y
Generation Information (15-minute dispatch data) to analyse capacity factors and demand profiles	https://www.pucsl.gov.lk/generation-information-archived/	Y
Annual energy demand data (historic) and information on trends	SLSEA. (2017). Sri Lanka Energy Balance 2017. SLSEA. (2018). Sri Lanka Energy Balance 2018. http://www.energy.gov.za/files/energyStats_frame.html SLSEA. (2019). Sri Lanka Energy Balance 2019. http://www.energy.gov.lk/images/energy-balance/energy-balance-2019-lq.pdf SLSEA. (2020). Sri Lanka Energy Balance 2020. https://www.energy.gov.lk/images/energy-balance/energy-balance-2020.pdf	Y
Annual electricity demand, electricity generators operational in each year (historic)	CEB. (2020a). CEB Annual Report 2020. https://ceb.lk/front_img/img_reports/164887150703-CEB-Annual_Report-2020-English.pdf CEB. (2020b). CEB Statistical Digest 2020. CEB. (2020c). Ceylon Electricity Board Sales and Generation Data Book 202 (Issue March). CEB. (2020d). Ceylon Electricity Board Sales and Generation Data Book 2020 (Issue March). https://ceb.lk/front_img/img_reports/1642757328Sales_and_Generation_Data_Book_2020.pdf CEB. (2020e). Historical Data Book 1969 - 2020 (Vol. 21, Issue 1). https://ceb.lk/front_img/img_reports/1646997209Historical_Data_Book_1969-2020_Readable.pdf CEB. (2021a). CEB Statistical Digest 2021. https://ceb.lk/front_img/img_reports/1656311266CEB-Statistical-Digest-2021-cover.pdf CEB. (2021b). Ceylon Electricity Board Sales and	Y

	Generation Data Book 2019. https://ceb.lk/front_img/img_reports/1664784123Sales_and_Generation_Data_Book_2021.pdf CEB. (2021c). Ceylon Electricity Board Sales and Generation Data Book 2021. https://ceb.lk/front_img/img_reports/1664784123Sales_and_Generation_Data_Book_2021.pdf CEB. (2022a). CEB Statistical Digest 2022. https://www.ceb.lk/front_img/img_reports/1687251830Statistical_Digest_2022.pdf CEB. (2022b). Ceylon Electricity Board Sales and Generation Data Book 2022. CEB. (2023a). CEB Statistical Digest 2023. CEB. (2023b). Long Term Generation Expansion Plan 2023-2042. https://ceb.lk/front_img/img_reports/1677040471CEB_LTGEP_2023-2042_DL-LINK-.pdf	
Power Generation availability factors	Ministry of Power and Energy. (2021). Annual Performance Report. http://powermin.gov.lk/english/wp-content/uploads/2022/11/03-English-2021.pdf NREL. (2010). Cost and performance assumptions for modeling electricity generation technologies. (Issue November). http://www.osti.gov/bridge PUCSL. (2014). Generation Performance in Sri Lanka 2016 (Draft) (Vol. 2014). http://www.pucsl.gov.lk/english/wp-content/uploads/2015/01/Generation-Performance-Report_2014-First-Half.pdf	Y
Fuel Costs	CEB. (2023b). Long Term Generation Expansion Plan 2023-2042. https://ceb.lk/front_img/img_reports/1677040471CEB_LTGEP_2023-2042_DL-LINK-.pdf CEYPETCO. (2020). CEYPETCO Procurement Plan 2021-2023. CEYPETCO. (2021). CEYPETCO Procurement plan 2022 - 2024. International Energy Agency. (2023). World Energy Outlook 2023 | Enhanced Reader. 23–28. https://www.iea.org/news/the-energy-world-is-set-to-change-significantly-by-2030-based-on-today-s-policy-settings-alone JICA. (2018). Project on Electricity Sector Master Plan	Y

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	Study in Democratic Socialist Republic of Sri Lanka.	
Socio economic data	Central Bank of Sri Lanka. (2023a). Economic and Social Statistics of Sri Lanka. https://www.cbsl.gov.lk/en/publications/other-publications/statistical-publications/economic-and-social-statistics-of-sri-lanka/ess-2023	Y
Land use for electricity generation	Strarta. (2017). The Footprint of Energy: Land Use of U.S. Electricity Production. https://docs.wind-watch.org/US-footprints-Strata-2017.pdf	Y
Area harvested, yield, crop demand (historic)	Central Bank of Sri Lanka. (2023a). Economic and Social Statistics of Sri Lanka. https://www.cbsl.gov.lk/en/publications/other-publications/statistical-publications/economic-and-social-statistics-of-sri-lanka/ess-2023	Y
Land cover, crop specific yields	GeoClews: https://github.com/OSeMOSYS/CLEWs_GAEZ	Y
Emission Factors	IPCCC 2006 Guidelines : https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html GHG Protocol (Online) : https://ghgprotocol.org/sites/default/files/Emission_Factors_from_Cross_Sector_Tools_March_2017.xlsx	Y

4.3 Preliminary results and main insights

A preliminary study was conducted to assess the land-use implications of ambitious renewable energy expansion in Sri Lanka. It considered land use competition due to increasing demands for food and energy within the context of Sri Lanka's GHG mitigation targets. The study examined two scenarios: a Base case with existing growth rates of new renewable energy sources against a *High_RE* scenario which anticipated accelerated investments made into solar and wind power technologies. The main variance between the scenarios was the annual investment

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limits towards newly developed renewables with regards to their capacity alone.

