IAM COMPACT

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

31/07/2025

D6.8 – Open-access models for case-study countries – Update

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

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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 presents the final results of the modelling work initially documented in *D6.7 – Open-access models for case-study countries*. The updated version of each model was developed based on the enablers and barriers found in D6.6 and on the second policy response mechanism (PRM) conducted within IAM COMPACT. As in the previous deliverable, we follow the FAIR principles (Findable, Accessible, Interoperable, and Reusable), to ensure transparency and reproducibility in both national (where they are intended for) and international contexts.

The work led also to the development of two workflows for standardising the modelling input data and results for the CLEWs models. The first workflow post-processes the modelling results into indicators selected after the second PRM and described in *D5.9 – Climate action in the sustainability spectrum - Update*. The second converts the input and output data into IAMC format, allowing a more transparent and consistent comparison among the other Integrated Assessment Models. By changing the format, it was also possible to validate the data through the IAM COMPACT validation/vetting app tool. Both workflows had the final objective of making the analysis carried out with an energy system model comparable to the integrated assessment models.

The models described in this deliverable aim to address context-specific needs with the possibility of contributing to the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (ARs). Additionally, this report can be used for uptaking and improving the models and furthering research in the related contexts, for supporting stakeholder needs and ensuring policy coherence in energy and resource planning. Supported by standardisation of outputs and indicators, it can contribute to the NDC update for the case-study countries. The two additional workflows can support the creation and standardisation of new CLEWs applications in different contexts.

3. Short summary of results (<250 words)

The joint effort of Tasks 6.4-6.5 of IAM COMPACT led to the updated versions of the tools utilised in the first modelling work described in D6.7. The five open-access models (called tools as they can be used as modelling 'frameworks' to produce new context-specific scenarios/analyses) were updated to address key policy questions in Ethiopia, Sri Lanka, Kenya, and Ukraine as well as feedback received from stakeholders during the second round of the project's policy response mechanism. The updated versions of the CLEWs models encompass a more refined representation of land. Each crop was characterised by two irrigation schemes (naturally rainfed and irrigated) and two levels of mechanisation (low and high) as defined by the Global Agro-Ecological Zones (GAEZ) documentation. In Ethiopia, the geospatial electrification tool OnSSET was soft-linked to MicroGridsPy to explore a more refined and site-specific sustainable development. Finally, Ukraine was the only case study that developed a new model using EnergyPlan (instead of OSeMOSYS, used previously), which allowed the team to simulate the operation of the Ukrainian energy system in post-war reconstruction scenarios.

4. Evidence of accomplishment

The data and metadata as well as the executables of the models described in this report are publicly available on the IAM COMPACT project's Zenodo community, under CC BY 4.0 license.

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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	
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BC3 – Asociacion BC3 Basque Centre for Climate Change – Klima Aldaketa Ikergai	ES	
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Executive Summary

This deliverable provides a final technical report for the work conducted in Ethiopia, Kenya, Sri Lanka. and Ukraine. It is an update of the preliminary analysis documented in D6.7, using key findings of D6.6 as a basis for enhancement and refinement of the modelling work.

The case studies of **Ethiopia, Kenya, and Sri Lanka** present the final results of *CLEWs* models aiming at enhancing the integrated assessment toolkit for supporting the design of coherent policies across climate, land, energy and water sectors. In IAM COMPACT, the model results also informed country-specific policy briefs, delivered as part of Task 6.2. By distinguishing between traditional and modern farming, adding refined carbon accounting for land use and land use change, and carefully calibrating each system's dynamics, it is now possible to use these models for addressing complex challenges and ensuring policy coherence in resource management.

The case study of **Ethiopia** also explores the country's energy access and universal electrification pathways, as a response to needs put forward by national stakeholders through the first PRM cycle. The final modelling cycle sees the soft-link between two open-source models: *OnSSET* and *MicroGridsPy*. In order to overcome the energy sector barriers identified in D6.6, Ethiopia needs to adopt effective policies and promote private investment. The linkage with MicroGridsPy enables site-specific analysis, thereby improving the understanding of intervention priorities across different regions.

The case study of **Ukraine** adopted a new modelling tool to assess the operation of the national energy system with increased temporal resolution. The adoption of *EnergyPLAN* instead of (or in addition to the first round's) *OSeMOSYS* allowed the team to simulate, instead of optimising, three main scenarios as described in Section 6.5, looking at 2025 as base year and 2035. Thanks to the additional incorporation of heating sector and infrastructure for generation units, it was possible to analyse post-war reconstruction scenarios.

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1 Introduction

This report is a factsheet for the final updated version of 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 technical overview of the models developed to an audience with modelling background. As in *D6.7 – Open-access models for case-study countries*[1], the extensive documentation is publicly available on IAM PARIS and the datasets described on Zenodo. These are designed to make the models Accessible, Interoperable, Reusable (and reproducible). This factsheet provides links to the documentation and guidelines on how it may be used, addressing the Findable part of the FAIR criteria.

1.1 General overview of work development, aim of the models and target audiences

Deliverable D6.8 presents the final results from the modelling work conducted by national analysts in D6.7. The modelling refinements and updates were designed to assess some of the mitigation drivers, barriers, and policy options found in D6.6. Additionally, the context-specific scenario design and the refinement of the modelling methodologies address questions emerged in the policy response mechanism. This deliverable provides a technical overview of the updated models and serves as a documentation for the national policy briefs published as part of Task 6.2 of IAM COMPACT. These models can support and inform stakeholders, policymakers, and be taken up and further developed by researchers. Furthermore, they can provide meaningful national insights to inform the IPCC's evaluations of climate change impacts and mitigation and adaptation strategies, complementing its underpinning modelling toolkit. Detailed instructions of how to run the models can be found in D6.7 Section 1.2.1 and are not repeated in this deliverable.

[1] DOI 10.5281/zenodo.13643021

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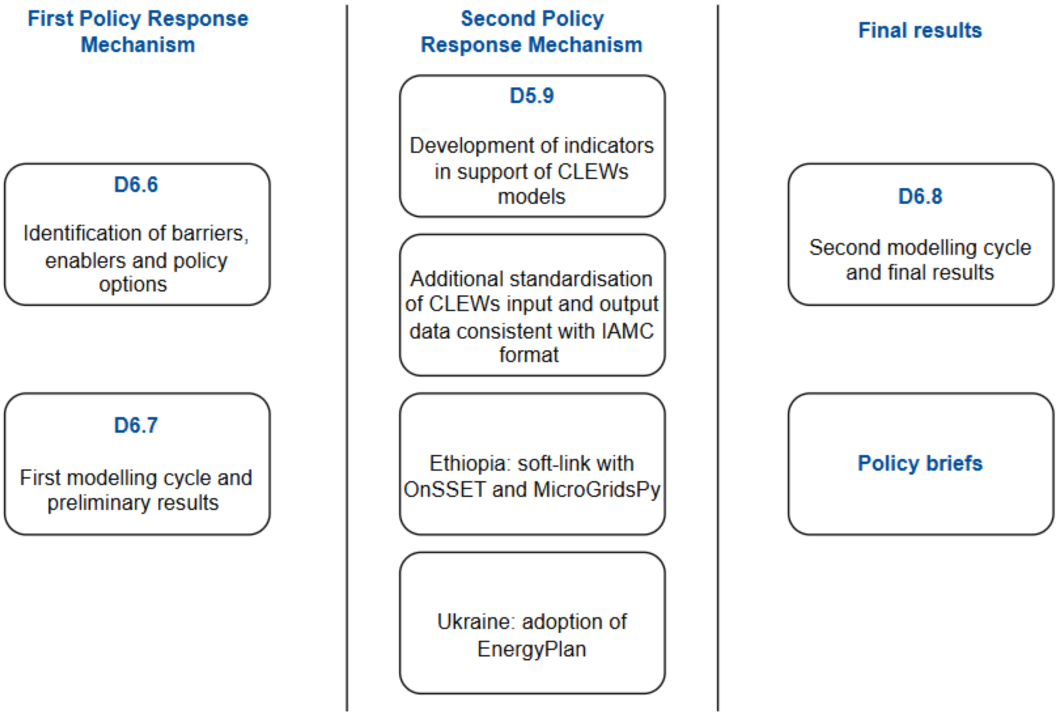

Figure 1. Schematic overview of deliverables and methods in support of D6.8

Table 1 Link to deliverables and repositories in support of D6.8

Deliverable/repositories	Reference
IAM COMPACT D6.6 - Report on drivers, barriers and policy analysis	Elsner, C., Bauer, J., Beuermann, C., Diek, A., Kiyar, D., Obergassel, W., Tholen, L., Xia-Bauer, C., Platias, C., Frilingou, N., Nikas, A., Gadaksaz, H., Keppo, I., Kebede, F., Teferi, S., Jayasuriya, L., Tsipouridis, I., Maitha, J., Abdulhalim, S., … Heussaff, C. (2024). IAM_COMPACT_D6.6_Report_on_drivers_barriers_and_policy_analysis. Zenodo. https://doi.org/10.5281/zenodo.13643214
IAM COMPACT D6.7 - Open access models for case study countries	Gardumi, F., Lo Giudice, C., Salehu, F., Abdulhalim, S., Tsipouridis, I., Jayasuriya, L., Dodonov, B., Kravtsev, A., & Piddubnyi, I. (2024). IAM_COMPACT_D6.7_Open_access_models_for_case_study_ countries. Zenodo. https://doi.org/10.5281/zenodo.13643022
Indicators4CLEWs	https://github.com/IAM-COMPACT/Indicators4CLEWs
IAM COMPACT D5.9 - Climate action in the sustainability spectrum - Update	Frilingou, N., Ferreras-Alonso, N., Hernando, G., Miguel González, L. J., Pérez, J., Miguel González, L. J., Mateo, A., García-Yustos, D., Mediavilla, M., de Blas Sanz, I., Nikas, A., Koasidis, K., Horowitz, R., Rodés-Bachs, C., Rouhette, T., Arto, I., Lo Giudice, C., Zamanipour, B., & Keppo, I. J. (2025). IAM_COMPACT_D5.9_Climate_action_in_the_sustainability_spectrum_Update. Zenodo. https://doi.org/10.5281/zenodo.16632050
CLEWS2IAMC	https://github.com/IAM-COMPACT/CLEWs2IAMC
Zenodo repository (Version v2)	Gardumi, F., Lo Giudice, C., Salehu, F., Abdulhalim, S., Tsipouridis, I., Jayasuriya, L., Dodonov, B., Kravtsev, A., & Piddubnyi, I. (2025). IAM_COMPACT_Open_access_models_for_case_study_countries_datasets [Data set]. Zenodo. https://doi.org/10.5281/zenodo.16570539

2 Model factsheet: Ethiopia - CLEWs

2.1 Stakeholder engagement

The Ethiopian CLEWs model version 2.0 stems from the second policy response mechanism (PRM) designed within IAM COMPACT. The first step in the model development consisted of organizing a workshop for "*land requirements and potential land use competition"*, held in April 2025, where project partners met with stakeholders from the European Commission's Directorate-General for Agriculture and Rural Development, the European Environment Agency, Climate Action Network (CAN) Europe, and WWF European Policy Office. Despite being focused on the European context, one of the identified stakeholder needs (the fourth question) was intended to understand what type of indicators are of interest for measuring a sustainable energy and land use transition (See D5.9 section 4.1 for more specifications). The feedback received was then extended and used for understanding the main areas of interest. Subsequently, the priorities of intervention were co-designed thanks to the complementary feedback provided by World Resources Institute's (WRI)- Water Program in Ethiopia and Addis Ababa University. This process has allowed us to go from a general overview of challenges and practices needed for ensuring sustainable energy and land-use transition, to more context-specific needs (in Ethiopia), ensuring the policy relevance of the work conducted while still fitting the scope of analysis initially mentioned in the DoA.

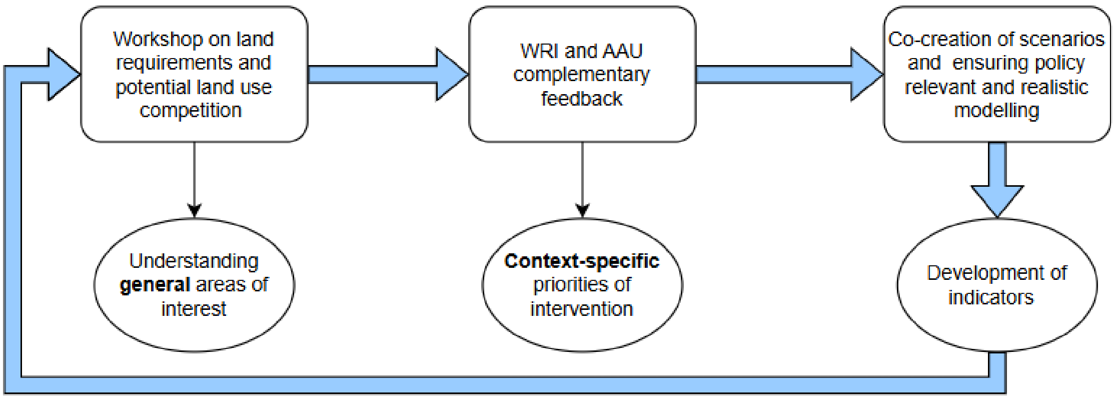

Figure 2. The PRM for the case study of Ethiopia - focus on climate-land-energy-water nexus.

The stakeholder engagement highlighted questions of policy coherence in the current development plans presented in the long-term low emission strategy for Ethiopia (Ministry of Planning and Development, 2022). Its adaptation strategy includes an increase of irrigated land for ensuring food security while increasing afforestation and biodiversity. Because of that, we assessed the resource stress, the land use change and potential competing land demand for increasing forest cover and biodiversity if such a plan is put in place. Moreover, the workshop highlighted the need for transparency for both assumptions and modelling results. This was addressed through the development of a workflow for standardising the models' inputs and outputs and quantifying the modelling results. With the joint effort of developing *"Truly sustainable decarbonisation pathways, including biodiversity, materials and biophysical limits"* presented in deliverable D5.9[2], we then used the same workflow for comparing scenarios, ensuring transparency and supporting the management and interpretation of modelling results.

2.2 Brief history and model development (v.2.0)

This model is an enhanced version of the former CLEWs model described in D6.7. It enhances two scenarios, the

[2] DOI 10.5281/zenodo.16632049

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Business as usual and the combination of NDCs and the long-term low emissions development strategies (namely LTLEDS) by refining the land system. In particular, the updates consist of distinguishing between two levels of mechanization (high and low), adding costs to the crops, and improving the emission accounting for the land use sector. The levels of mechanization refer to the generic levels defined by the Global Agro-Ecological Zone database (GAEZ) (*Global agro-ecological zone V4 – Model documentation*, 2021). We referred to "High input level" as an advanced management with improved yields, and "Low input level" as more traditional farming.

The development of the second version of the model has been supported by the Energy Modelling Platform Global (EMP-G) held in August 2024 in Trieste at the International Centre of Theoretical Physics.

Finally, the study is supported by the development of selected indicators designed for D5.9. For a more detailed and comprehensive explanation of the indicators developed, see the online Indicators4CLEWs GitHub repository[3].

2.2.1 Aim of the model and target audiences

The Ethiopia CLEWs updated model is designed to provide a comprehensive understanding of the interconnections between the climate, land, energy and water systems. The updated version refines the land system identifying conflicts and synergies among resources, biodiversity, and food security. Target audiences for the Ethiopia CLEWs model include researchers analysing resource management, non-governmental organizations, and policy-makers responsible to ensure policy-coherence in long-term planning and NDC future updates.

2.3 Model scope and structure - updated

Table 2. Model scope and structure - Ethiopia

	Scope	Detail version 1.0	Detail version 2.0
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.	Refinement of the land sector adding two levels of mechanization: high and low. This has an impact on each crops' associated yields, costs, emissions and energy requirements.
Type of analysis	Cost-optimization; 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,	-

[3] https://github.com/IAM-COMPACT/Indicators4CLEWs

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		national, and multi-regional levels. CLEWs is a methodology that enables the representation of the Climate, Land, Energy and Water systems nexus.	
Open-source code	Yes	https://github.com/OSeMOSYS/CLEWs	https://github.com/IAM-COMPACT/Indicators4CLEWs
Open access data	Yes	License and link to repository	
Documentation	Yes	Link to OSeMOSYS documentation: https://osemosys.readthedocs.io/en/latest/manual/Introduction.html Link to key CLEWs information: https://iopscience.iop.org/article/10.1088/1748-9326/abd34f/meta l	
Previous use	Yes	https://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1820331&dswid=5103	
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 optimization, where the objective function is the minimization 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	-

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		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.	The total amount of modelled technologies is 71 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 33.
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	• OSeMOSYS UI: 5.3 • RAM: 32 GB • Processor: 13th Gen Intel(R) Core(TM) i7-1370P 1.90 GHz

2.3.1 Key data sources – updated

Table 3. Key data sources - Ethiopia.

Dataset	Source	Open access
Emission accounting	https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_04_Ch4_Forest_Land.pd	Y
Forest emission absorption	https://www.bcg.com/publications/2020/the-staggering-value-of-forests-and-how-to-save-them	Y
Irrigation	https://api.data.apps.fao.org/api/v2/bigquery?sql_url=https://data.apps.fao.org/catalog/dataset/945666e6-7803-4621-b8ef-cfd885a84596/resource/4a000a1b-24f0-4328-aab6-b9b525892090/download/query_en.sql	Y
Food imports	https://wits.worldbank.org/trade/comtrade/en/country/ETH/year/2023/tradeflow/Imports/partner/ALL/product/110100?utm_source	Y
Updated NDCs	https://unfccc.int/sites/default/files/NDC/2022-06/Ethiopia%27s%20updated%20NDC%20JULY%202021%20Submission_.pdf	Y

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2.4 Reference system – updated

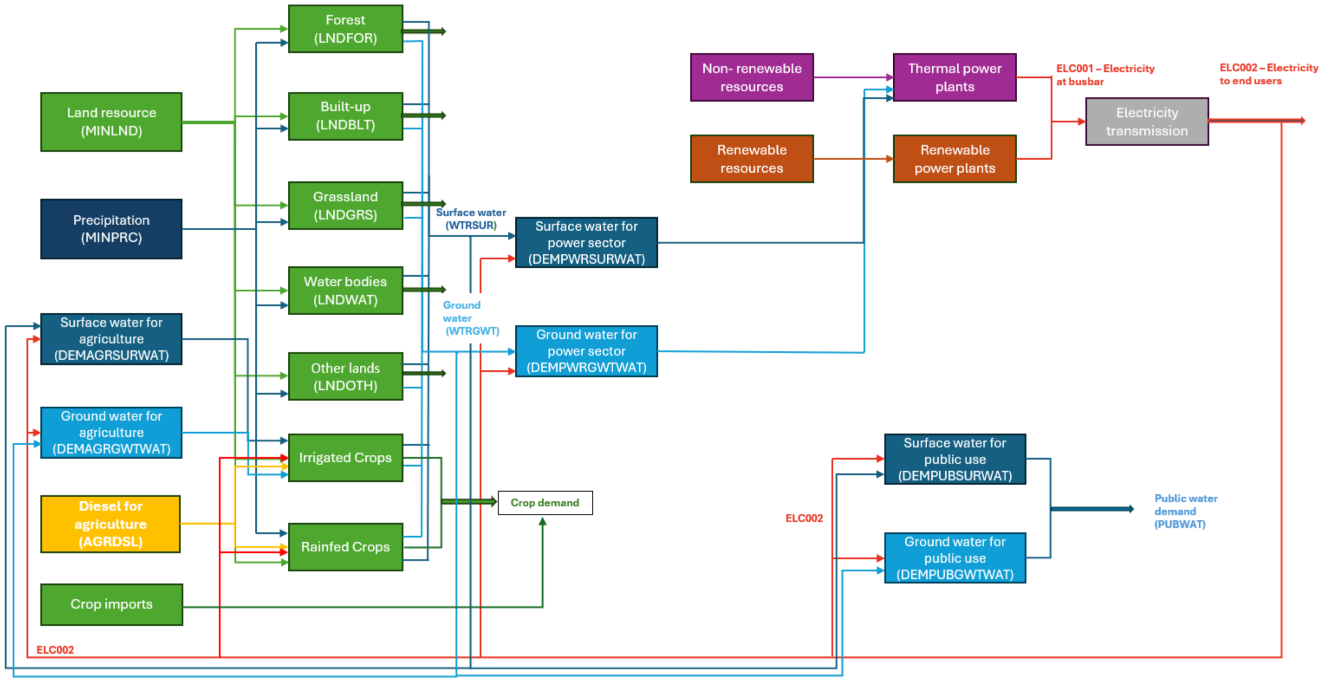

Figure 3. Ethiopia simplified CLEW reference system – updated

2.5 Scenarios

Table 4 Scenarios - Ethiopia CLEWs

Name	Description
BAU – Business As Usual	It serves as a baseline scenario and has no constraints on resource use or targets for achieving stated policies.
NDC-LTLEDS	It is the national determined and long-term-low-emission-development strategy scenario. It is set to achieve the afforestation, irrigation and renewable share targets stated by the Ministry of Planning and Development.