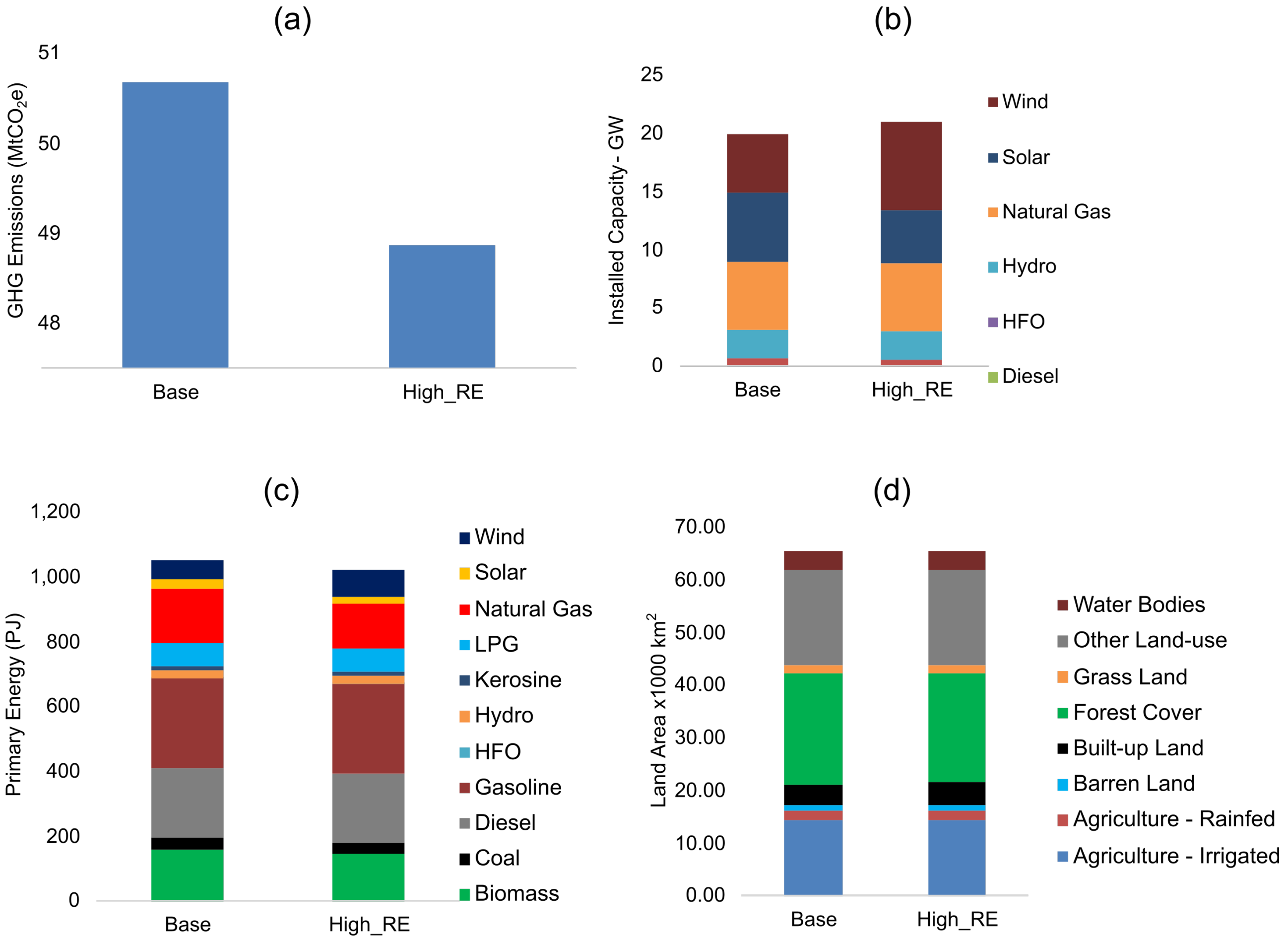

Figure 13 Indicative results from a preliminary study conducted using CLEWs Sri Lanka; (a) GHG emissions, (b) Installed Capacity of Power Generation by Fuel, (c) Primary Energy Supply by Fuel, and (d) Lan-use by type for the Base and High_RE scenarios in 2050.

Despite having a favourable investment environment for renewable energy projects, preliminary findings suggest that land-use constraints may limit the extent to which solar and wind plants could be built in Sri Lanka. The High_RE option has resulted in only 2MtCO2e GHG emissions reduction when compared with Base case scenario as illustrated above. In the High_RE scenario, increased capacity would be installed than is noted for solar PV because wind power plants have higher capacity factors that would allow maximizing energy intensity from such locations used for energy generation. High_RE also shows low primary energy consumption level than Base case due to more input of renewables.