2.6 Final results and main insights

The development of the indicators in support of the CLEWs models allowed us to conduct broader cross-sectoral analyses thanks to the biodiversity habitat index (BHI) and average annual water stress. These indicators proved to be crucial for understanding the consequences of development plans on dimensions that are not strictly confined to direct CLEWs outputs. As this deliverable is intended as a technical report, this section will mostly focus on the final results and main insights provided by the development of the CLEWs indicators. For a more detailed description of the overall results and conclusions please refer to D5.9 Section 4.5.

The first result shows the variation in the annual water stress. The indicator follows the same methodology adopted by WRI (Kuzma et al., 2023) and adapted to a CLEWs model. Already starting from a medium stress in

2020, Ethiopia will face a rapid increase in both scenarios. The main reason lies in the use of irrigation for tackling both food security and competing land-uses. Apart from being the most cost-effective alternative in a BAU scenario, irrigation is supported also by Ethiopian updated NDCs and long-term-low-emission strategy (Ministry of Planning and Development, 2022). Because of that, in both scenarios we can see a rapid increase in the water stress reaching the highest score from 2033 on.

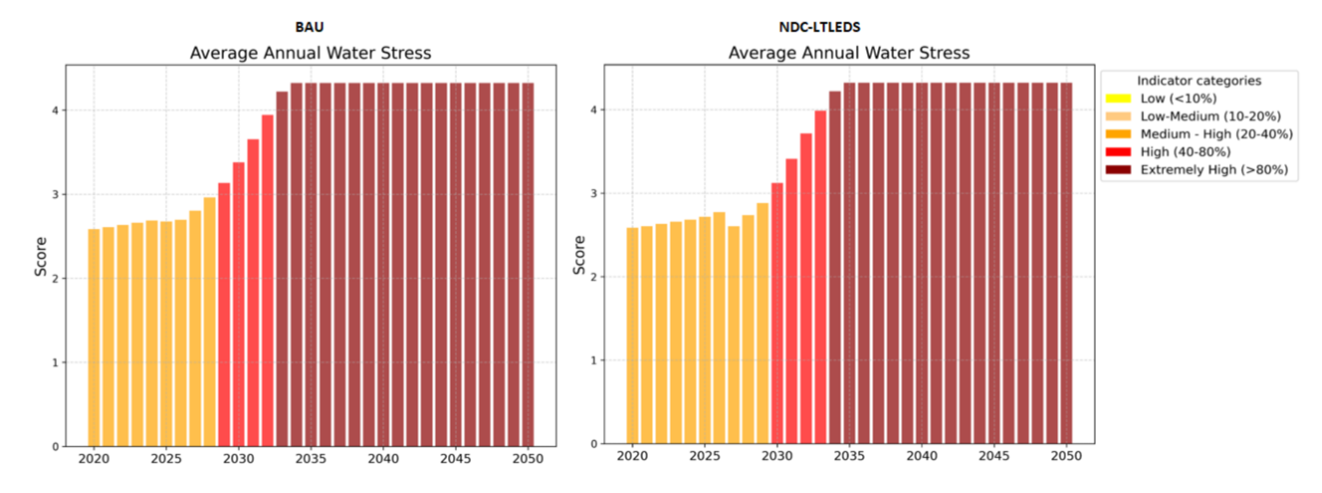

Figure 4. Average annual water stress - CLEWs Ethiopia.

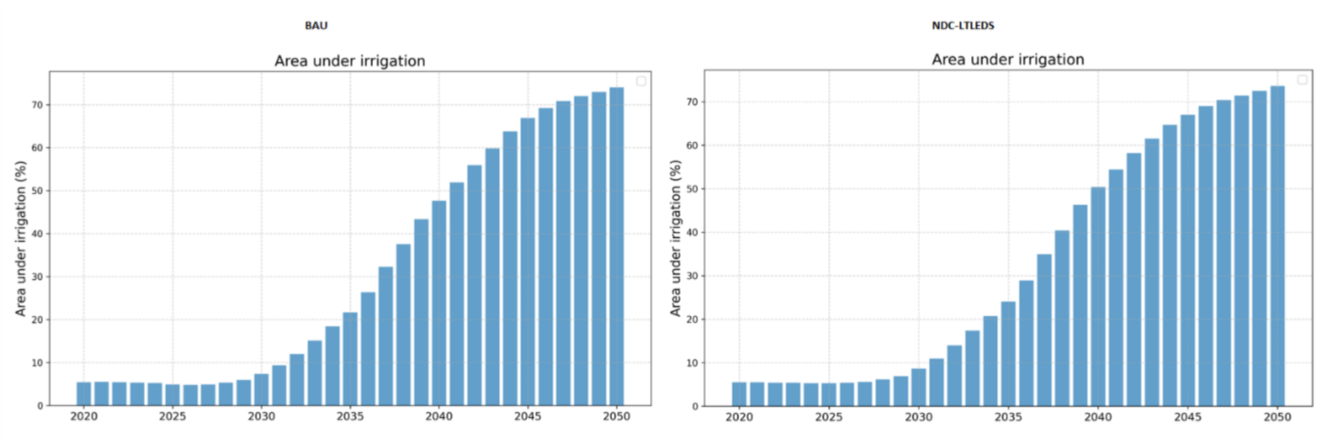

Figure 5. Share of irrigated land with respect to all harvested area - CLEWs Ethiopia.

Using the BHI we were able to assess the effects of habitat loss, degradation and fragmentation on biodiversity. In the literature, it is possible to find more accurate estimations of this index exploiting the species-area relationship for each piece of land. Since CLEWs models are not spatially explicit, we used a simplified relationship as described in (Ferrier et al., 2004) which assesses the ratio of the forest area retained over the original area using 0.25 as the exponent z of the species-area relationship:

$$BHI = \frac{Forest\ area\ retained}{Original\ forest\ area}^{0.25}$$

Due to the afforestation targets stated in the NDC-LTLEDS policies, the second scenario shows indeed an increase in the BHI index. However, this is possible with an increase of crop imports assessed with the Import Dependency Ratio (IDR) indicator:

$$Crop\ IDR\ = \frac{Total\ annual\ imports}{Total\ annual\ demand}$$

This poses significant questions to the food security and dependency of Ethiopia on other countries for its food supplies.

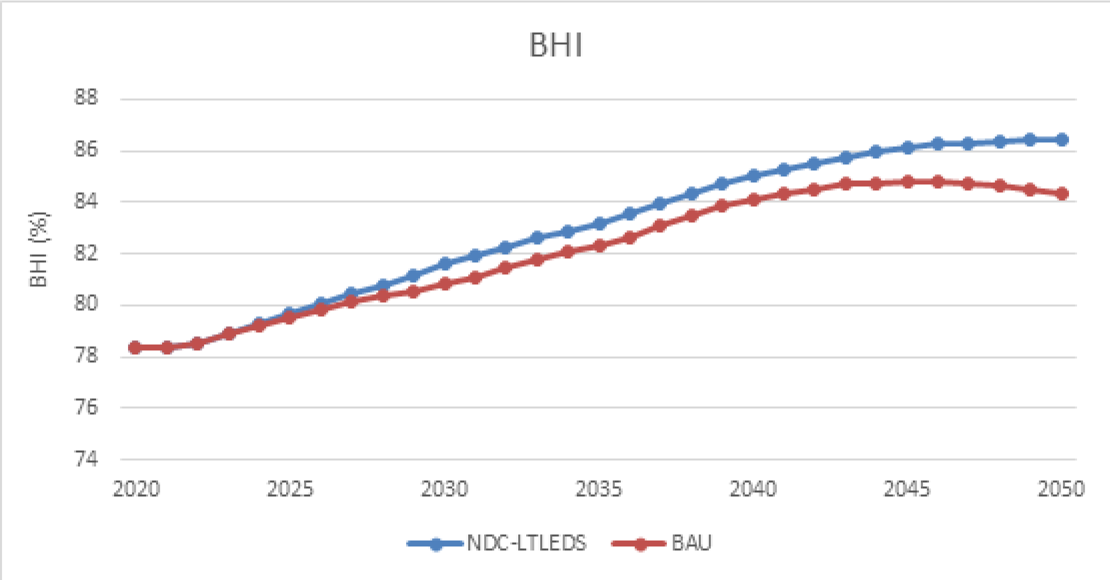

Figure 6. Biodiversity Habitat Index - CLEWs Ethiopia

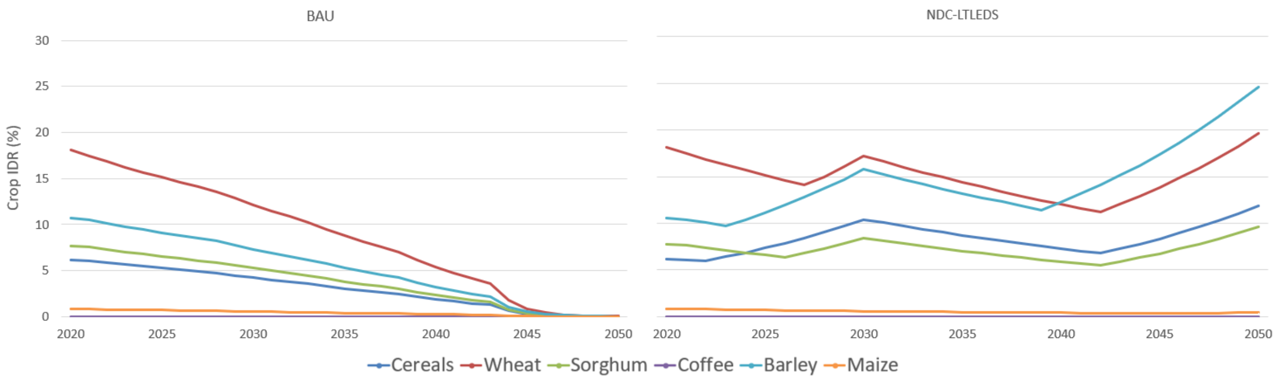

Figure 7. Crop Import Dependency Ratio (IDR) – CLEWs Ethiopia.

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3 Model factsheet: Ethiopia – OnSSET

3.1 Stakeholder engagement

In April 2023 one of the key stakeholder engagements was conducted within the framework of the scoping analysis of policy-relevant research questions. Senior staffs from the Ministry of Water and Energy (MoWE) were involved to inform national energy planning as the policy steering group (*see deliverable D2.2 - Scoping policy relevant research questions*). This dialogue highlighted critical areas which the modelling assessments in IAM COMPACT may provide insights on, particularly electrification strategies, energy security, optimising the use of micro- and mini-grids and providing support for informed investments in renewable energy. The discussions underscored the vulnerability of Ethiopia's hydropower-dominated generation mix, where about 86% of the 2022 installed capacity is hydropower, to climate risks such as drought and deteriorations in generation capacity. In response, participants emphasized the role of decentralized generation from renewables to diversify the generation portfolio, enhance rural energy access, and improve system reliability and energy security.

Additionally, a capacity development workshop was held in January 2024, for diverse stakeholders on energy systems modelling basics and the use of the Open-Source Spatial Electrification Tool (OnSSET) and MicroGridsPy tools, to train participants in the modelling fundamentals and support evidence-based policymaking/planning (*see deliverable D2.4 Proceedings of stakeholder interactions*). Occasional bilateral exchanges have also been taking place in different instances, taking advantage of meeting different stakeholders on various other activities.

With these modelling needs in mind, the stakeholder engagement led to the choice of focusing the modelling analysis on the study of electrification pathways. This, in turn, drove the choice of the modelling tools towards the most appropriate for the tasks: OnSSET – the geospatial and techno-economic least cost electrification modelling tool, complemented by MicroGridsPy – for more close-up hybrid and decentralized micro-grid modelling and detailed scenario analysis, especially for rural electrification. The soft-link greatly reduced diesel dependency, with about 76% of primary energy coming from PV-battery, while diesel serving mainly as backup during low solar or battery power. The results also show an effective micro-grid sizing and demonstrate a reliable dispatch with minimal load losses or curtailment

OnSSET supports informed policy making on grid extension versus mini-grid or standalone deployment, reinforcing the importance of decentralized electrification solutions, whereas MicroGridsPy further supports the design and optimisation of single-community mini-grids (mainly from solar PV optionally integrating diesel generations as highlighted from the OnSSET results).

3.2 Brief history and model development (v.2.0)

The OnSSET model, previously developed for assessing the least-cost solutions for Ethiopia, is used to guide national electrification strategies. The model aims to identify the least-cost mixes of grid, mini-grid, and off-grid solutions to achieve universal electrification. OnSSET uses geospatial analysis to compare different electrification options, considering population density, infrastructure, and energy demand.

Building on this foundation, the open-source tool MicroGridsPy, is employed for detailed optimisation of the energy operation of selected village-level mini-grid components. This includes sizing, load management, and energy dispatch. MicroGridsPy complements the macro-scale OnSSET output by translating national-scale electrification solutions into site-specific applications. This ensures both scalability and real-world viability in the universal electrification strategies. The model designs and optimises hybrid mini-grids, incorporating renewable energy sources like solar PV and backup diesel generators.

3.2.1 Aim of the model and target audiences

The recent update to the OnSSET spatial electrification model in Ethiopia aims to supporti national efforts to

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achieve least-cost universal electrification, by identifying optimal electrification pathways—whether via main grid extension, mini-grids, or standalone systems. This update emphasizes the critical role of decentralized options, especially mini-grids and standalone solar systems, in reaching remote and underserved communities.

To deepen the critical role of the least-cost decentralized electrification options (main grid, mini-grids, or standalone systems) in Ethiopia, the MicroGridsPy model was developed and applied for a more granular analysis to a specific candidate site identified by OnSSET as suitable for mini-grid deployment. The aim is to design a mini-grid system based on specific energy demand profiles and solar resource by optimising component sizing (PV, batteries, diesel generators) and determining the most cost-effective energy dispatch strategy.

As a target audience for this integrated modelling, this model helps national energy planning and policy-making experts, the utility operator as a key player in rural electrification, energy sector development organizations, and technical stakeholders involved in Ethiopia's electrification pathway. This modelling supports evidence-based planning and cost-effective energy access solutions that align with Ethiopia's electrification strategies.

3.3 Model scope and structure - updated

Table 5: Model scope and structure - Ethiopia

Properties	Scope	Detail version 1.0	Enhanced version 2.0 integrating with MicroGridsPy[4]
Sectoral coverage	Spatially explicit electrification	Covering grid, mini-grid and standalone electricity access technologies.	Village-level micro-grid system
Type of analysis	Least cost optimisation.	Minimisation of the levelised cost of energy (LCoE)	Two-stage optimization mixed integer linear programming approach
Modelling tool used	OnSSET	Open-Source Spatial Electrification Tool (http://www.onsset.org)	MicroGridsPy (GitHub Link, under active development)
Open-source code	-	Yes	Yes
Open access data	Yes	License and link to repository	-
Documentation	Yes	OnSSET	Microgrids.py
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	

[4] The details of version 2.0 refer only to MicrogridsPy.

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Properties	Scope	Detail version 1.0	Enhanced version 2.0 integrating with MicroGridsPy[4]
		1, link 2.	
Institution(s) that created model	Addis Ababa Institute of Technology and Politecnico di Milano		
Institution(s) that maintain model	Addis Ababa Institute of Technology		
Geographical coverage	National and local	Ethiopia	Targeted rural sites
Geographical resolution	Geospatially explicit		
Time domain	Year(s) modelled	2024 - 2035	2024 - 2035
Time resolution	Modelling time steps	Yearly: 2024 – 2028 - 2035	hourly
Deterministic	Yes	Yes	Yes
Dynamic	No	Static – i.e. giving a snapshot at the target year	Yes
Mathematical formulation	Linear program	LCoE minimisation for every settlement (grid cell) based on local spatial electricity infrastructure, demand, resource potential and other peculiar characteristics.	MILP
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	Gurobi

Properties	Scope	Detail version 1.0	Enhanced version 2.0 integrating with MicroGridsPy[4]
Solution		Processor: Intel(R) Core(TM) i7-10610U CPU @ 1.80GHz RAM: 16GB 31.7 minutes	Processor: Intel(R) Core(TM) i7-10610U CPU @ 1.80GHz RAM: 16GB 8.2 minutes

3.3.1 Key data sources – updated

No updates from previous Deliverable D6.7.

3.4 Reference system – updated

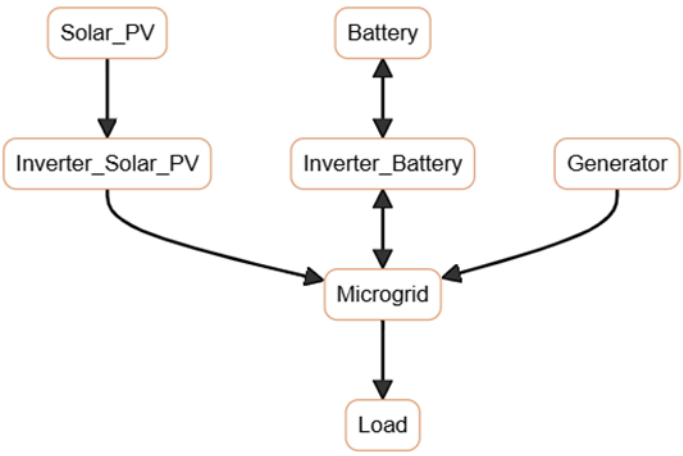

Figure 8. Mini-grid system energy dispatch flow diagram (MicroGridsPy).

3.5 Final results and main insights

The analysis targeted candidate rural sites that are most likely to be suitable for mini-grid electrification according to OnSSET initial results. The candidate sites were selected for further hourly full-year (8760 hours) system optimization and multi-year simulation of the micro-grid using the MicroGridsPy tool. For the daily demand profile of the site (Figure 9), the optimal system configuration comprises of PV, battery, and genset with corresponding sizes of 19 kW, 617 kWh, and 3 kW, respectively. The single objective optimization result, which minimizes the system net present cost (NPC), is depicted in the following one-week hourly energy dispatch (Figure 10). This initial simulation highlights the energy flow dynamics of the PV-diesel generation, storage, and demand, with a corresponding cost of energy (CoE) of about 0.85 USD/kWh, 70% yearly solar penetration, and 73% generator annual load factor. In this typical week, solar PV (yellow) predominantly meets the energy demand, peaking with daily solar availability. The battery storage plays a key role in balancing supply and demand, charging during PV surplus production, and discharging when solar is unavailable. Starting with full charge for the simulation period, the battery's state of charge (SoC, purple dashed line) follows a diurnal cycle, complementing PV in later afternoon periods. The minimal use of diesel generator indicates that the system primarily relies on solar and storage. Notably, both energy curtailment and loss of load are nearly zero, demonstrating optimality of the dispatch strategy. Further model runs will be conducted to refine and expand the analysis for further scientific publication.