The study finds that just decreasing forest cover and grassland areas by 2% could create enough land for renewable energy construction. In Sri Lanka, as an island country with growing population, demand for agricultural use of land is rising, especially among the built-up areas. This would also mean that it is difficult to achieve what has been proposed concerning rising forest cover, unless proper management of land-use is realised.

5 Model factsheet: Kenya - CLEWs

5.1 Context and need

Kenya, a country in the East coast of Africa is one of the countries with the lowest carbon intensive power systems in the region (Kahlen et.al, 2021). By 2023, Kenya's GDP was $107.44 billion, and its economic growth having grown to 5.4% (World Bank, 2023). It hosts a population of over 55 million Kenyans, a low GDP per capita of $1949.9 and a human capital index of 0.5 (World Bank, 2023).

According to IRENA, Kenya's total energy supply consisted of 75% renewables by 2021 and 86% of electricity generation coming from renewables (IRENA 2024). 76% percent of the population has access to electricity, and only 30% access to clean cooking (IRENA, 2024). By 2022, Kenya's Carbon emissions had grown to an annual amount of 24.85 million tonnes which in total accounts for 0.03% of the global cumulative carbon emissions (our world in data, 2022). However, despite emissions not being a primary concern considering Kenya's energy mix, Kenya's economy would still benefit from combating climate change by maintaining its low carbon emission policies (World Bank Group 2023a,2023b). While Kenya has a large integration of renewable energy sources it still faces some challenges regarding decarbonisation and approaching the net zero target, especially in the transport and industries sector.

24% of the population in arid and semi-arid lands in Kenya face high levels of acute food insecurity. This is caused by prolonged drought and shorter cycles of drought. This has led to severe decrease in crop yield as well as livestock dying (USAID, 2022). To address the severe economic impacts of extreme weather changes, Kenya has set an updated NDC for emission reduction by at least 32% in 2030 compared to BAU (Ministry of Energy and Petroleum 2023a). Kenya is yet to set NDC sectoral mitigation targets that would address the different emissions produced by each sector. The model aims to inform policymakers on what policies and strategies that can be created to address such.

5.1.1 Aim of the model and target audiences

The Kenya CLEWS model has been developed with an aim of providing an integrated assessment of the Energy, Land and Water resources in the country and how these resources can be used. By integrating various sectors, the model seeks to inform policy decisions that would promote sustainability and reduce the negative impacts of climate change in a holistic manner. The key target users are government officials for policy-making, researchers for further research studies on similar topics, the private sector, and non-governmental organisations working on promoting sustainability, climate mitigation and adaptation strategies as well as guide efficient use and allocation of resources through integrated resource management. International organisations could also use the model to better understand regional challenges and opportunities, facilitating targeted assistance and fostering collaboration between Sri Lanka and other countries or entities facing similar challenges.

5.1.2 Brief history on model development

The model has mainly been developed and maintained by Technical University of Mombasa (TUM) under the IAM COMPACT project. The model creation has been supported by training from the International Centre for Theoretical Physics (ICTP) via their program Energy Modelling Platform Global (EMP-G) that took place in August 2023 with established datasets obtained from Climate Compatible Growth (CCG). CCG is a UK funded project which aims to support investments in sustainable energy and transport systems to meet development priorities in the Global south.

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5.2 Model scope and structure

Table 7 Model scope and structure - Kenya

	Scope	Detail
Sectoral coverage	Climate, Land, Energy and Water	Covering geothermal, hydro, solar, wind powerplants as well as light fuel oil and diesel imports. It also covers 5 main crops including maize, beans, tea, sorghum and cowpeas for both irrigated and rainfed land during high and low season. Lastly it covers water demand for public use, energy use and land use.
Type of analysis	Cost-optimisation; Long-term planning	All the scenarios represent cost-optimal solutions since the objective function consist of the minimisation of the Net Present Value. Additionally, all of them are subjected to specific constrains (such as GHG emissions, resource availability etc.) with the final aim of reaching specific targets set by the government while respecting environmental goals. Finally, the long-term planning is set on a 30-years time period.
Modelling tool used	OSeMOSYS	OSeMOSYS is an Open Source Energy Modelling System created to aid in the formation of energy strategies at local, national, and multi-regional levels. CLEWs is a methodology that enables the representation of the Climate, Land, Energy and Water systems nexus. Link to OSeMOSYS documentation: https://osemosys.readthedocs.io/en/latest/manual/Introduction.html Link to CLEWs documentation: https://iopscience.iop.org/article/10.1088/1748-9326/abd34f/meta
Open source code	Yes	https://github.com/OSeMOSYS/OSeMOSYS
Open access data	Yes	
Documentation	Yes	
Previous use	No	
Institution(s) that created model	Technical University of Mombasa	https://www.tum.ac.ke/
Institution(s) that maintain model	Technical University of Mombasa	https://www.tum.ac.ke/
Geographical coverage	Kenya	
Geographical resolution	National	
Time domain	2020-2050	
Time resolution	Intra-annual time steps	The model covers 4 seasons: 2 wet seasons and 2 dry seasons. The day is divided into day and night.
Deterministic	Yes	
Dynamic	Yes	Year-by-year capacity expansion, with intra-annual operation.

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Mathematical formulation	Linear programming	Constrained optimisation, where the objective function is the minimisation of the total net present cost of the whole land-energy-water system for all the years, with perfect foresight. Key constraints are availability of energy, land and water resources, demands for energy, food and water (which must be met), techno-economic constraints of technologies and policy constraints
Rationale	Optimisation	See above
Technology richness	Bottom-up	The total amount of modelled technologies is 60 and they can be divided in these main groups: conversion (such as power plants), supply (fossil fuel resources), land (crops), water supply and transmission and distribution. Then each technology receives as an input and has as an output a commodity (such as electricity, land, fossil fuel etc.). The total number of commodities is 31.
Solver(s) used	CBC solver	Free and open source: https://github.com/coin-or/Cbc
Solution	6 minutes	2. OSeMOSYS UI: 4.6 3. RAM: 16 GB 4. Processor: Intel core i7

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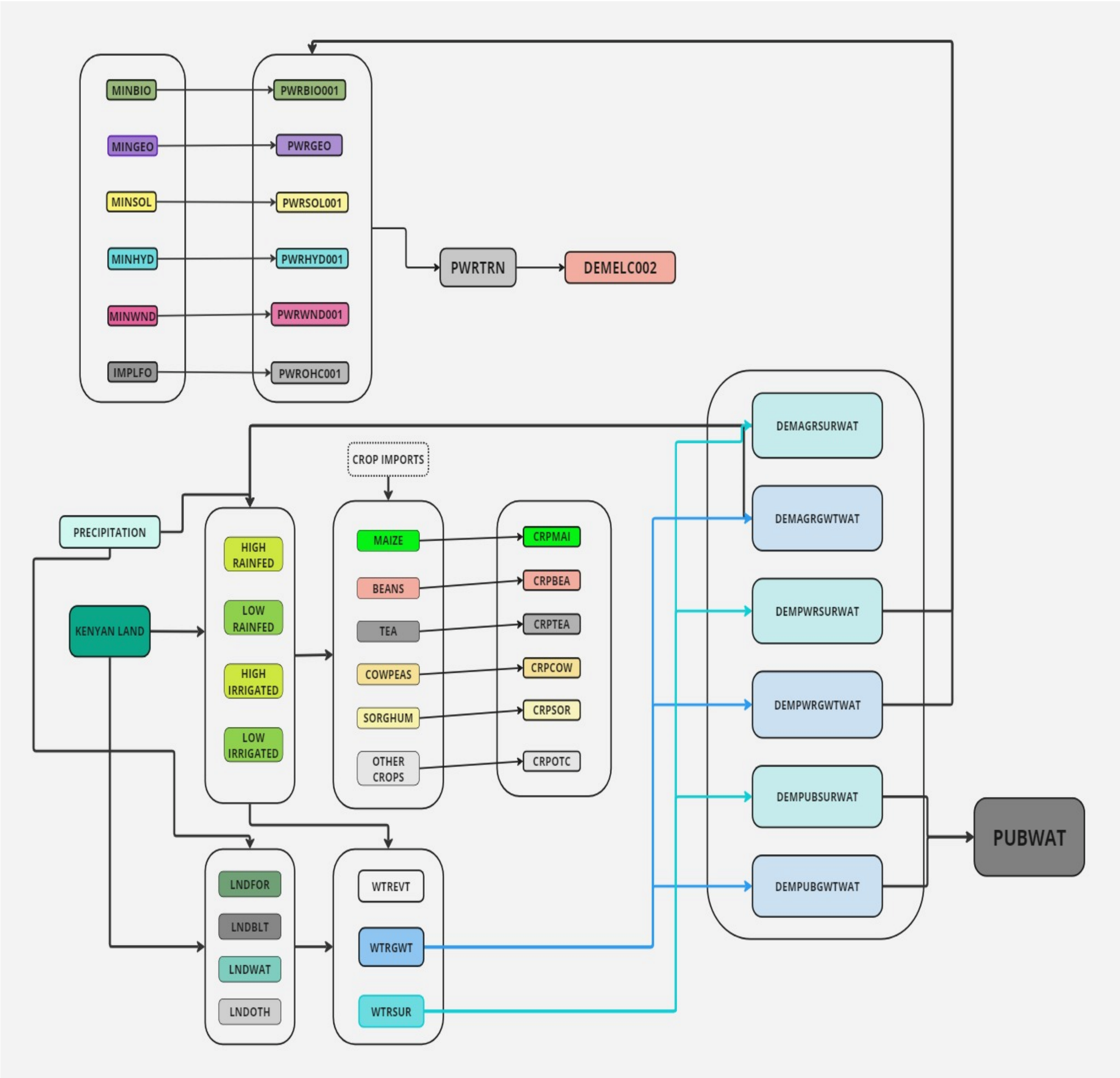