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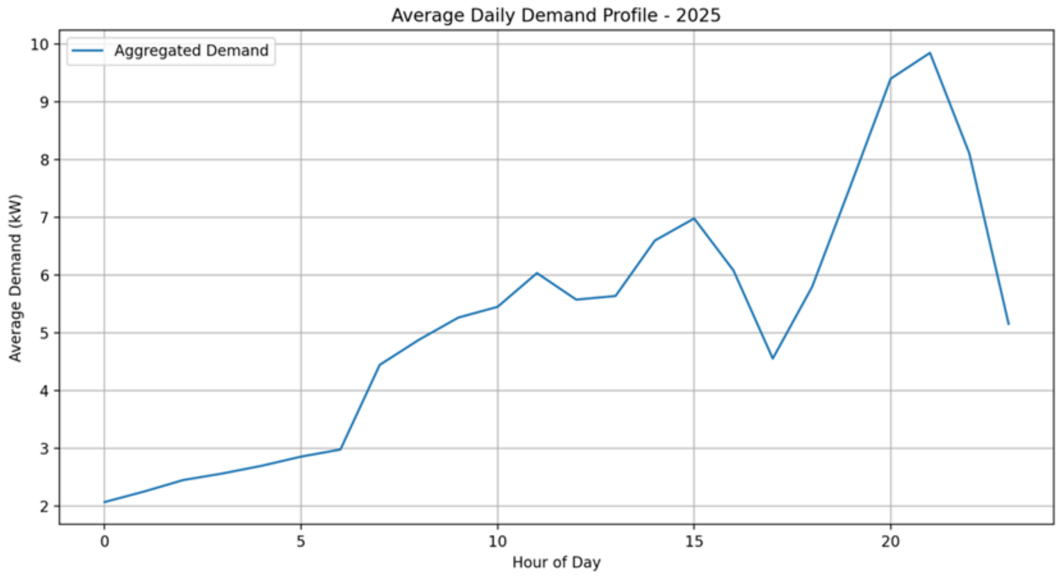

Figure 9. Daily demand profile.

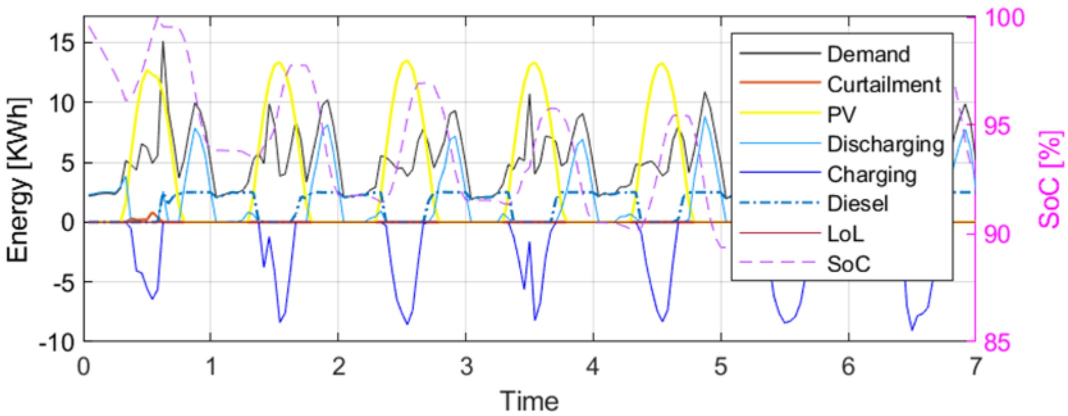

Figure 10. Energy balance, a dispatch for a typical one week period, (time in days).

4 Model factsheet: Sri Lanka - CLEWs

4.1 Stakeholder engagement

The development of the Sri Lankan CLEWs model has involved discussions with key policymakers and project partners to ensure its relevance and applicability. A Sri Lanka Policy Steering Group meeting was held on June 8th, 2023, via Zoom, where participants included Mr. J.M. Athula (Director General, Sri Lanka Sustainable Energy Authority), Mr. Shantha Jayasinghe (Deputy Director, Public Utilities Commission of Sri Lanka), Mr. Gamini Sarachchandra (Director of Renewable Energy and Energy Efficiency, Public Utilities Commission of Sri Lanka), Dr. Tilak Siyambalapitiya (Consultant/Managing Director, Resource Management Associates (Pvt) Ltd.), and Mrs. Sureka Perera (Programme Quality and Design Analyst, Climate and Environment Team, UNDP, Sri Lanka). Project partners, including Lahiru Jayasuriya (RUSL), Francesco Gardumi (KTH), Conall Heusaff (Brugel), Georg Zachman (Brugel), and Eftychia Ntostoglou (KTH), were also present.

During these discussions, policymakers highlighted key challenges in Sri Lankan energy and climate policy, such as the lack of coordination among institutions (e.g., Mahaweli Authority, Sri Lanka Wildlife Department, Forest Department, Land Commission), the need for consistent policies, attractive investment opportunities, and appropriate tariff systems for renewable energy. The importance of evidence-based decisions, policy analysis, and balancing affordability for consumers with cost-reflective tariffs was also emphasized. These discussions directly informed the model's focus on addressing interlinkages between sectors and providing an evidence base for decision-making. The feedback on the need for improved modelling capabilities and thorough analysis, considering various sectors and stakeholders, has guided the model's scope and the types of scenarios explored.

4.2 Brief history and model development (v.2.0)

The CLEWs model for Sri Lanka is an advancement of the work initiated during the CLEWs Training Programme organized by UNDP and UNDESA South Asia Region in 2020. The earlier version utilized a more abstract representation of energy, land, and water systems with preliminary data validation. For the IAM COMPACT project, the CLEWs model has been redeveloped from scratch, incorporating additional details, particularly within the power generation sector. This includes modelling individual major power stations and validating data against up-to-date government publications. Where feasible, parameter definitions now include detailed historical data analysis, for example capacity factors for power generation plants in CLEWs Sri Lanka are now derived from 15-min power dispatch data published by the Public Utilities Commission of Sri Lanka. Latest CLEWs Sri Lanka model was developed using the Modelling User Interface for OSeMOSYS (MUIO) v5.1. Data preprocessing is performed using Microsoft Excel, with future automation planned for repetitive tasks to improve efficiency and reduce manual errors.

4.2.1 Aim of the model and target audiences

The primary aim of the Sri Lankan CLEWs model is to gain detailed insight into the complex interactions among the climate, land-use, energy, and water systems. Such a model will highlight existing or potential conflicts and opportunities for achieving sustainable development by assessing interdependencies across different sectors. It is intended to be a crucial tool for projecting the impacts of climate change, identifying vulnerable areas for policymakers and stakeholders, and informing the development of policies and strategies for sustainable development, economic growth, and climate resilience. The ultimate vision is to enable evidence-based decision-making, which has been a lacking aspect in the Sri Lankan context. This will empower decision-makers to work towards a sustainable future for Sri Lanka through informed choices and the exploration of future scenarios using the CLEWs model.

The target audience for the CLEWs model includes various stakeholders. Primarily, government policymakers across different ministries and institutions such as the Ministry of Power, Sri Lanka Sustainable Energy Authority, Ceylon Electricity Board and Ministry of Environment are expected to utilize this tool to inform their decision-

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making and even supporting the next round of NDCs. Researchers and academics from universities and research institutes such as the National Science Foundation (NFS) and National Institute for Fundamental Studies (NIFS) will find the model a valuable resource for their studies on climate change, energy, water, land use, and sustainability in Sri Lanka. Additionally, international organizations, the private sector, and civil society organizations can use the model in their efforts to support and contribute to sustainable development in Sri Lanka.

The CLEWs model for Sri Lanka has been developed to attempt to answer critical multi-sectoral policy objectives and scenarios, which directly stem from the challenges and priorities identified during stakeholder discussions. Some of these questions include:

- How can increasing electricity demand be met by indigenous resources (i.e., renewable energy)?
- How can increased renewable energy share help the country to diversify its energy mix, and reduce emission footprint, and cost of energy?
- What is the overall impact of renewable energy infrastructure development on agriculture in terms of land use constraints and development needs?

Ultimately, the model examines how renewable energy and natural gas penetration can increase the power sector's fuel diversity and its implications on costs (investment + operation), land use, and the environment (GHG emissions).

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4.3 Model scope and structure - updated

Table 6 Model scope and structure - Sri Lanka

	Scope	Detail version 1.0	Detail version 2.0
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.	**Energy:** Minor refinements made. Energy use across, Industry, Power, Residential, Commercial, Transport and Agriculture sectors are included. All major fuels included: Biomass, Kerosene, Diesel, Coal, Heavy Fuel Oil, LPG and Natural Gas. JetA1, and Naptha use in Sri Lanka are not currently modelled. All major power stations are modelled to signify their impact in the existing system, as well as their planned retirement over the short-term upto 2030, given satutory 70% renewable energy target. Electricity demand for transport and agriculture is parameterised alongside electricity demand for water pumping for irrigation and public water supply. Transmission and Distribution losses are included. Model validated against historic data. **Land-use**: No changes from V1.0. Agriculture data (crop, area harvested) validated against historic data. **Water**: No changes from V1.0. Public water demand and cooling water demand for thermal power stations modelled. **Climate:** No explicit modelling performed.

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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	MUIO v5.1 used.
Open-source code	Yes	https://github.com/OSeMOSYS/CLEWs	-
Open access data	Yes	License and link to repository	-
Documentation	Yes	https://zenodo.org/records/16570539	-
Previous use	Building on existing model	(Jayasuriya et al., 2023)	Build on v1.0
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 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.	Expanded to a total of 67 commodities and 156 technologies.
Solver used	CBC	Free and open source: https://github.com/coin-or/Cbc	-
Solution		• OSeMOSYS UI: 4.9 • RAM: 16 GB • Processor: Intel(R) CoreÜM) i7-8550U CPU @ 1.80GHZ (8 cpus), 2.0 GHz	• MUIO v5.1 • RAM: 16 GB

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		• 20.45 seconds for BAU scenario	• Processor: Intel(R) CoreÜM) i7-8550U CPU @ 1.80GHZ (8 cpus), 2.0 GHz • 48.6 seconds for BAU scenario

4.3.1 Key data sources – updated

Table 7. 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.)	CEB Long-Term Generation Expansion Plan 2023-2042 : https://ceb.lk/front_img/img_reports/1677040471CEB_LTGEP_2023-2042_DL-LINK-.pdf JICA Project on Electricity Sector Master Plan Study in Democratic Socialist Republic of Sri Lanka: Final Report 2018 : https://openjicareport.jica.go.jp/pdf/12303673_01.pdf NREL Electricity Generation Baseline Report 2017 https://www.nrel.gov/docs/fy17osti/67645.pdf Sri Lanka Sustainable Energy Authority (SLSEA). Sri Lanka Energy Balance 2022. https://energy.gov.lk/images/energy-balance/energy-balance-2022.pdf	Y

	Ministry of Environment – Sri Lanka. Carbon Net Zero 2050 Roadmap and Strategic Plan, 2023. https://env.gov.lk/web/images/pdf/divisions/climate_change_division/publications/2023/Synthesis_Report_for_Carbon_Net_Zero_2050_Roadmap_and_Strategic_Plan.pdf Public Utilities Commission of Sri Lanka (PUCSL). Study on Electricity Demand Response to Price Changes, 2025. https://www.pucsl.gov.lk/wp-content/uploads/2025/04/Final-Report-Study-on-electricity-demand-response-to-price-changes.pdf International Renewable Energy Agency (IRENA). Renewable Power Generation Costs and other related publications (various years). https://www.irena.org/data/renewable-power-generation-costs-and-other-related-publications International Energy Agency (IEA). World Energy Outlook (various editions) and Technology Roadmaps. https://www.iea.org/reports/world-energy-outlook-2023 National Renewable Energy Laboratory (NREL). Annual Technology Baseline (ATB). https://atb.nrel.gov/ United Nations Development Programme (UNDP) & Asian Development Bank (ADB). 100% Renewable Electricity Roadmap for Sri Lanka, 2017. https://asiacleanenergyforum.adb.org/wp-content/uploads/2017/06/8_100-	

	Renewable-Electricity-in-Sri-Lanka.pdf	
Generation Information (15-minute dispatch data) to analyse capacity factors and demand profiles	PUCSL – Generation Information (Achieved) https://www.pucsl.gov.lk/generation-information-archived/	Y
Annual energy demand data (historic) and information on trends	Sri Lanka Sustainable Energy Authority (SLSEA). Sri Lanka Energy Balance 2022 https://energy.gov.lk/images/energy-balance/energy-balance-2022.pdf	Y
Annual electricity demand, electricity generators operational in each year (historic)	CEB Long-Term Generation Expansion Plan 2023-2042 : https://ceb.lk/front_img/img_reports/1677040471CEB_LTGEP_2023-2042_DL-LINK-.pdf CEB Sales and Generation Data Book : https://www.ceb.lk/publication_media/other-publications/131/en CEB Statistical Reports: https://www.ceb.lk/publication_media/other-publications/131/en Lanka Electricity Company Statistical Reports: https://www.leco.lk/pages_e.php?id=101	Y
Power Generation availability factors	Ministry of Power: Annual Performance Reports: http://powermin.gov.lk/english/wp-content/uploads/2022/11/03-English-2021.pdf NREL Electricity Generation Baseline Report 2017 https://www.nrel.gov/docs/fy17osti/67645.pdf PUCSL Generation Performance Reports: https://www.pucsl.gov.lk/wp-	Y

	content/uploads/2019/02/GenPerformance-2016_Draft.pdf	
Fuel Costs	International Energy Agency (IEA). World Energy Outlook (WEO) : https://www.iea.org/reports/world-energy-outlook-2023 Energy Information Administration (EIA). Annual Energy Outlook (AEO). https://www.eia.gov/outlooks/aeo/ World Bank. Commodity Markets Outlook https://www.worldbank.org/en/research/commodity-markets Ceylon Petroleum Coorporation Procurement Plans: https://ceypetco.gov.lk/wp-content/uploads/PROCUREMENT-PLAN-2021-2023-1.pdf CEB Long-Term Generation Expansion Plan 2023-2042 : https://ceb.lk/front_img/img_reports/1677040471CEB_LTGEP_2023-2042_DL-LINK-.pdf	Y
Socio economic data	Central Bank of Sri Lanka, Economic and Social Statistics: https://www.cbsl.gov.lk/en/publications/other-publications/statistical-publications/economic-and-social-statistics-of-sri-lanka/ess-2023 UNFPA Sri Lanka, 2011, Medium-Term Population Projection for Sri Lanka: 2012 to 2037 https://srilanka.unfpa.org/sites/default/files/pub-pdf/Population%20Projection%20Publications%20%20for%20WEB%20%281%29_0.pdf)	Y
Land use for electricity generation	STRATA – The footprint of Energy: Land-use of US Electricity Production: https://docs.wind-	Y

	watch.org/US-footprints-Strata-2017.pdf	
Area harvested, yield, crop demand (historic)	Food and Agriculture Organization of the United Nations. (2024). FAOSTAT: Land-Use https://www.fao.org/faostat/en/#data/RL Central Bank of Sri Lanka, Economic and Social Statistics: https://www.cbsl.gov.lk/en/publications/other-publications/statistical-publications/economic-and-social-statistics-of-sri-lanka/ess-2023 Department of Census and Statistics, Agriculture: Paddy Statistics 2024 https://www.statistics.gov.lk/Agriculture/StaticalInformation/PaddyStatistics Food and Agriculture Organization of the United Nations. Global Agro-Ecological Zones (GAEZ) v.4 data https://gaez.fao.org/	Y
Land cover, crop specific yields	Food and Agriculture Organization of the United Nations. Global Agro-Ecological Zones (GAEZ) v.4 data https://gaez.fao.org/ Food and Agriculture Organization of the United Nations. (2024). FAOSTAT: Land-Cover https://www.fao.org/faostat/en/#data/LC	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

Public Water Demand	National Water Supply and Drainage Board: Annual Reports: https://www.waterboard.lk/annual-report/	Y

4.4 Reference system – updated

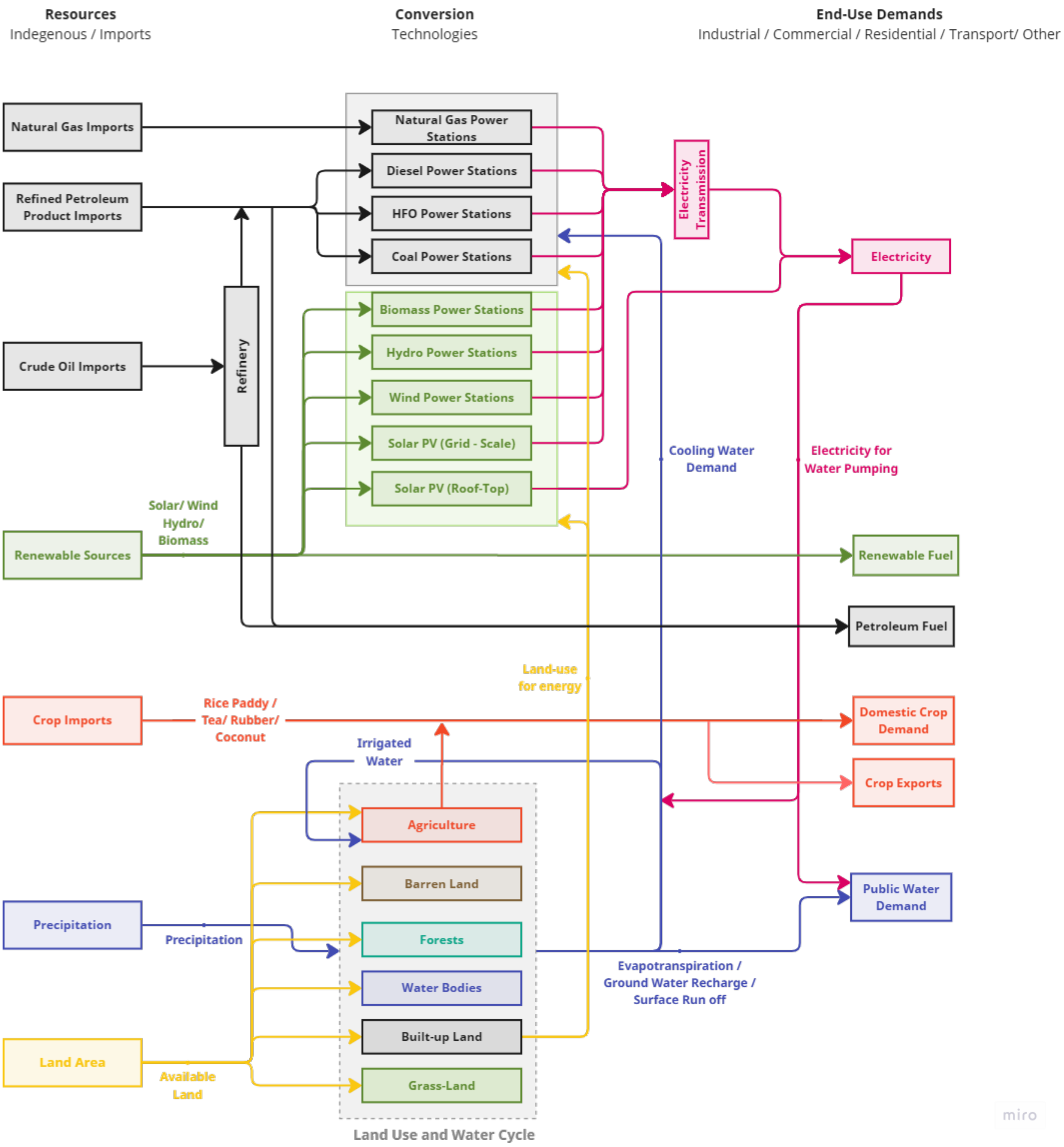

Figure 11. Reference system - Sri Lanka CLEWs

4.5 Scenarios

Three scenarios were defined and assessed using CLEWs-Sri Lanka. The three scenarios represent distinct future pathways for Sri Lanka, ranging from minimal intervention to aggressive decarbonization efforts, each with unique assumptions, and technological adoption rates.

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Table 8 Scenarios - Sri Lanka CLEWs

Name	Description
BAU- Business as usual	o Sri Lanka continues its current energy policies and established development patterns. o There are no significant interventions in clean energy development, energy efficiency, forest conservation, agriculture modernization, or transport decarbonization. o Uptake of renewable energy, specifically solar and wind, is delayed. o Land-allocation frameworks prioritize agriculture focusing on limiting crop imports (specially rice paddy) and other infrastructure (such as roads) over renewable energy zones. o Limited progress on transport electrification and urban energy efficiency. o The country expects to recover crop export earnings to the pre-COVID19 levels and maintain that level going forward. In addition, Sri Lanka expects to expand the industrial sector to support GDP growth, thus economic recovery.
NDC – Nationally Determined Contribution	o This pathway builds on BAU, but the national policies are now aligned with Sri Lanka's updated NDCs — signalling an effective mobilization of resources and political will. o Renewable capacity is moderately scaled up. Natural gas power stations are taken into the electricity mix as a key resource sustaining fuel diversity and increase security of supply. o Fossil fuel reliance decreases progressively, where residential cooking, industrial and commercial activities shifting to electricity as the grid electricity dominates renewable energy. o By 2030, the scenario aims to achieve 70% of electricity generated from renewables (solar, wind, hydro, biomass). o Moderate electrification of transport. o Grid capacity and efficiency upgraded to accommodate variable renewables. o Land use reforms support renewable energy but safeguard food/agricultural security and forest conservation. Particularly meeting the NDC target of

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	increasing the forest cover to 32% of land-area by 2030.
Ambitious RE – Ambitious Renewable Energy	Builds upon NDC scenario, with aggressive renewable energy deployment, and the other assumptions from the NDC scenario remains the same.