Figure 14 CLEWs Reference System – Kenya

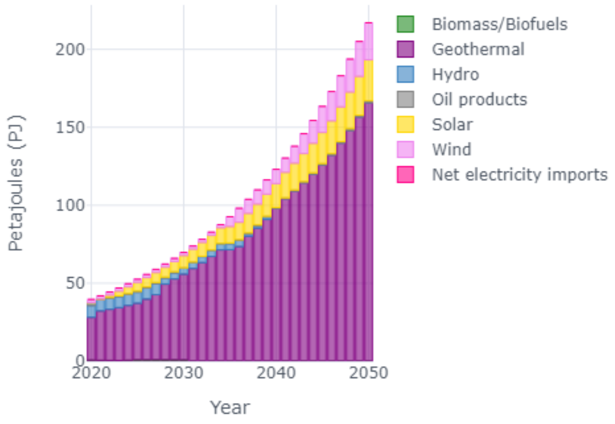
5.2.1 Key data sources

Table 8 Key data sources - Kenya

Dataset	Source	Open access
Energy data – Installed capacity	EPRA- https://www.epra.go.ke/bi-annual-energy-petroleum-statistics-report-financial-year-2023-2024/	Y
Crop data – Production, Imports, Exports, Area Harvested, Yield	FAOSTAT - https://www.fao.org/faostat/en/#data	Y
Water data – Irrigation, Irrigation potential,	AQUASTAT- https://data.apps.fao.org/aquastat/	Y
Climate data- Carbon emissions	Our world in data - https://ourworldindata.org/co2/country/kenya	Y
Economic Integration – Capital cost, Fixed costs, variable costs, Total technology annual activity upper limit, accumulated annual demand, Specified demand profile, Specified Annual demand	CCG starter kit - https://zenodo.org/records/7539097	Y

5.3 Preliminary results and main insights

Kenya has a high renewable energy share of over 90% that is bound to expand in the future due to untapped potential. A preliminary study for decarbonisation as part of the Kenya's net zero target shows that over 50% of the land is categorised under other land uses which includes grasslands, shrublands, wetland and barren lands. This shows that there is a huge amount of land that is available not just for urbanisation but as well as reforestation procedures which are part of the country's targets. The water demand is currently set at 1.5 billion cubic meters – 4.5% of actual water demand - and is expected to grow to 2.2 billion cubic meters by 2050. Future modelling efforts would address the full water demand and water scarcity in Kenya.



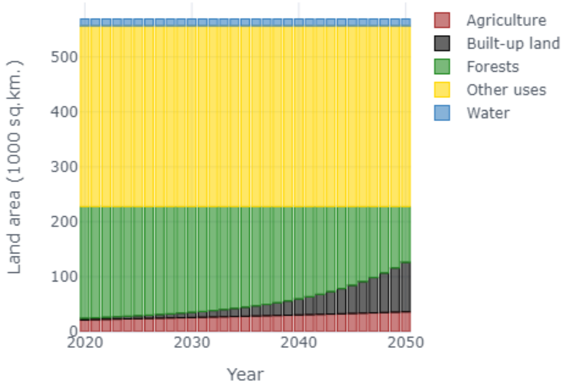
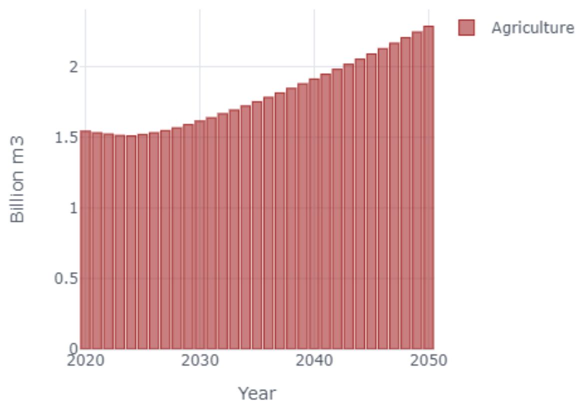


Figure 15 Power generation (left) ; area by land cover (right) – Kenya



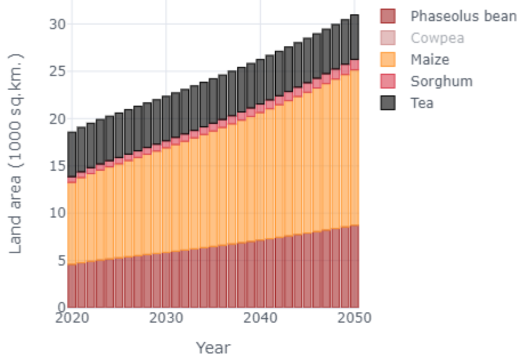


Figure 16 Water demand for agriculture (left); area by crop (right) - Kenya

The agricultural sector was assessed through a scenario for agricultural mechanisation for two crops; maize and beans was transitioned from using diesel fuel to instead use electricity which comes from a high renewable share. This showed a considerable drop in emissions of over 50% since these two crops are the largest in terms of area harvested. This shows that a future where we transition to electrical mechanisation in agricultural would have a great impact on decarbonisation considering the sector has a share of over 58.6% in GHG emissions.

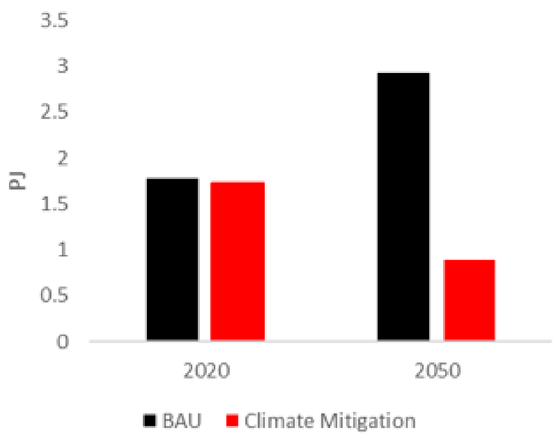


Figure 17 Agricultural diesel consumption - Kenya

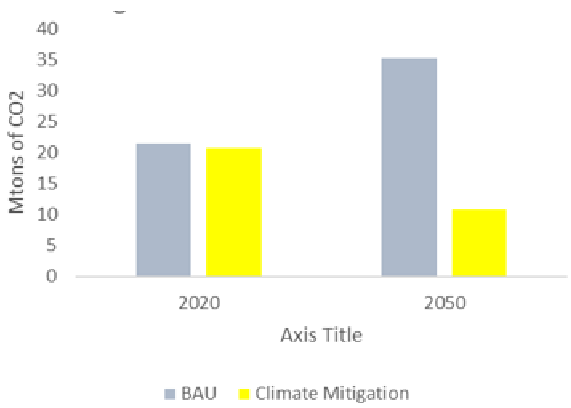


Figure 18 Agricultural carbon emissions

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6 Model factsheet: Ukraine - OSeMOSYS

6.1 Context and need

As of February 2022, Ukraine's energy sector was one of the most robust in Europe, with several significant achievements and advantages. According to the National Council for the Recovery of Ukraine from the Consequences of the War (2022):

- Ukraine ranks among the top 10 European countries in terms of installed electricity generation capacity and is one of the top 3 natural gas producers. Additionally, it possesses the largest underground gas storage facilities in Europe.
- The country has extensive and reliable systems for transporting gas, oil, petroleum products, and electricity, connecting neighbouring EU countries and Moldova.
- Ukraine boasts one of the highest shares of carbon-neutral generation in Europe, with approximately 70% of its electricity produced from nuclear, hydro, and renewable sources.

However, the full-scale Russian invasion that began in early 2022, accompanied by the subsequent destruction of Ukraine's energy infrastructure, necessitated adaptation to the current situation and the modelling of potential electricity generation scenarios.

This model utilises data pertaining to the Ukrainian energy sector prior to 2022 to identify the most optimal model for Ukraine's energy system before the invasion and the resulting destruction of energy facilities. The key task of this simulation was to find the optimal solution for the production of electricity by various types of generating plants from the point of view of their efficiency and cost, while meeting the demand for energy. Taking into account a significant number of parameters made it possible to determine which types of generating plants will produce the largest amount of electricity. Also, considering the ongoing military operations in Ukraine, which present substantial challenges to the nation's decarbonisation efforts and infrastructure reconstruction, this model strategically incorporates the phased decommissioning of thermal power plants (TPPs) utilising solid fuels, due to their significant emissions of CO_2, CH_4 and N_2O.

Such analysis will help to understand the strengths and weaknesses of this sector and to develop the next model, considering critical and significant changes due to the scale of the damage.

6.1.1 Aim of the model and target audiences

The Ukrainian energy model assesses the energy demand including a wide range of resources: biofuels and waste, various types of coal, petroleum products, natural gas, nuclear, and renewables to identify the most cost-effective and sustainable energy mix. Additionally, it evaluates the environmental impact of different energy production methods, helping to determine optimal strategies for reducing emissions. The target audience for the Ukraine OSeMOSYS model embeds government organisations and agencies involved in energy planning and policymaking. This includes the Ministry of Energy of Ukraine, which can use the model for strategic planning and policy development in the energy sector, and the Ministry of Ecology and Natural Resources of Ukraine, which can assess the environmental impacts of different energy policies and develop appropriate regulations, while the State Agency for Energy Efficiency and Energy Saving of Ukraine can leverage the model to promote and implement energy efficiency measures. Additionally, the model is valuable for researchers, international organisations, and non-governmental organisations focused on energy sustainability, climate mitigation, and adaptation strategies in Ukraine. By providing a detailed analysis of energy production, demand, and environmental impacts, the OSeMOSYS model supports evidence-based decision-making to ensure a sustainable energy future for Ukraine.

6.1.2 Brief history on model development

OSeMOSYS is an open-source optimisation modelling system designed for long-term integrated assessment and energy planning. The first version of the OSeMOSYS code was released in 2008, and has been utilised in scientific research, academic teaching, and capacity building for energy planners to offer insights into transformation pathways of energy systems and their effects on the economy, society, and the environment (Howells et. al., 2011). It has been used to develop energy system models at various scales, ranging from global and continental levels to national, regional, and even village scales. The model can focus on detailed representations of power generation or on multi-resource systems that encompass materials, finances, and all forms of energy. OSeMOSYS - Ukraine was created for the scope of IAM COMPACT.