4.6 Final results and main insights

The overarching objective of the modelling effort using CELWs Sri Lanka is to **identify the land-use and water systems implications of renewable energy expansion** in Sri Lanka up to 2050.

4.6.1 Primary Energy Supply

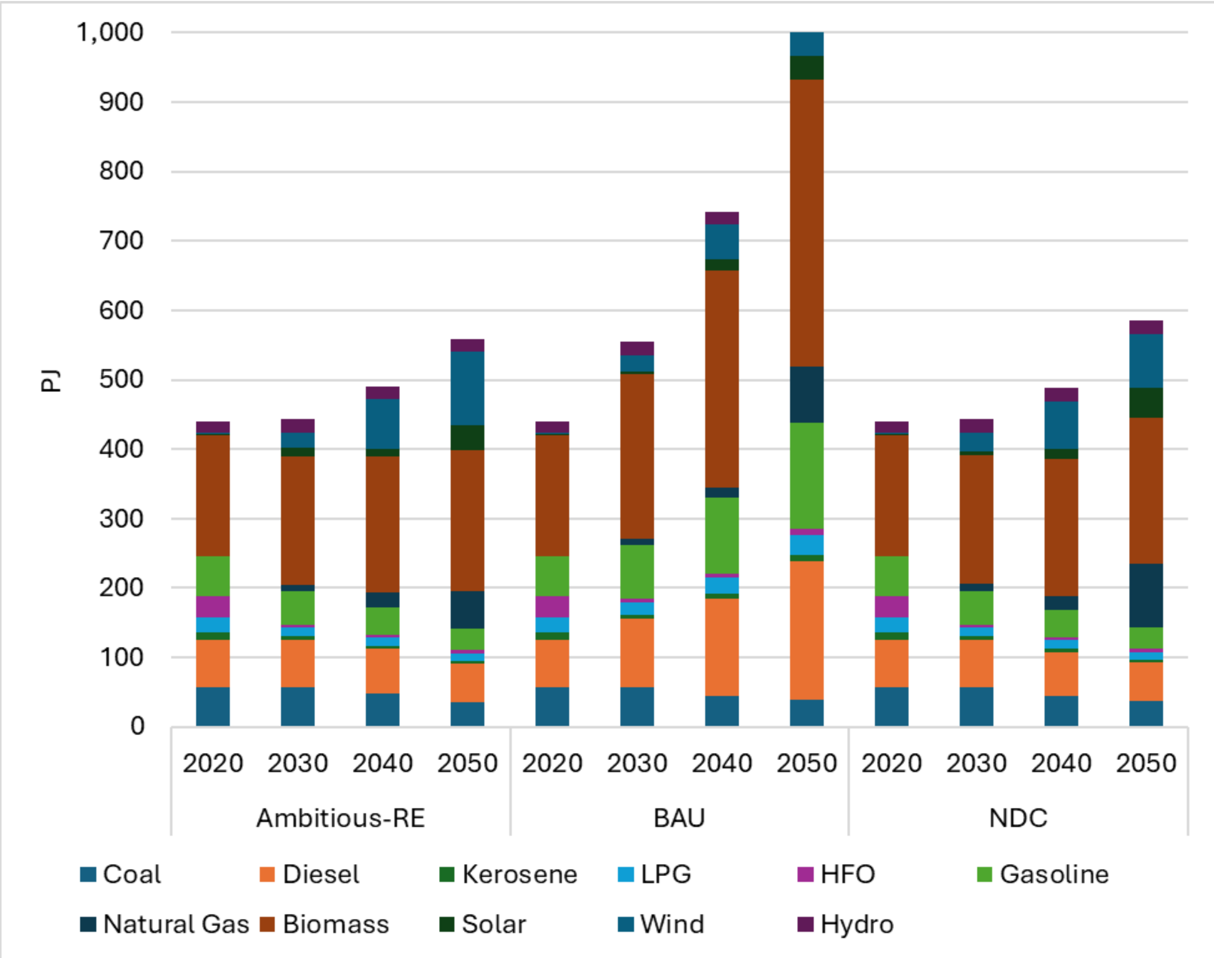

Figure 12. Primary energy supply for the three scenarios in selected years; 2020, 2030, 2040 and 2050.

Historically, primary energy supply in Sri Lanka is dominated by Biomass, followed by Diesel, Coal and HFO. Solar and Wind contributed relatively smaller shares. Figure 12 shows NDC and Ambitious-RE scenarios shows a limited growth reflecting energy efficiency measures and demand reductions. Solar and Wind become dominant beyond 2030 for the same scenarios. A significant share of fossil fuel use from transportation is now shifted to electricity. The BAU scenario retains the reliance on fossil fuels even through there is growth in solar and wind energy technologies.

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4.6.2 Electricity Demand

As shown in Figure 13, all scenarios show a continuous increase in the electricity demand over time. This reflects the drivers such as population growth and economic development. The shift to electricity from fossil fuels across sectors indicates a growth in electricity demand more than three folds in 2050 compared to 2020.

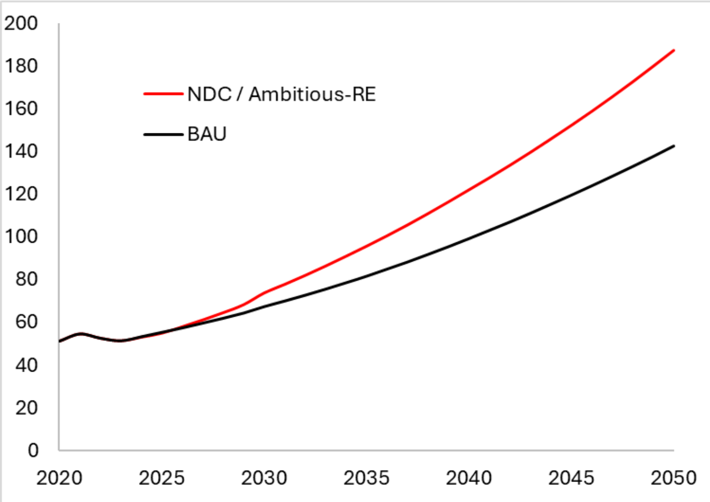

Figure 13. Electricity demand growth up to 2050

4.6.3 Total Installed Capacity for Power Generation

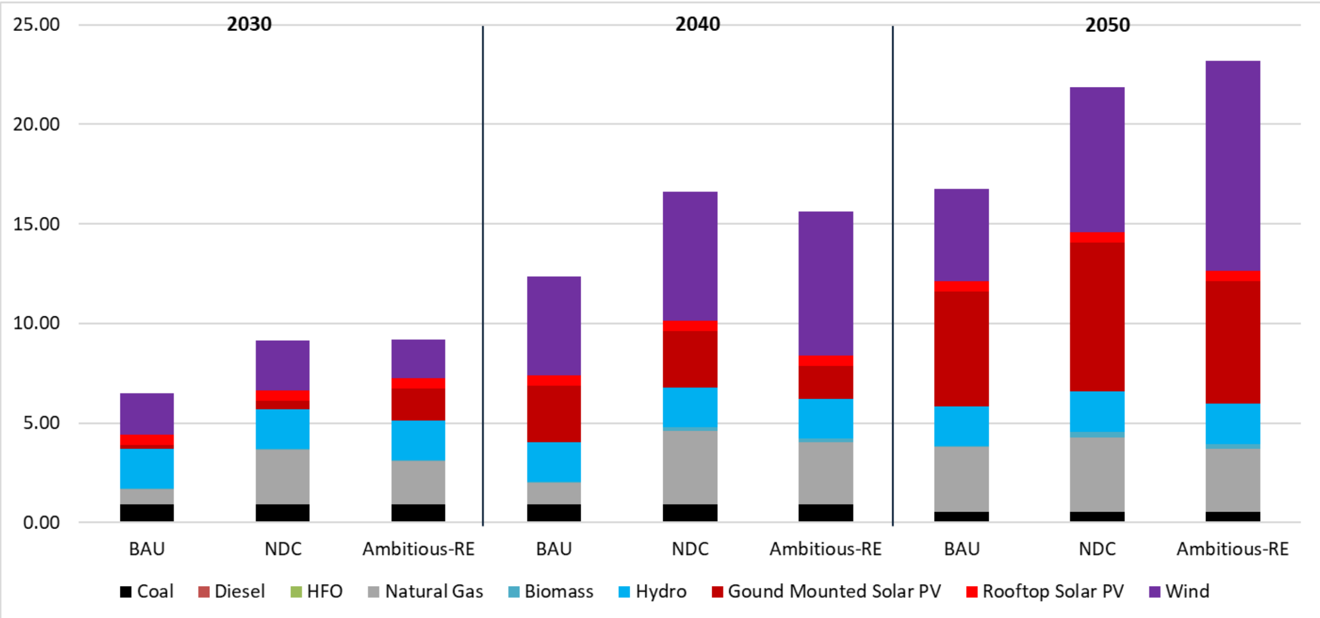

Figure 14. Total installed power generation capacity (GW) in 2030, 2040 and 2050 across the scenarios.

All scenarios follow a growth in electricity generation capacity in line with the electricity demand growth. Figure 14 shows that the majority of new generation capacity comes from solar PV, onshore wind (offshore development is not considered for this model version), and natural gas as a prominent choice for grid balancing and peak demand services as no further high carbon intensive fossil fuelled power generation (coal, diesel and HFO) is not favoured in any scenario. The large uptake of solar and wind as renewable energy sources is due to the fact that Sri Lanka's large hydro generation capacity is already saturated, and the growth in mini hydro systems is small, with limited suitable geographic locations for development.

The BAU scenario shows overall three-fold generation capacity growth, where Ambitious-RE scenario's capacity growth is almost five-fold. This is an expected outcome when integrating high shares of Variable Renewable Energy like Solar and Wind, as their lower capacity factors (compared to thermal plants) necessitate a larger installed GW base to produce the required energy.

Sri Lanka's NDCs focus largely on increasing fuel diversity by introducing natural gas into the mix short-term (2030-2040) thereby having more natural gas power stations in 2030 and 2040. When the availability of Solar and Wind resource is high, they become cost competitive compared to natural gas as fuel needs to be imported to Sri Lanka. Therefore, in the Ambitious-RE scenario, compared to NDC scenario, there is less uptake in natural gas and high uptake in renewables. Additionally, this update in renewables become further increased in the Ambitious-RE scenario during 2040-2050 period.

4.6.4 Power Generation

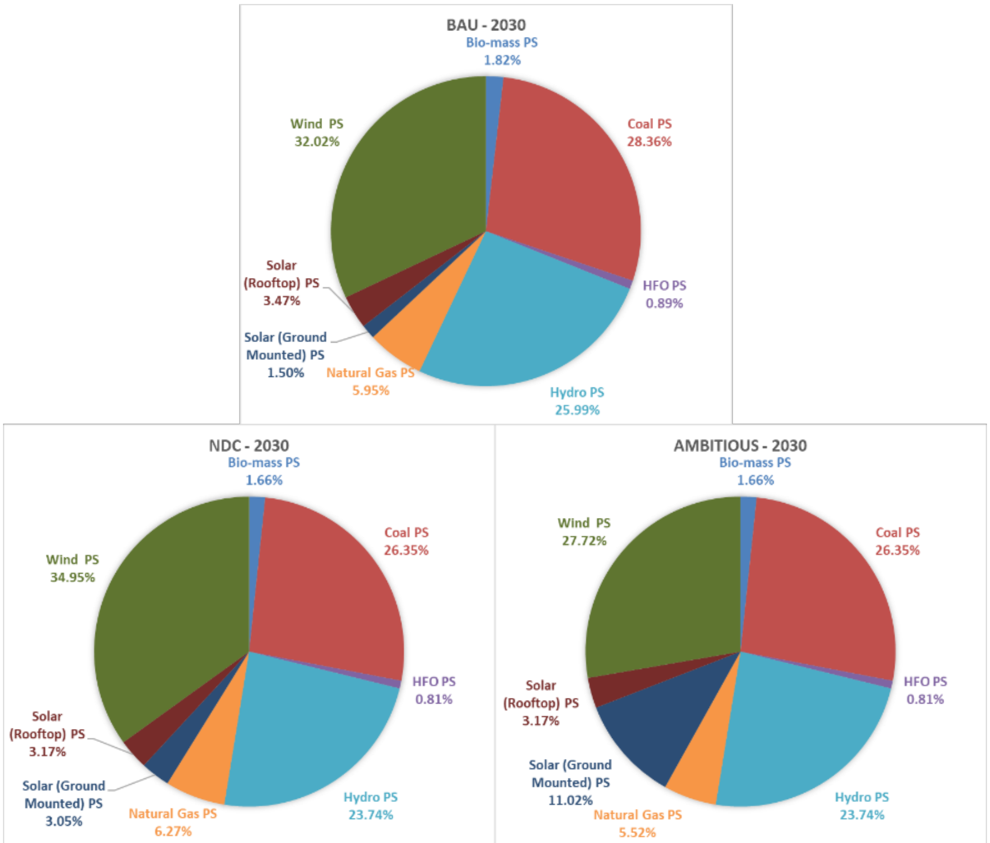

Figure 15. Share of annual power generation by fuel in 2030 across the three scenarios

Figure 15 shows the power generation share by fuel in 2030 comparatively across the three scenarios. By 2030, BAU has 64.8%, NDC has 66.5% and Ambitious-RE has 67.1% share of electricity generated from renewable sources. This indicates the NDC target of reaching 70% renewable electricity generation in 2030 would require an ambitious solar and wind capacity uptake than the existing plans.

The share of renewable capacity in the NDC scenario would only exceed 70% beyond 2030 and it reaches only 73.3% in 2050. BAU scenario falls short of the target, with 67.6% in 2050, while Ambitious RE scenario reaches 82% renewable electricity share in Sri Lanka.

4.6.4.1 Power Generation – Night Peak

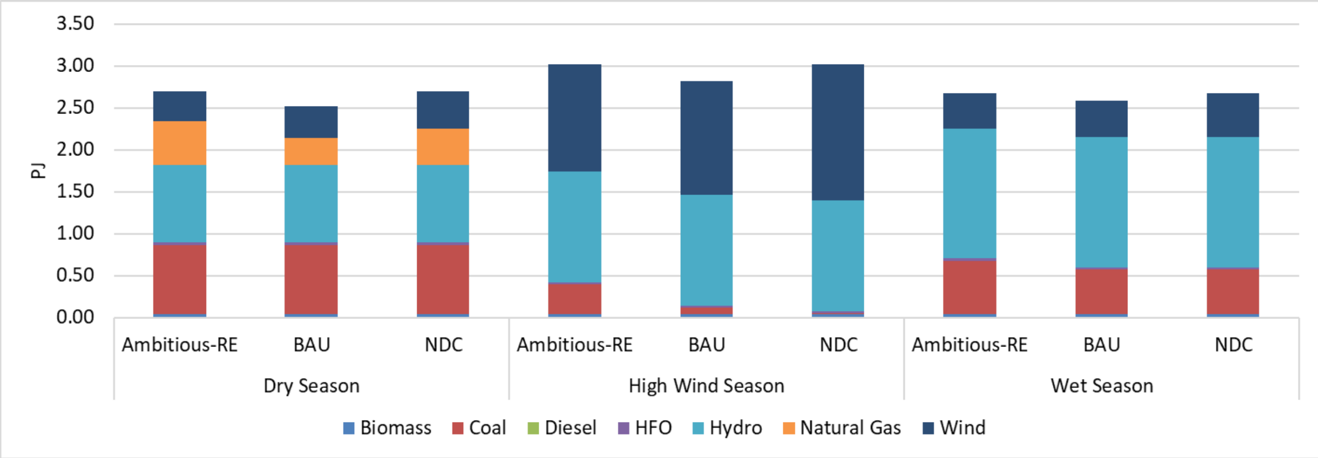

Figure 16. Electricity generation during Night Peak hours (7pm to 10pm) across three scenarios in 2030 disaggregated for Dry (January to April), High Wind (May to August) and Wet (September to December) weather seasons of Sri Lanka.

The total generation for night-peak period as shown in Figure 16 is broadly similar across scenarios within each weather season, but the technology mix varies significantly. The Dry season shows significant use of fossil fuel generation across all scenarios with regards to the lowest capacity factors of renewables. The BAU scenario heavily relies on a diverse mix of fossil fuels (Coal, Diesel, HFO, Natural Gas) to meet the demand. In contrast, the NDC and Ambitious scenarios show a notable shift towards increased renewable dispatch from Hydro, Biomass, and Wind, with Natural Gas playing a strategic and substantial role as a key flexible resource to ensure supply security.

4.6.4.2 Power Generation – Day Peak

Figure 17 shows electricity generation during day-peak hours (6am to 6pm), significantly dominated by wind followed by ground mounted solar PV and rooftop PV systems even by 2030. This leads to above 90% renewable electricity generation during day-peak period across all scenarios in high-wind season. This is followed by the wet-season where ample hydro generation comes into play in-place for solar PV reaching 80% renewable electricity share in Ambitious-RE scenario, and 76% in NDC scenario and even 74% in BAU. Particularly in the Dry season where less hydro generation is available, natural gas comes into the mix as dispatchable generation compensating the variability of renewables.