6.2 Model scope and structure

Table 9 Model scope and structure - Ukraine

	Scope	Detail
Sectoral coverage	Energy system. Production and use of electricity	Analysis of the installed capacities of the energy system of Ukraine, the structure of electricity production in Ukraine and the structure of electricity consumption
Type of analysis	Cost-optimisation; Long-term planning	Optimisation of installed capacities and volumes of production of generating capacities depending on changes in the volume of electricity consumption. The objective function minimizes the costs, while the long-term planning is set on a 30-year time period.
Modelling tool used	OSeMOSYS	OSeMOSYS - the Open Source Energy Modelling System. This tool helps in optimizing the installed capacities and their volumes depending on the change in the volume of electricity consumption. Link to OSeMOSYS documentation: https://osemosys.readthedocs.io/en/latest/manual/Introduction.html
Open source code	Yes	https://github.com/OSeMOSYS/OSeMOSYS
Open access data	Yes	
Documentation	Yes	I2AM Paris and this factsheet
Previous use	None	
Institution(s) that created model	KSE Institute - Kyiv School of Economics	https://kse.ua/kse-department/kse-institute/
Institution(s) that maintain model	KSE Institute - Kyiv School of Economics	https://kse.ua/kse-department/kse-institute/
Geographical coverage	Ukraine	All regions of Ukraine are covered, excluding the temporarily occupied territory of the Autonomous Republic of Crimea, the city of Sevastopol and part of the temporarily occupied territories in the Donetsk and Luhansk regions
Geographical	National	

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resolution		
Time domain	2019 - 2050	
Time resolution	Intra-annual time steps	The distribution period is made for 12 months and 8 day-types.
Deterministic	Yes	
Dynamic	Yes	Annual change in the amount of energy produced at various generating facilities
Mathematical formulation	Linear programming	A linear programming optimisation model that is built into OSeMOSYS. The model focuses on minimizing the total cost of the power system over a period of time while meeting the energy demand and satisfying various constraints.
Rationale	Optimisation	See above
Technology richness	Bottom-up	The reference energy system schematically represented below, includes the technologies modelled with the OSeMOSYS tool. It is possible to group them in 5 main categories: imports, domestic mining, generation, transmission (under the name of transport) and final demand. Ukraine's energy generation system includes: • Thermal Power Plants (TPPs) with an installed capacity of 21.8 GW, accounting for 38% of total generation capacity. • Nuclear Power Plants (NPPs) with 14.4 GW. • Solar Power Plants (SPPs) with 6.3 GW. • Combined Heat and Power Plants (CHPs) with 6.1 GW. • Hydropower Plants (HPPs) with 4.5 GW. • Wind Turbines with 1.5 GW. • Pumped Storage Power Plants (PSPPs) with 1.5 GW.
Solver(s) used	CBC	Free and open source: https://github.com/coin-or/Cbc
Solution	5 hours.	• OSeMOSYS UI: 4.6 • RAM: 16 GB • Processor: AMD Ryzen 7 5825U with Radeon Graphics (2.00 GHz) and 64-bit operating system, x64-based processor

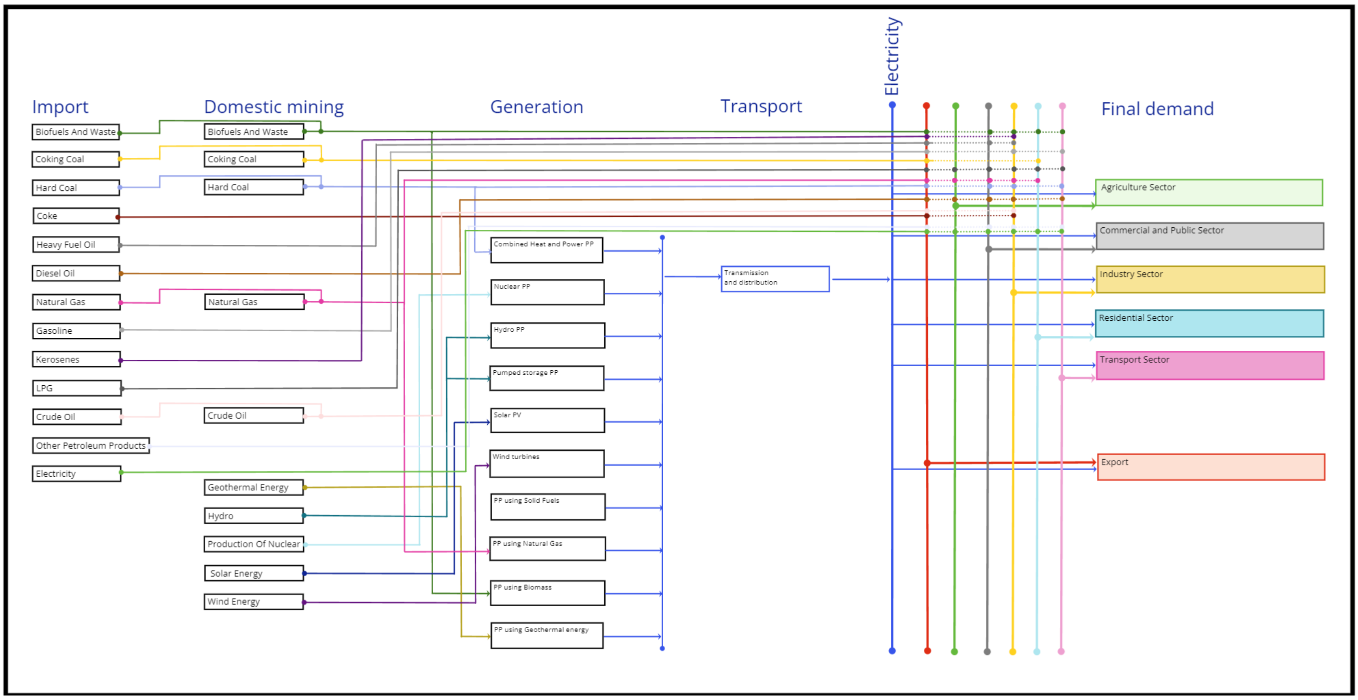

Figure 19 Reference energy system - Ukraine

6.2.1 Key data sources

Table 10 Key data sources - Ukraine

Dataset	Source	Open access
AccumulatedAnnual Demand	Energy balance of Ukraine https://ukrstat.gov.ua/operativ/operativ2021/energ/En_bal/Bal_2020_ue.xls	Y
AvailabilityFactor	State Agency on Energy Efficiency and Energy Saving of Ukraine https://map.ua-energy.org/uk/datasets/932bd83e-10c8-450e-943c-2c7775b9522f/resources/	Y
CapacityFactor	State Agency on Energy Efficiency and Energy Saving of Ukraine https://map.ua-energy.org/uk/datasets/932bd83e-10c8-450e-943c-2c7775b9522f/resources/	Y
CapitalCost	Long-term Energy Modelling and Forecasting in Ukraine. IRENA. Renewable Power Generation Costs https://ens.dk/sites/ens.dk/files/Globalcooperation/long-term_energy_modelling_and_forecasting_in_ukraine_english.pdf https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021	Y
VariableCost	Long-term Energy Modelling and Forecasting in Ukraine. Ukraine's NPP operator Energoatom Ukraine's HPP operator Ukhydroenergo	Y

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	https://ens.dk/sites/ens.dk/files/Globalcooperation/long-term_energy_modelling_and_forecasting_in_ukraine_english.pdf https://old.energoatom.com.ua/parts/pdf-file/finreport01-2021.pdf https://uhe.gov.ua/pro_kompaniyu/dokumenty	
FixedCost	World Bank Group 2020. Demystifying the Costs of Electricity Ukraine's NPP operator Energoatom Ukraine's HPP operator Ukhydroenergo https://documents1.worldbank.org/curated/en/125521593437517815/pdf/Demystifying-the-Costs-of-Electricity-Generation-Technologies.pdf https://ens.dk/sites/ens.dk/files/Globalcooperation/long-term_energy_modelling_and_forecasting_in_ukraine_english.pdf https://old.energoatom.com.ua/parts/pdf-file/finreport01-2021.pdf https://uhe.gov.ua/pro_kompaniyu/dokumenty	Y
DiscountRate	The National Bank of Ukraine https://bank.gov.ua/en/monetary/archive-rish	Y
EmissionActivityRatio	United States Environmental Protection Agency https://ghgprotocol.org/sites/default/files/Emission_Factors_from_Cross_Sector_Tools_March_2017.xlsx	Y
OperationalLife	Project of the Recovery Plan of Ukraine https://www.kmu.gov.ua/storage/app/sites/1/recoveryrada/ua/energy-security.pdf	Y
ResidualCapacity	State Agency on Energy Efficiency and Energy Saving of Ukraine https://map.ua-energy.org/uk/resources/61978c64-c4d5-43c3-b2f3-b7aef623f4be/	Y
SpecifiedAnnualDemand	Energy balance of Ukraine Ukrenergo https://map.ua-energy.org/uk/datasets/category/32	Y

6.3 Preliminary results and main insights

The preliminary results from the OSeMOSYS model for Ukraine's energy system suggest several key insights for the period 2019-2050. Combined heat and power plants (CHPs) using hard coal and thermal power plants (TPPs) using natural gas are projected not to contribute to electricity generation, while TPPs using solid fossil fuels will account for the generation of approximately 2.5 TWh annually until 2039. Nuclear power is expected to dominate electricity generation, accounting for about 77-78% of total output, followed by hydroelectric power and solar energy. However, emissions from solid fuel CHPs will pose environmental concerns until 2040.

Additionally, Ukraine's energy sector must adapt to the significant damage caused by recent conflicts. The Russian military aggression has resulted in significant direct and indirect financial losses, estimated to be more than 56 billion dollars since the beginning of 2022 (Piddubnyi et al., 2024). Because of that, the country needs updates to its energy sustainability strategy and continued use of modelling tools like OSeMOSYS for future planning.

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