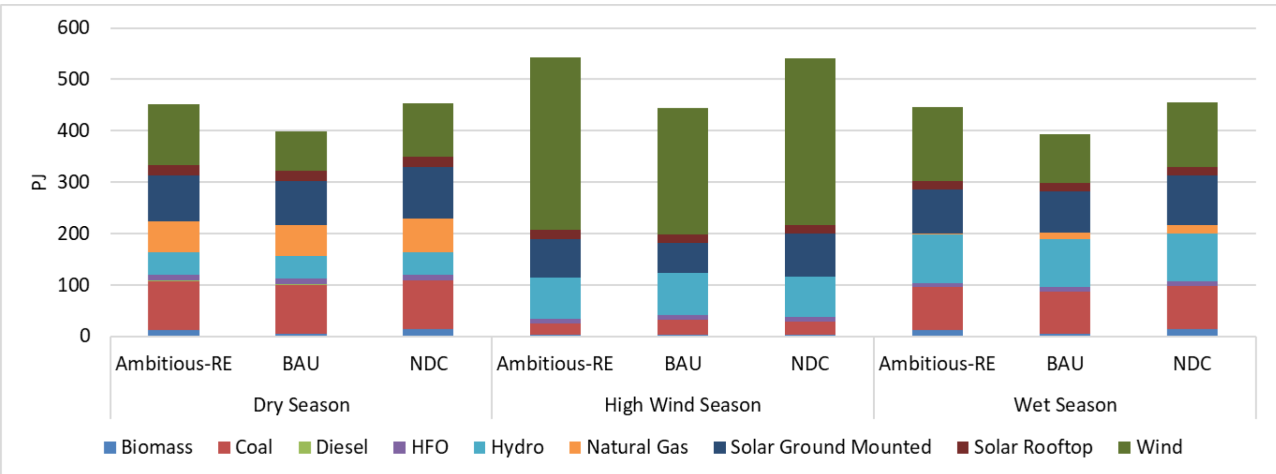

Figure 17. Electricity generation during Day Peak hours (6am to 6pm) across three scenarios in 2030 disaggregated for Dry (January to April), High Wind (May to August) and Wet (September to December) weather seasons of Sri Lanka

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4.6.5 Land-use

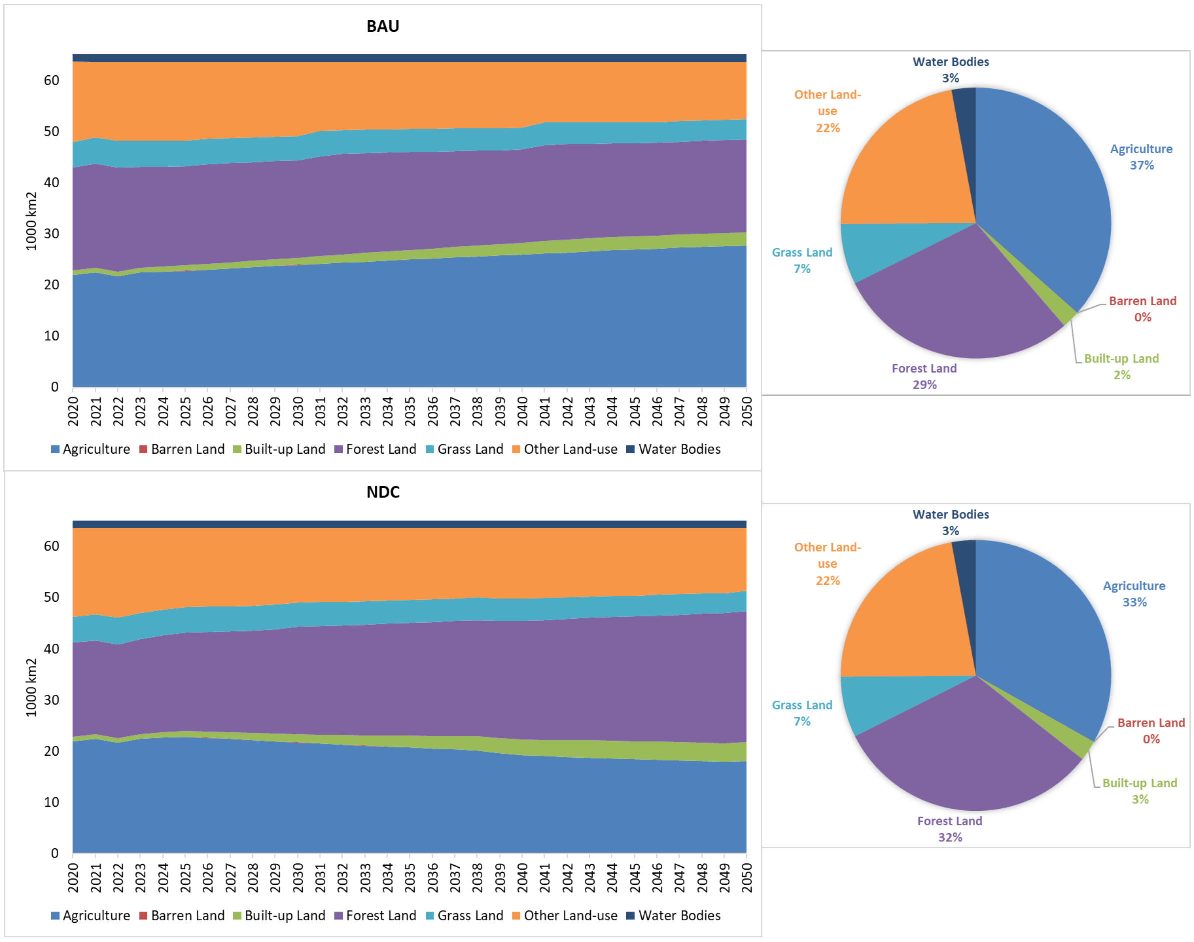

Figure 18. Total Land-use in Sri Lanka for BAU and NDC scenarios (left) and snapshot of share by land-use for the same scenarios in 2030 (right).

Figure 18 indicates significant differences in forest cover between BAU and NDC scenarios. The NDC scenarios meets the target of increasing forest cover to 32% of the total land area in Sri Lanka whereas BAU scenario falls short at 29%.

4.6.5.1 Land-use change

Figure 19 illustrates the dynamic changes in key land-use categories—Forest Cover, Agriculture Land, and Built-up Land—across the three scenarios in Sri Lanka from 2020 to 2050, highlighting the intricate trade-offs and impacts of different development pathways.

The forest cover increase is sustained up to 2050 in the NDC scenario which is also similar to the Ambitious-RE scenario. The sustained forest cover increase is mainly compensated by a decrease in agricultural land up to 2050 (Figure 19) suggesting a greater reliance on agricultural intensification (higher yields) to meet food security needs.

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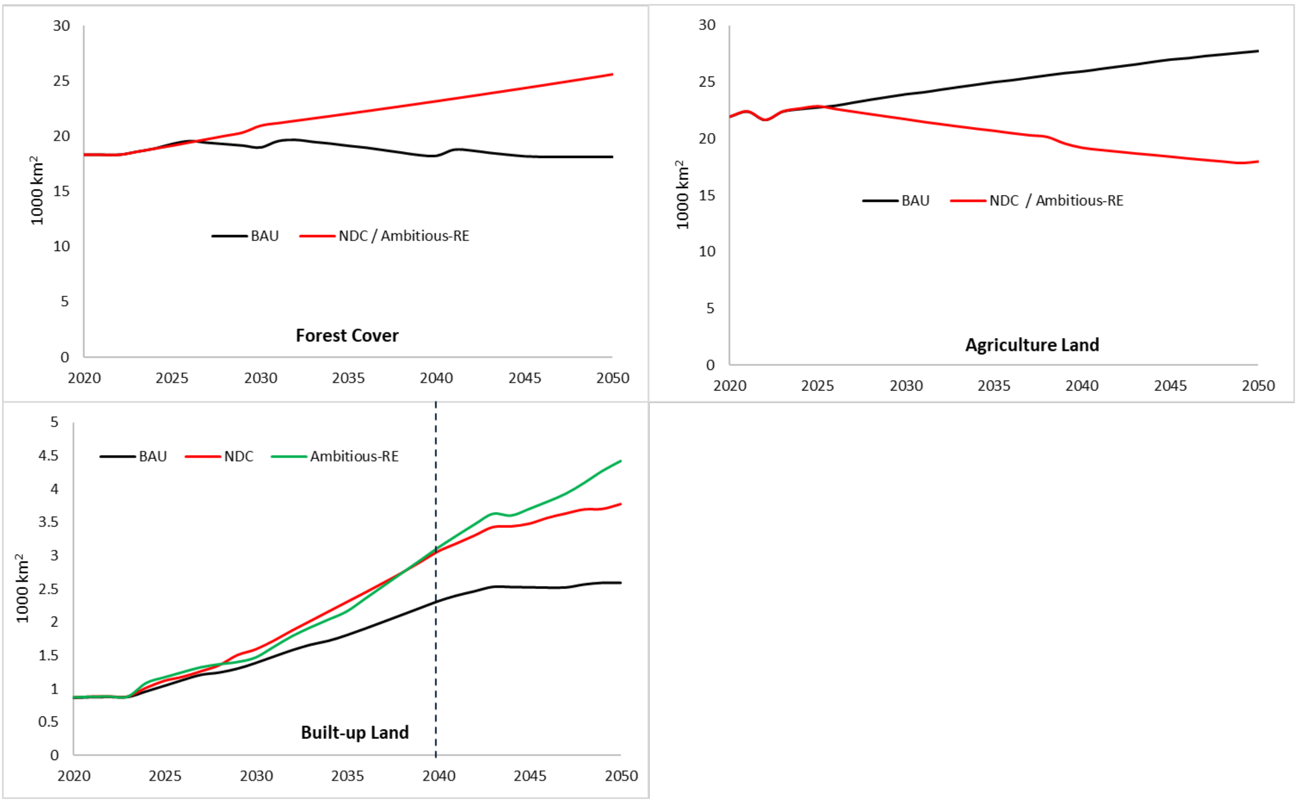

Figure 19. Changes in Land-use, particularly Forest Cover, Agriculture Land and Buit-up Land in Sri Lanka for the three scenarios.

Built-up land increases in all three scenarios in line with population growth and the associated expansion of housing, roads, and general infrastructure. However, the trajectory diverges significantly, particularly after 2030. While the BAU scenario shows a steady rise in built-up land, the NDC and Ambitious-RE scenarios exhibit a faster increase. This accelerated growth, especially in Ambitious-RE after 2040, is primarily driven by the significant uptake of wind farms which require additional land for turbines and associated infrastructure. This demand for land by wind farms in NDC and Ambitious-RE effectively outweighs the gains made through more efficient urban planning and densification policies implemented in those scenarios.

4.6.5.2 Agriculture land-use change (NDC/Ambitious-RE vs BAU)

Figure 20 further shows how agriculture land intensification occurs through strategic internal land reallocation and improvements in crop yields due to modernisation of traditional agriculture practices. Positive values indicate more land of that specific type in NDC compared to BAU, while negative values show less. Tea crops demonstrated no changes between NDC and BAU scenarios as there is no significant domestic demand, and also no noticeable changes in tea exports. The overall change is similar between NDC and Ambitious-RE scenarios.

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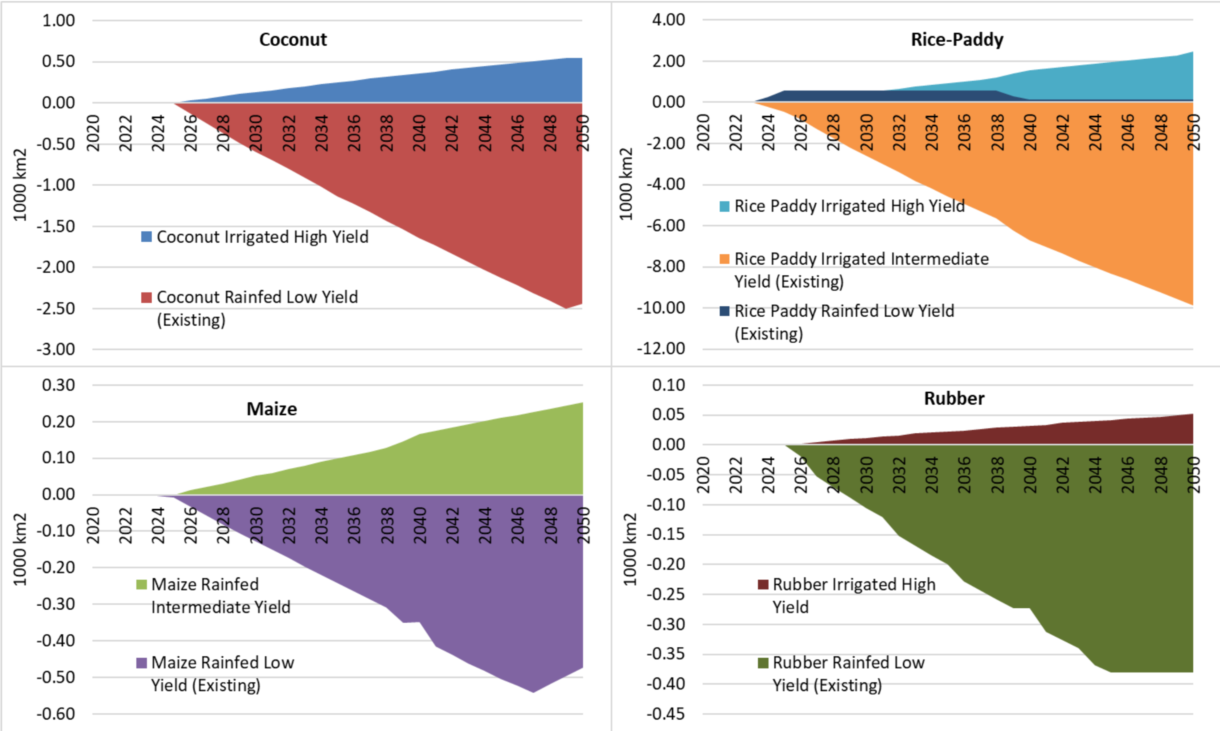

Figure 20. Change in Agriculture Land-use in the NDC scenario compared to BAU scenario for major crops – Coconut, Rice-paddy, Maize and Rubber

The overall reduction in agricultural land in the NDC scenario is achieved by a deliberate shift away from lower-yielding and rainfed cultivation towards more productive land categories. Rice-Paddy is the largest contributor to agricultural land, thereby showing the most pronounced intensification among all major crops in Sri Lanka. The NDC scenario aggressively converts existing rice-paddy land for high-productivity farming. Similarly, for Coconut, there is a clear trend of retiring existing Low Yield Rainfed land while simultaneously expanding into new high-productivity irrigated farming. A similar shift of cultivation practices is seen in Rubber lands. Maize cultivation takes a trend that involves a shift from existing Low Yield Rainfed farming towards expansion to an Intermediate Yield given the modest demand for Maize in Sri Lanka. These detailed shifts indicate how the NDC scenario, through moderate yield improvements and strategic land management, ensures food security and meets crop demands with a smaller overall agricultural footprint, freeing up land for competing demands such as vital forest expansion and renewable energy infrastructure.

4.6.6 Water Use

Figure 21 (Top) shows the water supply in three leading sectors: public water, irrigation and cooling thermal power stations within the BAU scenario. It shows a steady and continuous increase in overall water demand, rising from approximately 1.8 BCM in 2020 to around 2.6 BCM by 2050. Irrigation constitutes the largest and a steadily growing component of this demand, reflecting the expansion of agriculture land. Public Water Supply is the second major contributor, also demonstrating consistent growth with population and economic development. Lastly, Cooling Power Stations represent the smallest but a noticeable and increasing share of water demand, consistent with the continued reliance on thermal power generation in the BAU scenario.

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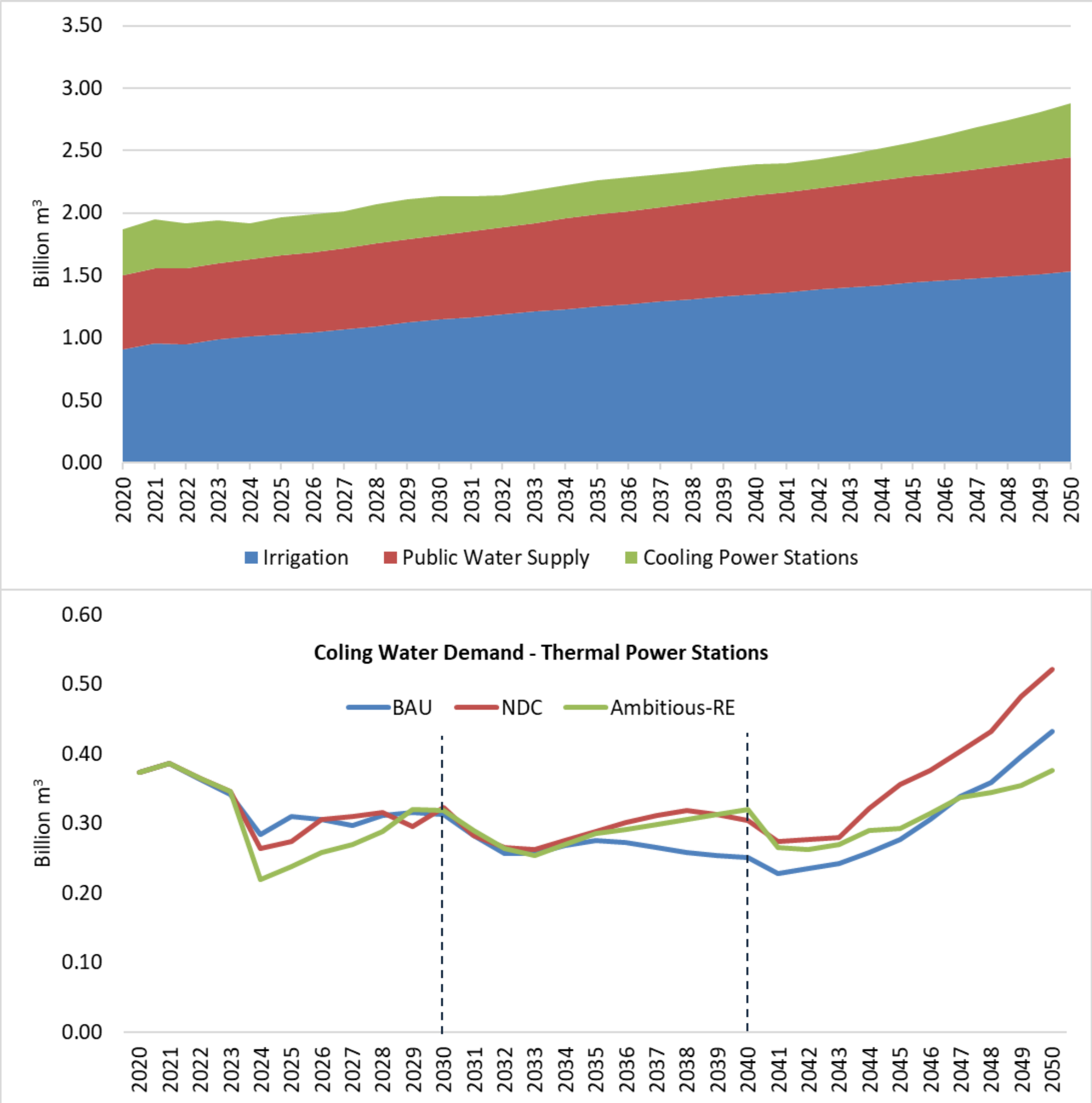

Figure 21. Water Supply in BAU (Top) and changes in cooling water demand for thermal power stations across the three scenarios (Bottom).

Figure 21 (bottom) specifically focuses on cooling water demand for thermal power stations across all three scenarios (BAU, NDC, Ambitious-RE) from 2020 to 2050. The Ambitious-RE scenario (green line) shows an initial decline and then maintains the lowest overall cooling water demand throughout the projection period, directly aligning with its aggressive fossil fuel phase-out using renewable power generation methods. The NDC scenario uptakes a larger share of natural gas power stations compared to Ambitious-RE scenario, leading to the largest annual electricity generation. In-line with this power generation, the cooling water demand increases. This outcome suggests that despite its overall decarbonization goals, the specific mix and operational characteristics of the remaining thermal power fleet in the NDC scenario might be more water-intensive than BAU's fleet, leading to higher absolute cooling water withdrawals.

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4.6.7 Emissions

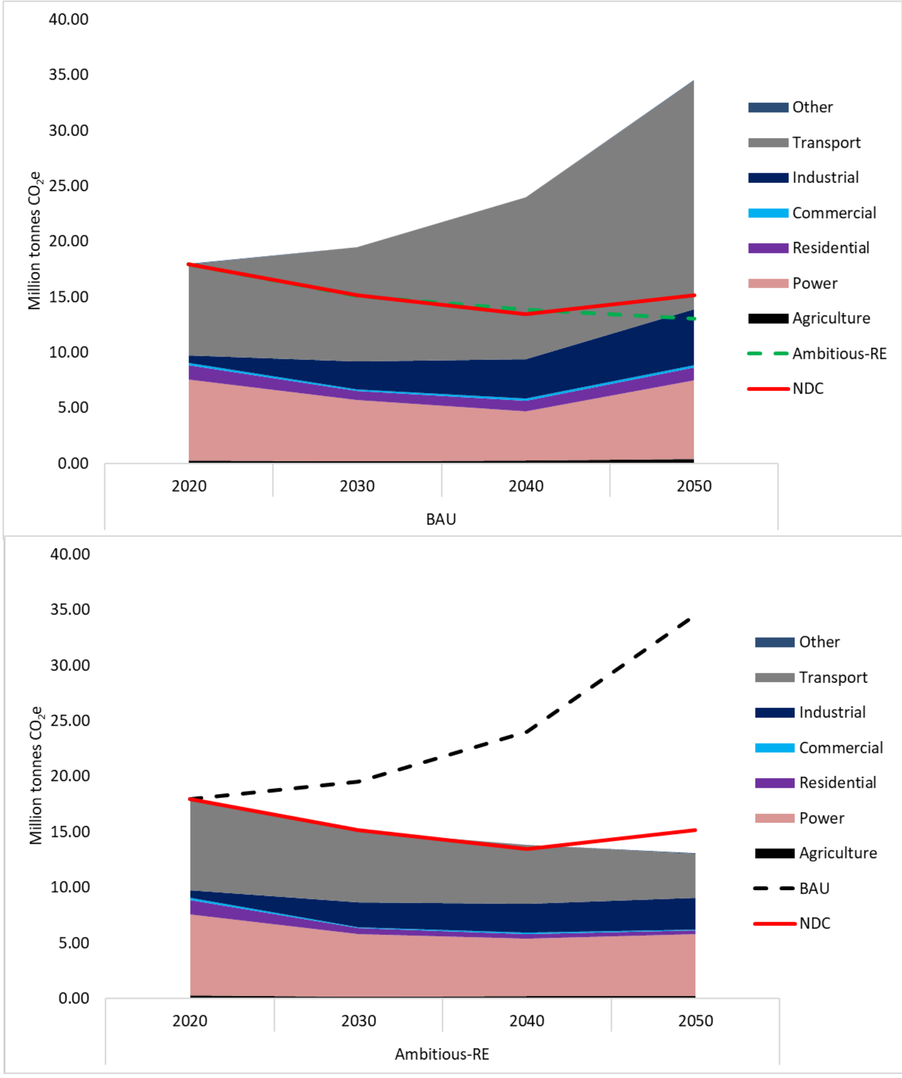

Figure 22. Annual GHG emissions by sector for the (Top) BAU and (Bottom) Ambitious-RE scenario in comparison among overall GHG emissions to other scenarios (line-charts).

Figure 22 (Top) shows the emissions profile for the BAU scenario, with comparison lines for NDC (red) and Ambitious-RE (dashed green). In the BAU scenario, total GHG emissions show a continuous and significant two-fold increase from 2020 to 2050. This rise is primarily driven by the expansion of Transport sector remaining the largest emitting sector in Sri Lanka without strategic interventions to decarbonise over the years and minimal electrification of sector. This is followed by the Industrial, and Power sectors, consistent with the scenario's high energy demand growth and continued reliance on fossil fuels without significant decarbonization efforts. The comparison lines clearly show that both NDC and Ambitious-RE achieve substantial emission reductions relative to BAU even diverging sharply beyond existing levels of emissions.

Figure 22 (bottom) chart focuses on the Ambitious-RE scenario's emissions, providing comparison lines for BAU (dashed black) and NDC (red). In the Ambitious-RE scenario, overall GHG emissions are declining to around 14-15 $MtCO_2e$ by 2050. This deep decarbonization is largely due to the aggressive renewable energy deployment and fossil fuel phase-out and significant reductions in Transport and Industrial emissions due to ambitious electrification and efficiency measures.

It is also seen that the use of natural gas power stations as a mean of fuel diversification and as a flexible source would sustain emissions from the power sector as seen in the NDC scenario by 2050. This might impact the overall decarbonisation efforts from the power sector and achieving net-zero emissions in 2050.

4.6.8 Overall Take-aways

- Sri Lanka faces a clear choice between a high-emission, fossil-fuel-dependent future (BAU) and ambitious low-carbon pathways (NDC, Ambitious RE) that lead to profoundly different outcomes across energy, land, and water systems.
- Aggressive renewable energy expansion, particularly wind, significantly increases demand for land, creating a notable competition with other land uses.
- Meeting growing food demand while simultaneously expanding renewables and forests necessitates a strong focus on agricultural intensification (improving yields per unit of land) to free up land, especially in ambitious decarbonization scenarios.
- Achieving national climate targets (NDC, Ambitious RE) is strongly linked to significant forest expansion, highlighting the critical role of nature-based solutions for overall decarbonization and ecosystem health.
- Sustainable development pathways (NDC, Ambitious RE) require enhanced water efficiency in public water supply and potentially other sectors, easing pressure on vital water resources.
- The model underscores the strong interdependencies between energy, land, and water. Tackling climate change and achieving sustainable development requires integrated planning and policy implementation across all these sectors.
- While pursuing ambitious decarbonization involves crucial trade-offs (e.g., land for RE vs. agriculture), it also unlocks powerful synergies (e.g., agricultural intensification enabling both RE expansion and forest restoration).

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5 Model factsheet: Kenya - CLEWs

5.1 Stakeholder engagement

The CLEWs Kenya stakeholder engagement took place during a two-day in-person workshop hosted in Mombasa, from August 31st to September 1st, 2023. Organized by RECCReC (Technical University of Mombasa) with contributions from KTH Royal Institute of Technology, Politecnico di Milano, Bruegel, NTUA, and Strathmore University, the workshop brought together Kenyan and international researchers and modelling experts to explore the role of open-source integrated assessment models in supporting sustainable policy planning.

Although the CLEWs Kenya model version 2.0 had not yet been initiated at that time (model development began in February 2025), the discussions were highly relevant in shaping its conceptual direction. The workshop introduced participants to the use of energy system models and scenario development, with particular emphasis on applications within Kenya's policy context, such as through examples from the Climate Compatible Growth (CCG) Programme.

Participants explored the water-energy-food nexus, considering how multi-resource planning tools like CLEWs can address Kenya's interlinked challenges of food security, water scarcity, and clean energy access. The hands-on sessions included using the UN DESA scenario explorer and basic input-output analysis to understand energy-economy interactions, as well as running and interpreting a simplified CLEWs nexus model using OSeMOSYS.

Group discussions allowed stakeholders to map resource interactions at the country level, revealing gaps in policy coherence and the need for scenario-based planning. While the participants were primarily academic and technical experts rather than formal policymakers, the event highlighted key modelling needs, such as:

- Addressing competing land-use objectives;
- Simulating regional water constraints;

Supporting cross-sectoral coordination in national planning.

After the workshop, TUM worked with the Wuppertal Institute to carry out further policy research. This research focused on identifying key policies in Kenya that affect different sectors, such as energy, industry, buildings, transport and AFOLU, and highlighting gaps, overlaps, and areas lacking coordination. The findings from this policy review were later used to inform the CLEWs Kenya model version 2.0 by pointing out critical policy gaps and conflicts that needed to be tested and modelled.

These engagements highlighted the importance of standardized workflows and capacity-development in local institutions to support integrated modelling approaches. These priorities later informed the structure and outputs of CLEWs Kenya version 2.0, ensuring its policy relevance and usability within Kenya's climate and development planning processes.

5.2 Brief history and model development (v.2.0)

The Kenya CLEWs model was initially developed to explore and assess the interlinkages between energy, land, and water sectors as well as the climate impacts of different strategies. While version 1.0 focused mainly on modelling these interdependencies and scenario exploration on reducing emissions, version 2.0 has built on these foundations to represent an advanced analysis of policy implementation in Kenya, NDC targets, future policy recommendations and best transition strategies. By examining scenarios such as biofuel integration, electrification of the transport sector, renewable energy expansion, and current policy evaluations, version 2.0 explicitly highlights the trade-offs among the different sectors, offering actionable insights for policy planning. By using real-time data, the model is able to showcase real life impacts that will support decision making.

5.2.1 Aim of the model and target audiences

The Kenya CLEWs model version 2.0 has been developed to provide an integrated sectoral analysis of current

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policies in Kenya , explore how NDC targets can be achieved, and provide relevant policy recommendations. Built on a cost optimization framework, it enables the evaluation of different trade-offs between key policy decisions and the impact on national development goals, SDGs, and NDCs. This model is primarily intended to support government policymakers involved in energy planning, climate strategy, and sustainable development. It also serves as a valuable tool for researchers in systems analysis, NGOs advocating for environmental and social sustainability, and international organizations working to advance Kenya’s NDC and SDG commitments.

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5.3 Model scope and structure - updated

Table 9. Model scope and structure - Kenya.

Scope		Detail version 1.0	Detail version 2.0
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.	Added Nuclear and Coal powerplants in Energy Sector. Added Grassland in Land use as well as Other Crops. Introduced demand for Transport Diesel and Transport Electricity.
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/MUIO	
Open access data	Yes	https://zenodo.org/records/13505931	
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.	
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	

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Solution	6 minutes	2. OSeMOSYS UI: 4.6 3. RAM: 16 GB 4. Processor: Intel core i7	OSeMOSYS UI: 5.3 RAM: 16GB Processor: Intel core i7

5.3.1 Key data sources – updated

Table 10. Additional 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	https://gaez.fao.org/	Y
Land Data - Capacity	FAOSTAT - https://www.fao.org/faostat/en/#data	Y
Water Data – Input, Output	AQUASTAT- https://data.apps.fao.org/aquastat/	Y
Climate Data – Carbon emissions	Our world in data - https://ourworldindata.org/CO_2 /country/kenya	Y
Economic Data - Capital cost, Fixed costs, variable costs	CCG starter kit - https://zenodo.org/records/7539097	Y
Other Data - Total technology annual activity upper limit, Accumulated annual demand, Specified demand profile, Specified Annual demand	CCG starter kit - https://zenodo.org/records/7539097	Y

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5.4 Reference system – updated

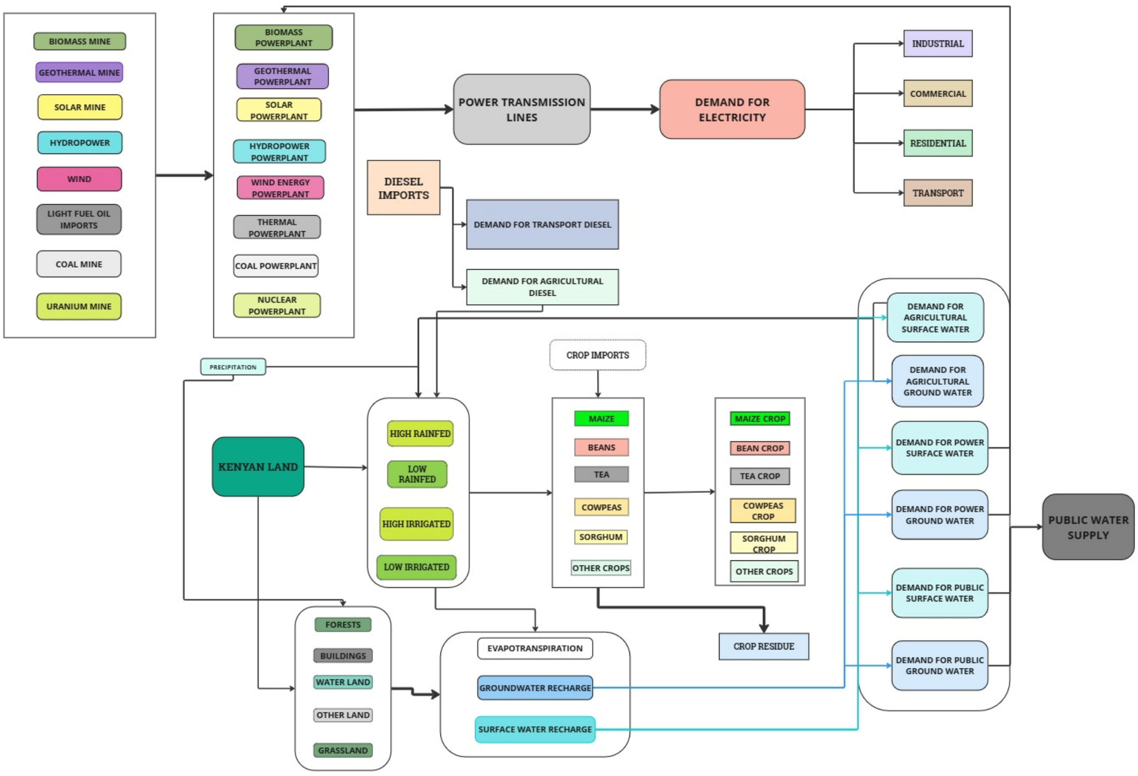

Figure 23. Reference system updated - Kenya CLEWs

5.5 Scenarios

Table 11 Scenarios - Kenya CLEWs

Name	Description
BAU – Business As Usual	The model follows Kenya's current growth trends with current implemented policies. Emphasis on the implementation of policies on Coal and Nuclear powerplants by 2030 and 2034 respectively. Implementation of afforestation targets set; 15 billion trees by 2032.
High Renewable	It explores a high renewable pathway with more investments in the current renewable potential in the country. Rescinding of implementation of Coal and Nuclear in prioritization of renewables. Afforestation targets remain the same as the Business as usual scenario.

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Biofuel Integration	In the Biofuel Integration Scenario, the model explores the use of crop waste to produce biofuels. This impacts both emissions and energy production. Policies implemented remain as in the Business as Usual
Renewable Transport	This scenario explores the electrification of the transport sector to reduce dependency on fossil fuels. Due to high renewable percentage in the energy mix it aims to reduce emissions to meet NDC targets. No intervention in Land or other energy policies

5.6 Final results and main insights

Model results indicate that while Kenya's current electricity mix boasts a renewable energy share exceeding 86%, the planned introduction of coal and nuclear power plants could significantly impede progress toward achieving 100% renewables despite the country's untapped renewable potential. Considering that coal and nuclear power plants have long operational lifespans, their inclusion in the energy mix could risk lock the country to a non-renewable path, making it harder to phase them out in favour of cleaner alternatives, even if renewable technologies become cheaper or more efficient. On the other hand, agricultural waste can be utilized for production of biofuels for electricity which would help reduce emissions as well as increase electricity production. Electrification of the transport sector may also be considered especially considering Kenya's energy mix is highly renewable. This would allow for energy efficiency due to high efficiency of EVs as well as greatly reduce emissions from the transport sector.

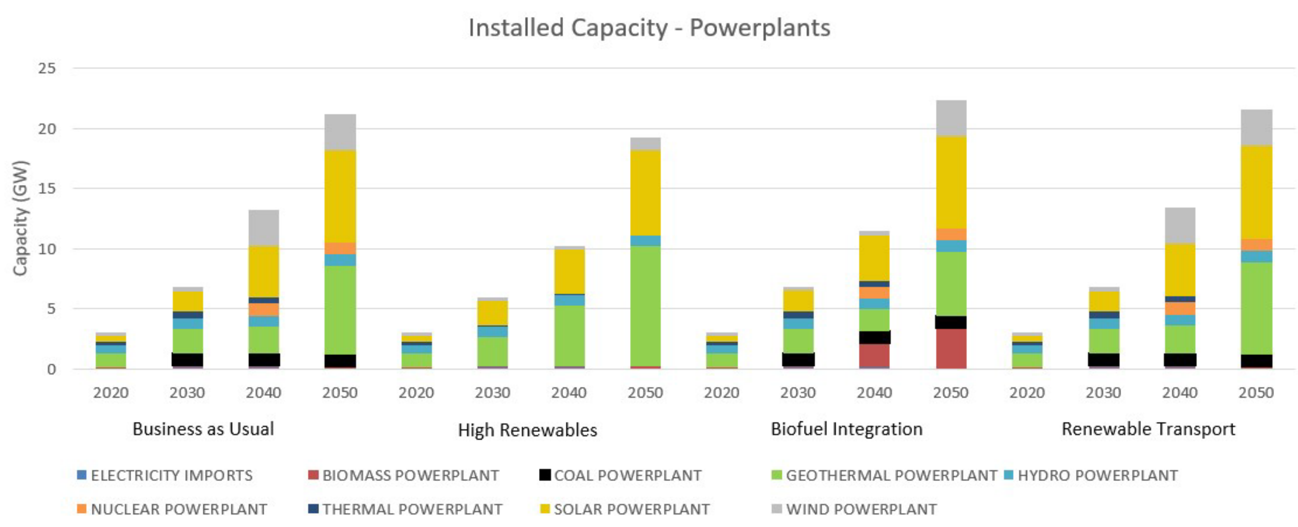

Figure 24. Total installed capacity - Kenya CLEWs.

Land availability is not a limiting factor for afforestation. Over 50% of Kenya's land remains underutilized, categorized as grasslands, shrublands, wetlands, or barren areas, ecosystems that in principle could support

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large-scale tree planting without displacing agricultural or urban land uses. This suggests that, in principle, Kenya has sufficient land to meet its afforestation targets. However, the scale of labour required renders the "15 billion trees by 2032" initiative potentially infeasible within the proposed timeframe. Land use remains consistent across different scenarios. However, linkages can be seen to the energy sector in the biofuel scenario where crop waste is used for biofuel production.

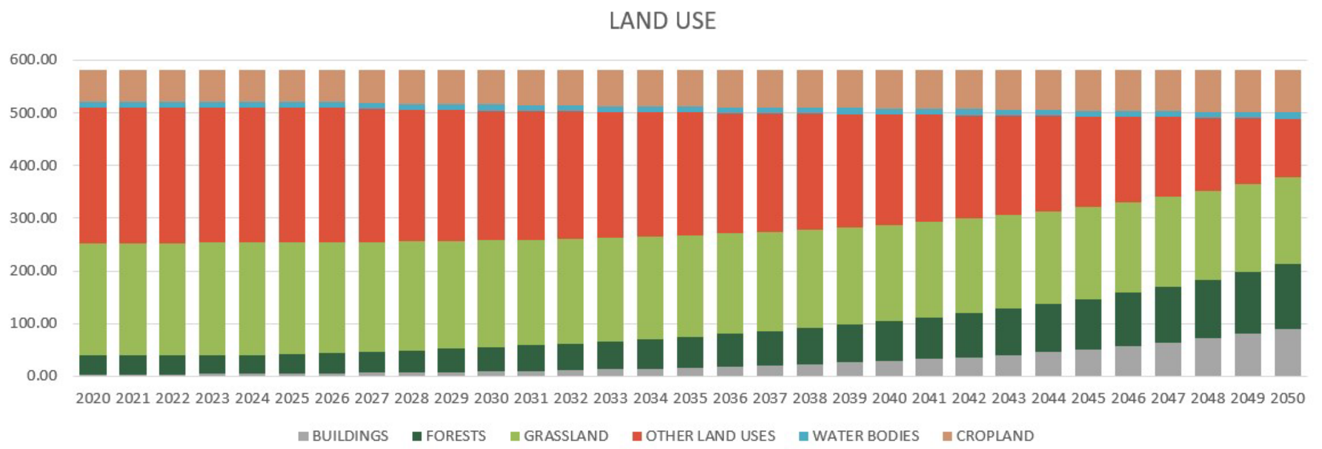

Figure 25. Land use - Kenya CLEWs.

Water resource implications are also critical for Kenya's future planning. Current national water demand is estimated at approximately 4.3 billion cubic meters annually. This figure is projected to rise by over 23 billion cubic meters with the introduction of coal and nuclear powerplants based on modelling results. These technologies would exacerbate water stress in a country already classified as water-scarce, with per capita water availability at just 647 m³—well below the global benchmark of 1,000 m³/capita. Additionally, the introduction of coal power is projected to increase carbon emissions by more than 1.5%, further undermining Kenya's climate commitments under its NDCs.

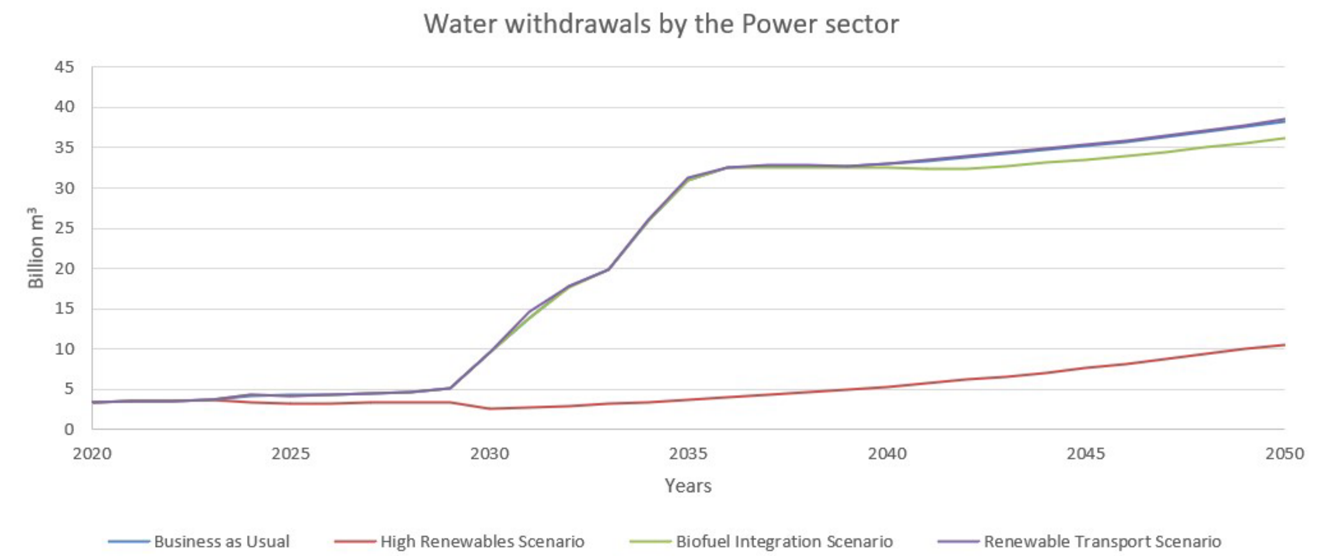

Figure 26. Use of water by power sector - Kenya CLEWs.

The highest sectoral emissions in Kenya are mainly from the agricultural and transport sector. Crop waste from the agricultural sector can be utilized to produce biofuels for electricity. This increases energy production while reducing emissions. On the other hand, the transport sector in Kenya is almost fully relying on fossil fuels. With Kenya's initiative to introduce electric vehicles, transitioning towards a more electrified transport sector would

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allow for even more reduction in emissions especially considering Kenya's high renewable energy mix at the moment. If the country was to commit to a high renewable scenario, it will move closer in achieving its NDC targets.

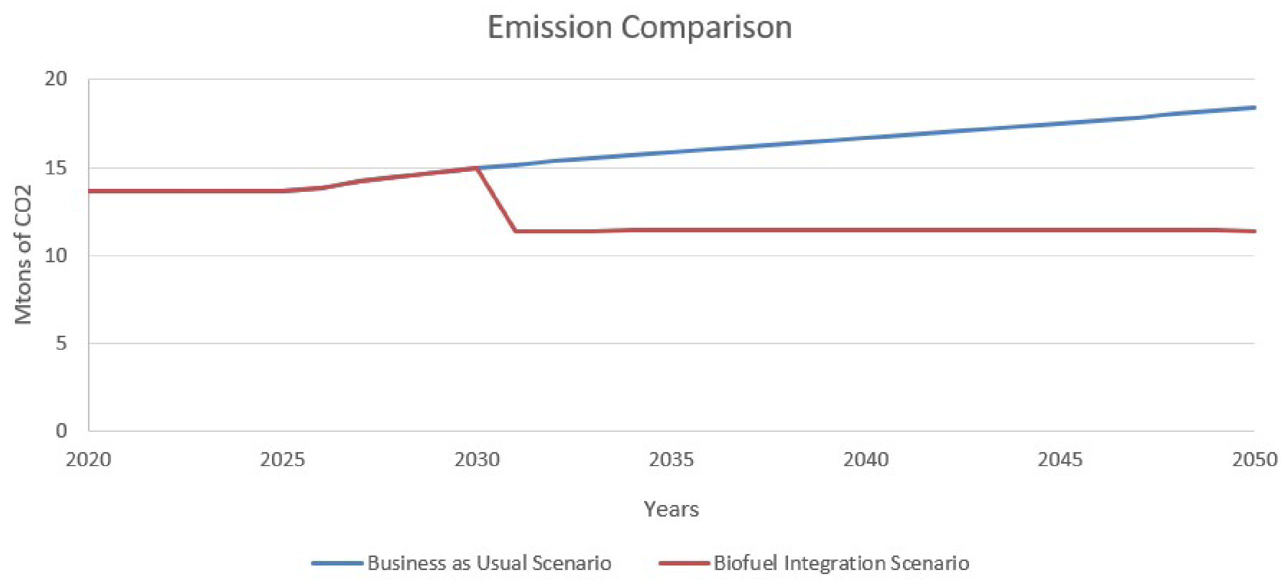

Figure 27. GHG Emissions Comparison – Biofuel Integration Scenario

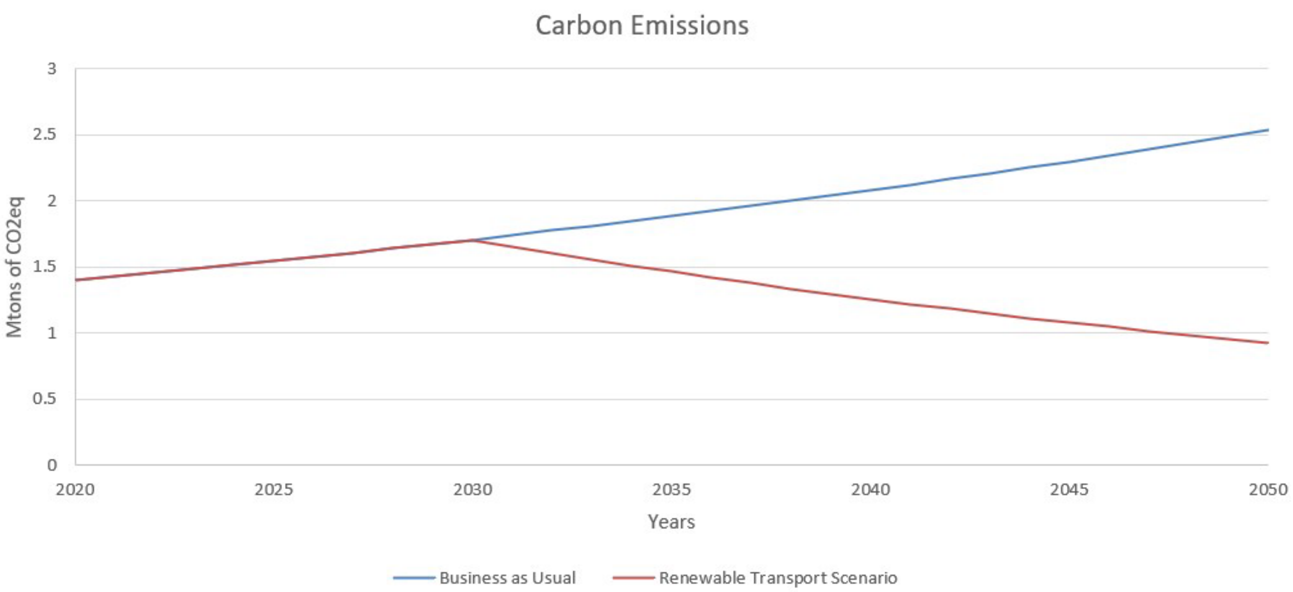

Figure 28. Carbon Emissions Comparison – Renewable Transport Scenario

6 Model factsheet: Ukraine

6.1 Stakeholder engagement

Nearly two-thirds of Ukraine's dispatchable power generation capacity has been occupied, damaged, or destroyed by Russia since the invasion (IEA, 2024). Russian missile and kamikaze drone attacks resulted in a series of rolling blackouts affecting the life of tens of millions of ordinary people as the availability of power was restricted. Therefore, the necessity for restoration of the power sector in a more secure and resilient way is among key government priorities.

KSE Institute chose the modelling of restoration of the power sector to assist the government in its efforts to ensure the availability and affordability of electricity and heat for population and businesses. The vision of the restoration of the power sector was discussed with a large number of experts from the Ministry of Energy, Ukrenergo (Transmission System Operator), Distribution System Operators as well as non-government Ukrainian scientists involved in energy sector studies. The discussions took place in a number of policy forums, in particular, dedicated to rebuilding the power sector before the winter 2025 and afterwards, development of distributed energy resources (DER), modernization of transmission and distribution networks in anticipation of large DER capacities deployment, and development of energy storages. Most government and non-government experts agreed that Ukraine needs to apply the principle of "build-it-better" and restore its power sector in a sustainable way. A full substitution of the coal-fired power fleet with massive variable renewable deployment, which is balanced by power storages and ultra-flexible (peak) gas generation, is also the least-cost way for sector's restoration. However, in order to balance the intermittency of renewable sources while achieving the net-zero target by 2050, Ukraine envisages also the restoration and maintenance of its nuclear power plants (IEA, 2024). Finally, the modelling results were included in the presentation of a Ukraine Recovery Conference 2025 held in Rome by the World Bank and KSE Institute.

6.2 Brief history and model development (v.2.0)

At the outset of February 2022, Ukraine's energy sector ranked among the most robust in Europe. Despite the widespread destruction caused by Russia's full-scale invasion, it remains a key player in the region. Ukraine is among the top ten European countries in terms of installed power generation capacity, ranks within the top three in natural gas production, and operates the largest underground gas storage facilities in Europe (National Council for the Recovery of Ukraine from the Consequences of the War, 2022).

However, the Russian aggression has led to the large-scale destruction of critical energy infrastructure, severely impacting the country's generation capacity and creating urgent challenges in balancing supply and demand, particularly during peak loads. As a result, an urgent need emerged to reassess the available energy assets, evaluate consumption and production imbalances, and identify critical vulnerabilities — particularly during peak electricity demand periods.

The initial version of the Ukrainian energy system model was developed through OSeMOSYS and focused solely on analyzing electricity production and consumption, without consideration of heat demand or heat generation capacities. Additionally, the first model did not account for dynamic changes in the generation infrastructure resulting from wartime damage, such as missile attacks and destruction of energy facilities neither cost structures nor economic feasibility of different technologies.

Version 2.0 of the model introduced several significant enhancements and improvements:

- **Incorporation of heat demand and supply:**
  The updated model includes both centralized and individual heating demands, as well as thermal generation capacities from technologies such as Combined Heat and Power (CHP) plants and boiler systems. This addition allows for a more holistic simulation of energy flows within the country.
- **Updated and detailed infrastructure data:**

More recent and accurate data were integrated regarding the operational status of existing generation units. This enabled a recalibration of load distributions across technologies and a more reliable simulation of how both electricity and heat demands are met.

- **Scenario-based forecasting for 2035:**
  Version 2.0 includes a comprehensive scenario analysis for the year 2035, consisting of three strategic outlooks: pessimistic, baseline, and optimistic. These scenarios are aligned with key national policy frameworks, such as the National Renewable Energy Action Plan until 2030, the Draft Recovery Plan of Ukraine, and other official strategic documents.
- **Inclusion of technology costs and expenses:**
  Unlike the first version, the updated model incorporates indicative technology costs, operation and maintenance (O&M) expenses, and fuel prices for key technologies. This allows for a basic estimation of the financial implications of operating and maintaining the energy system (cost-effectiveness analysis_ under different future conditions based on financial feasibility.

As a result, the second iteration of the model provides a more comprehensive and realistic framework of Ukraine's current energy system for assessing the country's energy future . It also delivers improved foresight into the expected state of the energy sector in 2035, while aligning with the country's long-term energy policy objectives and strategic development goals.

6.2.1 Aim of the model and target audiences

The primary aim of the model is to analyse the current state of Ukraine's energy sector as of 2025 and to assess energy system needs for planned sustainable restoration by 2035 under different development scenarios. Specifically, the model is designed to:

- Evaluate the existing energy balance, including electricity and heat generation and consumption;
- Forecast system requirements based on projected growth in electricity demand;
- Determine the necessary increase in the share of renewable energy sources;
- Reduce dependence on electricity imports by enhancing domestic generation capacity;
- Assess system resilience and its ability to meet peak demand without disruption;
- Identify pathways for phasing out coal-fired generation and supporting the decarbonisation of the energy system;
- Support modernisation strategies and long-term planning aligned with national climate and energy goals.

Target Audiences:

- Ministry of Energy of Ukraine – for strategic energy planning and national policy development;
- National Power Company Ukrenergo – for grid development, system reliability, and renewable integration;
- State Agency on Energy Efficiency and Energy Saving of Ukraine – for policy planning on energy efficiency and RES deployment;
- Ministry of Communities, Territories and Infrastructure Development – for heating sector reform and infrastructure resilience;
- Regional and municipal authorities – for local energy planning and implementation of sustainable energy initiatives;
- Academic and research institutions – for modeling support, forecasting, and analysis of long-term trends;
- International partners and donor organizations – for supporting Ukraine's energy transition and investment strategies.

The model serves as a strategic planning tool to guide energy policy and investment decisions, ensuring a more secure, sustainable, and carbon-neutral energy future for Ukraine.

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6.3 Model scope and structure - updated

Table 12. Model scope and structure – Ukraine

	Scope v1.0	Detail version 1.0: OSeMOSYS	Scope v2.0	Detail version 2.0: EnergyPlan
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	Electricity and heat sectors	The model covers both electricity generation and district heat supply. It includes various generation technologies such as nuclear, thermal, CHP, boilers, and renewables (solar, wind, hydro, and pumped hydro), and also models the heat sector through CHP, boilers, and heat pumps.
Type of analysis	The search for the optimal number of generating capacities and their volumes related to the structure of electricity consumption in the period from 2019 to 2050.	Optimization of installed capacities and volumes of production of generating capacities depending on changes in the volume of electricity consumption	Scenario-based simulation	The model performs a scenario-based analysis using the EnergyPLAN tool, focusing on the current state (2025) and a projected future (2035). It allows for evaluation of energy balances, import needs, generation mix, capacity utilization, and integration of renewables under various policy and infrastructure assumptions.
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.	EnergyPLAN	EnergyPLAN models the operation of national energy systems on an hourly basis, including electricity, heating, cooling, industry and transport. In this study, the EnergyPLAN tool was used to model different scenarios for 2025 and 2035 years. https://www.energyplan.eu/
Open source code	Yes		No	
Open access data	Only the ones available on Zenodo	https://zenodo.org/records/16570539	Only the one available on Zenodo	https://zenodo.org/records/16570539
Documentation	No		Yes	https://doi.org/10.5281/zenodo.16541378

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				Model Documentation - Ukrainian Energy System in EnergyPLAN
Previous use	No		No	
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		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		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 resolution	National		National	
Time domain		2019 - 2050		Base year 2025 and three future scenarios for 2035
Time resolution	Intra-annual time steps	The following distribution of time intervals is used in the model: 12 months and 8 days are used, which represent different times of the day. They are as follows (where the numbers in brackets are the hours of the day): 1. Early morning (4-7) 2. Late morning (8 - 10) 3. Noon (11 - 13) 4. Afternoon time (14 - 17) 5. Early evening (18 - 19) 6. Middle evening (20 - 21) 7. Late evening (22 - 0) 8. Night (1 - 3)	Hour-simulation model	The tool uses distributions based on the hourly distribution of demand, generation plant operation, and other parameters throughout the year. Each data distribution should include 8784 data points, one for each hour.
Deterministic	Yes		Yes	
Dynamic	Yes		No	

Mathematical formulation	Linear program	A linear programming optimization model 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.	Rule-based technical simulation	The second version expanded the scope to include both electricity and heat demand. To avoid electricity overproduction, the simulation applied constraints such as increasing hydrogen production, shifting heat generation from CHP units to boilers, and reducing renewable energy generation when necessary.
Rationale	Optimisation		Simulation	
Technology richness	Bottom-up	The OSeMOSYS model was used because OSeMOSYS can capture the complex interactions and potential trade-offs between different energy technologies and resources. This contributed to the optimization of the Ukrainian energy system on the basis of cost minimization while complying with such limitations as meeting demand, availability of resources and environmental standards, a variety of energy generating facilities (nuclear power plants, thermal power plants, combined and heat power plants, hydroelectric power plants and others). The model uses 268 commodities and 321 technologies that reflect the relationships between different fuels, generating plants and electricity consumption sectors such as: Agriculture, Commercial and Public, Industry, Residential and Transport.	Bottom-up	EnergyPLAN employs a bottom-up modelling methodology that explicitly represents individual technologies with their technical parameters such as installed capacity, efficiency curves, ramp rates, minimum load, and maintenance schedules. In Ukraine's case, this involves detailed parametrisation of nuclear power plants, thermal power plants, combined heat and power units, renewable energy technologies including photovoltaic, wind turbines, hydroelectric and pumped storage plants, as well as heat generation technologies like boilers and heat pumps. This level of granularity enables precise simulation of sector coupling between electricity and heat, hourly balancing of supply and demand, and system flexibility under variable renewable generation. It facilitates rigorous evaluation of operational constraints and dynamic dispatch, critical for assessing peak load management, import dependency reduction, and integration of renewables

				under realistic operational conditions.
Solver(s) used	OSeMOSYS UI	Free of use	-	
Solution	The OSeMOSYS optimization process took 5 hours.	Processor: AMD Ryzen 7 5825U with Radeon Graphics (2.00 GHz) Installed RAM: 16 GB 64-bit operating system, x64-based processor	Collecting, verifying and updating data: 25 hours. Optimizations and modelling performed by the tool: 5 hours in total (all iterations)	Processor: AMD Ryzen 7 5825U with Radeon Graphics (2.00 GHz) Installed RAM: 16 GB 64-bit operating system, x64-based processor

6.3.1 Key data sources – updated

Table 13. Additional key data sources - Ukraine.

Dataset	Source	Open access
Electricity demand	Project of the Recovery Plan of Ukraine	https://www.kmu.gov.ua/storage/app/sites/1/recoveryrada/ua/energy-security.pdf
Electricity demand distribution	National Power Company Ukrenergo	https://map.ua-energy.org/uk/resources/8998f2ed-379f-4fa9-9076-88782b32ee4f/
District heat demand	State Statistics Service of Ukraine International Energy Agency. Ukraine annual questionnaire electricity & heat (Confidential data)	https://map.ua-energy.org/en/resources/bb00fd93-8e0f-4d8b-9bb6-ba4e3f01eb48/
Individual heat demand	Energy balance of Ukraine, International Energy Agency. Ukraine annual questionnaire electricity & heat (Confidential data)	https://www.ukrstat.gov.ua/operativ/menu/menu_u/energ.htm
Industry fuel consumption	Energy balance of Ukraine, International Energy Agency. Ukraine annual questionnaire electricity & heat (Confidential data)	https://www.ukrstat.gov.ua/operativ/menu/menu_u/energ.htm
Transport fuel consumption	Energy balance of Ukraine, International Energy Agency. Ukraine annual questionnaire electricity & heat (Confidential data)	https://www.ukrstat.gov.ua/operativ/menu/menu_u/energ.htm
Boilers capacity	State Statistics Service of Ukraine	https://map.ua-

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		energy.org/en/resources/312022cb-2edb-4f37-b326-6d5eff089353/
Boilers fuel consumption	State Statistics Service of Ukraine	https://ukrstat.gov.ua/operativ/operativ2012/pr/etgv/etgv_u/ok_tm_11u.html
Combined heat and power capacity	State Statistics Service of Ukraine	https://map.ua-energy.org/uk/resources/2b8e4841-474d-49b7-930f-ed48610868f1/
Combined heat and power fuel consumption	Ministry of Energy of Ukraine	https://map.ua-energy.org/en/resources/32991d98-8e92-463d-b25c-5790f7a35fca/
Thermal power plants capacity	National Power Company Ukrenergo	https://map.ua-energy.org/uk/resources/c51a16bc-e990-40db-b790-63624d823daa/
Thermal power plants fuel consumption	Ministry of Energy of Ukraine	https://map.ua-energy.org/en/resources/32991d98-8e92-463d-b25c-5790f7a35fca/
Nuclear power plants capacity	Energoatom National Nuclear Power Company State Enterprise	https://www.energoatom.com.ua/en
Nuclear power plants production distribution	National Power Company Ukrenergo	https://map.ua-energy.org/uk/resources/8998f2ed-379f-4fa9-9076-88782b32ee4f/
Hydro power plant capacity	National Power Company Ukrenergo	https://map.ua-energy.org/uk/resources/c51a16bc-e990-40db-b790-63624d823daa/
Hydro power plant production distribution	National Power Company Ukrenergo	https://map.ua-energy.org/uk/resources/8998f2ed-379f-4fa9-9076-88782b32ee4f/
Pumped Storage Power Plant capacity	National Power Company Ukrenergo	https://map.ua-energy.org/uk/resources/c51a16bc-e990-40db-b790-63624d823daa/
Pumped Storage Power Plant production distribution	National Power Company Ukrenergo	https://map.ua-energy.org/uk/resources/8998f2ed-379f-4fa9-9076-88782b32ee4f/
Wind turbines capacity	National Power Company Ukrenergo	https://map.ua-energy.org/uk/resources/c51a16bc-e990-40db-b790-63624d823daa/
Wind turbines production distribution	Renewables.ninja	https://www.renewables.ninja/
Photo Voltaic capacity	National Power Company Ukrenergo	https://map.ua-energy.org/uk/resources/c51a16bc-e990-40db-b790-63624d823daa/
Photo Voltaic production distribution	Renewables.ninja	https://www.renewables.ninja/
Transmission line capacity	National Power Company Ukrenergo	https://ua.energy/
Electricity storage	Project of the Recovery Plan of	https://www.kmu.gov.ua/storage/app/sites/1/

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capacity	Ukraine	recoveryrada/ua/energy-security.pdf
Fuel storage capacity	Energy balance of Ukraine International Energy Agency. Ukraine annual questionnaire electricity & heat (Confidential data)	https://www.ukrstat.gov.ua/operativ/menu/menu_u/energ.htm
Combined heat and power, Thermal power plants, boilers, wind turbines, solar panel cost	Danish Energy Agency. Technology Data - Energy Plants for Electricity and District heating generation	https://ens.dk/en/analyses-and-statistics/technology-data-generation-electricity-and-district-heating
Hydro power plant, Pumped Storage Power Plant cost	International Renewable Energy Agency. Renewable energy technologies: cost analysis series	https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-HYDROPOWER.pdf
Heat pump, Nuclear power plant cost	Nordic Energy Research. Technology catalogue	https://www.nordicenergy.org/wordpress/wp-content/uploads/2021/09/Technology-Catalogue.pdf
Fuel prices	The TYNDP 2020 Final Scenario Report	https://2020.entsos-tyndp-scenarios.eu/fuel-commodities-and-carbon-prices/

6.4 Reference system – updated

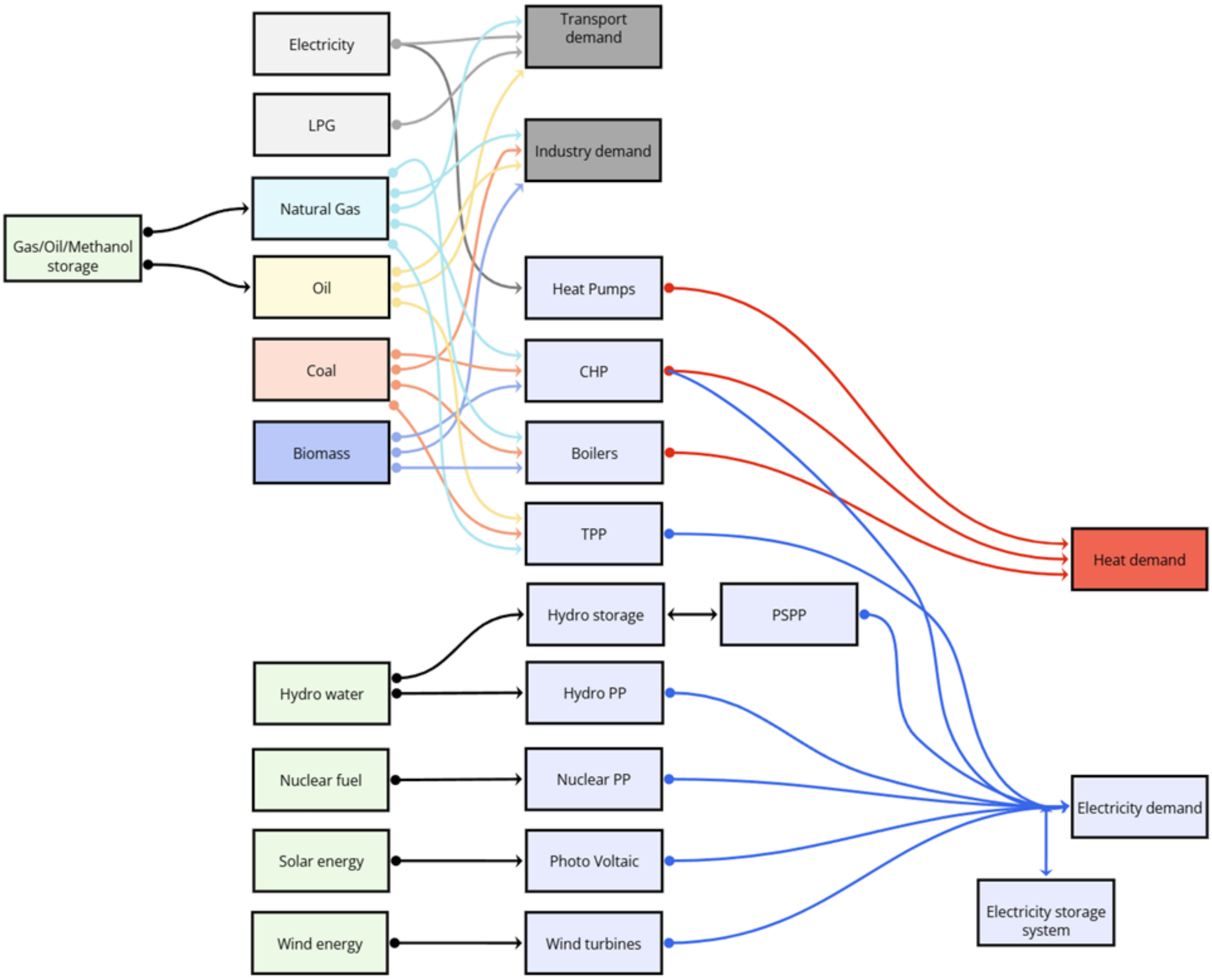

Figure 29. Reference energy system - Ukraine update.

6.5 Scenarios

The case study of Ukraine was the only one that adopted a completely different methodology with respect to the fist modelling cycle. The following section summarizes the main assumptions adopted and scenarios modelled in the second modelling cycle.

Table 14. Scenarios - Ukraine, EnergyPlan

Name	Description
Baseline (2025 and 2035)	• The war ends by 2026, Ukraine retains its pre-2022 territory with strong security guarantees but Russia remains unaccountable for invasion, and a risk of new war persists. • Medium-fast adoption of the EU acquis by Ukraine, Ukraine joins the EU by 2035. • Fast deployment of VRE, energy storage, and ultra flexible power generation to ensure the security, resilience, and sustainability targets.

	• Coal-fired power generation fleet was replaced by distributed energy resources. • Phasing out energy price subsidies in gas, heat, and electricity sector by 2030. Prices of gas and electricity reflect market value by 2030 which speeds up the heat pumps and biomass deployment in individual and district heating. • The electric vehicles fleet increases to 465 thousand by 2035. • Feasibility studies for hydrogen deployment are well developed but the construction has only begun by 2035.
Pessimistic	• The war ends by 2027. Ukraine controls only the territory it held as of 2025, but returns its control over Zaporizhzhia. It receives only poor security guarantees from allies, Russia remains unaccountable and militarised, and the risk of a new war remains very high. • Slow adoption of the EU acquis by Ukraine, Ukraine still negotiates the EU accession in 2035. • Slow deployment of VRE, energy storage, and ultra flexible power generation. • Coal-fired power generation fleet is partially restored (5 GW) and remains operational by 2035. • Residential energy prices continue to be subsidised. Slow heat pumps and biomass deployment. • The electric vehicles fleet increases to 300 thousand by 2035. Only feasibility studies for hydrogen deployment are completed and the technology is not competitive due to high costs and lack of incentives from the state and support from the EU funds
Optimistic	• The war ends by 2026, Ukraine retains its pre-2022 territory with strong security guarantees which leads to sustainable peace, and risk of new conflict is minimised. • Very fast adoption of the EU acquis by Ukraine, strong EU political will, Ukraine joins the EU by 2032. • Fast deployment of VRE, energy storage, and ultra flexible power generation to ensure the security, resilience, and sustainability targets. • Coal-fired power generation fleet is replaced by distributed energy resources combined

	with energy storages and peak-load gas generation. • Phasing out energy price subsidies in gas, heat, and electricity sector by 2030. Prices of gas and electricity reflect market value by 2030 which speeds up the heat pumps and biomass deployment in individual and district heating. • The electric vehicles fleet increases to 1,080 thousand by 2035. • First hydrogen capacities were completed, which enables to reach of 0.3 Mt per year (Mtpa) of clean hydrogen production by 2035.

Additional information in support of the updated energy system. The updates reflect refined data availability, improved demand projections, and the integration of post-war recovery dynamics:

- **Electricity and Heat Demand.**

  By 2035, under the baseline scenario, electricity demand is expected to grow to 159 TWh/year, driven by economic recovery, electrification of energy demand, and infrastructure development. Meanwhile, heat demand remains stable at 126 TWh/year, as improvements in efficiency and building insulation offset expansion in residential and industrial heating needs.

- **Fuel Consumption in the Transport Sector.**

  In the 2035 baseline scenario, fuel demand rises substantially to 137 TWh/year. This growth reflects the anticipated expansion of the transport sector, increased private vehicle fleet, and intensified freight activity, all correlating with broader economic development trends.

- **Fuel Consumption in the Industry Sector.**

  The 2035 baseline scenario forecasts this figure to increase to 70 TWh/year, indicating a significant recovery and revitalisation of industrial activity, aligned with national reconstruction efforts and economic resurgence.

- **Combined Heat and Power & Boilers.**

  The updated model included both CHP and boiler heat capacities, confirming the CHP electrical capacity at approximately 2.9 GW, based on more accurate and recent data. By 2035, the baseline scenario assumes an increase in CHP electrical capacity to 3.1 GW, supported by modernisation and rehabilitation of existing plants. Additionally, the scenario assumes a complete phase-out of coal in CHP plants, replaced by natural gas and biomass, in line with decarbonization policies and sustainability goals.

- **Thermal Power Plants and Nuclear Power Plants.**

  In the baseline scenario, thermal capacity is projected at 4.0 GW, serving as flexible (peaking) generation. These plants are assumed to operate exclusively on natural gas, ensuring lower emissions and improved adaptability to variable renewable energy output. The capacity of nuclear power plants (NPPs) remains largely unchanged between the initial and revised 2025 models, both maintaining a level of 7.8 GW. However, it is assumed that Ukraine will have regained operational control over the Zaporizhzhia Nuclear Power Plant, currently under occupation. As a result, the total nuclear capacity is projected to reach approximately 13.8 GW by 2035, reflecting a significant enhancement in baseload, low-carbon electricity generation.

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- **Renewable Energy Sources**

  Renewable energy capacities underwent the most dynamic changes across the modelling iterations. In the revised model, solar capacity increased significantly to 8.1 GW, while wind capacity declined to 0.5 GW. These variations reflect wartime impacts: many wind installations located near front-line zones were destroyed or rendered inoperable due to occupation, while solar power expanded rapidly due to its decentralised nature and ease of deployment. Governmental incentives and accessible credit programs further accelerated the adoption of solar PV by both households and public institutions. In the 2035 baseline scenario, rapid growth in renewable capacity is anticipated, with targets set at 20 GW of solar PV and 16 GW of wind power, supporting Ukraine's decarbonisation trajectory and energy independence.

- **Energy Storage Systems.**

  The 2035 baseline scenario anticipates further scaling of storage systems to at least 2 GW, depending on the scenario assumptions, supporting grid stability and the integration of variable renewable energy.

6.6 Final results and main insights

Results of the 2025 baseline simulation

The simulation of Ukraine's energy system for the base year 2025 produced the following key insights:

- Electricity balance and import needs
  Given an annual electricity demand of approximately 113 TWh, domestic generation capacities are able to meet only 92% of this requirement. Consequently, the model indicates a shortfall of nearly 10 TWh, which would need to be covered through electricity imports.

- Heat supply coverage
  The total demand for centralised heat supply is fully met by the operation of Combined Heat and Power (CHP) plants and heat-only boilers. CHP installations account for approximately 87% of the heat supply, while boilers provide the remaining 13%.

- Role of nuclear power
  Nuclear power plants represent the cornerstone of Ukraine's power system, both in terms of installed capacity and electricity output. In 2025, they are responsible for generating nearly 50% of the country's total electricity supply.

- Stress on thermal power plants
  The system shows a high utilisation rate of Thermal Power Plants (TPPs), which operate at approximately 84% of their maximum capacity. Given the aging infrastructure and the technical condition of these plants, such intensive use limits opportunities for scheduled maintenance and increases the risk of unexpected outages. This places further pressure on the system and increases dependence on electricity imports.

- Transmission capacity constraints
  To accommodate the projected 10 TWh of electricity imports and ensure system reliability during peak demand periods, the available transmission line capacity—currently 2.3 GW—must be expanded to 6.9 GW. This upgrade is essential to avoid bottlenecks and maintain security of supply.

Results of the 2035 baseline scenario simulation

The 2035 projection represents a more balanced and resilient configuration of Ukraine's energy system, with key improvements in domestic generation capacity, reduced import dependency, and a notable increase in renewable energy integration:

- Electricity balance and export potential

With projected electricity demand reaching 159 TWh, domestic generation is capable of meeting nearly the entire demand. The model indicates a minimal import requirement of only 1 TWh, suggesting an enhanced security with a high degree of energy self-sufficiency.

Moreover, Ukraine emerges as a potential net electricity exporter, with modeled export capacity reaching up to 11 TWh per year, provided favourable market and infrastructure conditions.

- Renewable energy contribution

The share of electricity generated from renewable energy sources — including solar PV, wind power, hydropower, and pumped storage — reaches 37% of total electricity domestic supply. This reflects a significant shift toward sustainable energy and diversified generation.

- Role of nuclear power

Nuclear power plants remain the backbone of the electricity sector, covering approximately 58% of total production. This outcome is both technically feasible and consistent with Ukraine's long-term energy strategy.

- Evolving role of thermal power plants

Thermal power plants (TPPs) transition from serving as baseload generators to becoming flexible, load-following units, helping to manage peak loads and system variability. Current coal-fired fleet mostly destroyed or severely damaged by Russian missile attacks was mostly built in 50-70s of the previous century and passed its projected life-time long time ago. The electrical efficiency of it was just 30-33% before the invasion. Coal-fired power plants worked both in the baseload as well as were used to cover the part of peak load demand. It is more cost-efficient to deploy more efficient ultra-flexible gas units and power storages to meet only the peak load demand as well as install variable renewables for the base load in a bundle with power storages than restore these outdated coal capacities. Thus, the average annual capacity factor of TPPs drops to 41%, compared to 84% in the 2025 baseline. This reduced load not only lowers operational stress but also allows for more frequent maintenance and extends plant lifespans.

- Transmission system adequacy

Despite improved system balance, occasional reliance on imports during peak hours necessitates upgrading border transmission line capacity from the planned 4.9 GW to 5.8 GW to accommodate occasional imports, enable exports, and maintain grid stability during high variability periods. This expansion ensures sufficient import/export flexibility and strengthens grid reliability.

- CHP and heat supply optimisation

The model shows a reduced reliance on CHP plants, many of which are aged and in deteriorating condition. In response, heat-only boilers and electric heat pumps take on a larger share of heat production. These technologies offer greater flexibility, are more cost-effective to maintain and replace, and contribute to a more resilient heat supply system.

- Overall system performance

While minor challenges remain in meeting electricity demand during peak periods, the average load levels of CHP, TPP, and nuclear power plants are within manageable ranges. This operational margin enables scheduled maintenance and reduces the risk of outages or emergency imports. The overall system shows enhanced technical sustainability, flexibility, and resilience compared to the 2025 baseline.

Annual CO_2 emissions are projected at 92 million tonnes, while annual investment requirements are estimated at $9 billion (in constant 2025 prices). This highlights not only the scale of the transformation but also the substantial capital intensity involved in modernising Ukraine's energy infrastructure and achieving long-term decarbonisation goals.

Results of the 2035 pessimistic scenario simulation

Compared to the baseline 2035 scenario, electricity demand in the pessimistic scenario is lower, amounting to 136 TWh/year. Electricity imports are almost negligible, reaching just 0.12 TWh/year, indicating that domestic generation is sufficient to meet national electricity demand. However, CO_2 emissions are expected to be 7% higher than in the baseline scenario despite 9% lower electricity generation due to a greater reliance on coal-fired power plants.

The role of renewable energy sources is significantly reduced. In this scenario, renewables account for only 23.9% of electricity generation, compared to 36.7% in the baseline case.

This decrease in renewable share is primarily due to significantly lower installed variable renewable capacities—12 GW of solar and 4.5 GW of wind, respectively — compared to the planned 20 GW and 16 GW in the baseline scenario.

Although annual electricity imports remain well below 1 TWh/year, the available domestic generation capacity is insufficient to meet peak demand compromising energy security of the country. As a result, the required import capacity must reach around 3 GW, exceeding the agreed with the ENTSO-E transmission line capacity of 2.3 GW for 2023.

Overall, while the system is capable of meeting most of the country's electricity and energy consumption needs, it falls short of achieving Ukraine's national energy strategy targets — particularly the goal of reaching a 27% share of renewable energy in electricity generation.

Total annual CO_2 emissions and needed annual investments are reaching 98 Mt and constant 2025 $8 bn in this scenario.

Results of the 2035 optimistic scenario simulation

According to the modeling results for the optimistic scenario, electricity consumption is projected to reach 175 TWh/year by 2035 — an increase of over 55% compared to 2025 levels. An increase in demand stems primarily with faster economic growth and consequently higher electricity demand in industry, much higher number of EV purchased and bigger number of appliances as well as electrification of energy demand in residential sector. The higher CO_2 emissions are lower than in all other scenarios, including the 2025 baseline, primarily due to the complete phase-out of coal in electricity generation.

The share of electricity produced from renewable energy sources (excluding nuclear) rises to 44%, which exceeds the national target of 27% by 2030. This is enabled by significant additional generation capacity, especially in solar (PV) and wind power, as well as the integration of electrolysis units. These developments support annual hydrogen production at a level of approximately 300,000 tones.

Furthermore, Ukraine is projected to become a net electricity exporter, with export volumes reaching 16 TWh/year, while import needs are limited to just 0.31 TWh/year.

The planned cross-border transmission line capacity of 4.9 GW fully meets the system's maximum capacity requirements for both imports (4.6 GW) and exports (4.9 GW), enabling a flexible response to peak load conditions and supports regional electricity trade.

The average annual load factors for combined heat and power (CHP) plants and thermal power plants (TPPs) are projected at 24% and 32%, respectively. These levels allow for routine maintenance and modernisation of aging infrastructure, which is crucial for ensuring long-term operational reliability while reducing operational costs.

Additionally, the average winter load for CHP and boiler systems used for heat production is estimated at 48%

and 19%, respectively. These values indicate that CHP and boiler systems have sufficient capacity to meet growing heat demand during peak periods, ensuring uninterrupted heat supply to the population even during extreme weather or supply disruptions.

Overall, the optimistic scenario reflects a positive outlook for Ukraine's energy system. It supports growing electricity demand through domestic generation, establishes Ukraine as an energy exporter, and ensures system flexibility for planned maintenance without major risks of blackouts or import dependency.

Total annual CO_2 emissions and needed annual investments are reaching 91 Mt and constant 2025 $11 bn in this scenario.

Table 15 Summary of results from the EnergyPLAN model and scenarios.

Parameter values according to EnergyPLAN (TWh/year)	2025 Basic Scenario	2035 Pessimistic Scenario	2035 Basic Scenario	2035 Optimistic Scenario
Electricity Demand	113	136	159	175
District Heating Demand	75.09	74.67	74.67	74.67
River Electr.	4.04	6.38	5.93	5.44
PV Electr.	8.73	13.01	19.89	23.11
Wind Electr.	0.91	8.12	28.82	53.87
Hydro Electr.	1.32	3.35	4.57	6.08
Hydro pump	0.02	0.48	2.38	4.75
Hydro Wat-Sup	1.63	3.8	3.8	3.8
CHP 2 Heat	65.35	54.7	49.92	37.89
HP 2 Heat		3.64	4.73	6.93
Boiler 2Heat	9.74	16.34	20.02	29.85
FlexibleElectr.		0.9	1.4	3.24
HP Electr.		1.33	1.93	2.67
CHP Electr.	9.8	8.67	8.79	6.68
PP2 Electr.	26.68	16.45	14.43	11.3
Nuclear Electr.	52.01	91.84	91.84	106.98
Charge2Electr.		0.01	0.23	0.67
Discharge2Electr.			0.16	0.48
H2 Electr.				11.76
HH-HP Electr.		0.12	0.36	0.36
HH Dem.Heat	69.84	70.95	71.67	71.67
HH CHP+HPHeat		0.36	1.07	1.07
HH Boil.Heat	69.84	70.6	70.6	70.6
Import Electr.	9.87	0.12	1.16	0.31
Export Electr.	0.35	9.22	10.67	16.16
EEEP Electr.	0.35	9.22	10.67	16.16
H2 prod.				10
H2 export				10

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Annex: List of abbreviations

Abbreviation	Definition
CLEWs	Climate-Land-Energy-Water systems
BHI	Biodiversity Habitat Index
NDC	National Determined Contributions
LTLEDS	Long Term Low Emission Development Strategies
IDR	Import Dependency Ratio
CHP Plant	Combined Heat and Power plant
TPP	Thermal Power Plants
PV	Photo Voltaic
NPP	Nuclear Power Plant