Helmholtz Open Models and Data in Energy Systems Analysis

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Abstract

The transition to a sustainable and resilient energy system is a cornerstone of contemporary climate- and environmental policy, yet the growing electrification of transport, heating, and industry simultaneously raises electricity demand and amplifies sectoral interdependencies, thereby increasing system complexity. Addressing this complexity requires energy-systems modelling tools that are both comprehensive and computationally tractable. This report gives concrete applications of the three current, interlinked advances that are reshaping the modelling landscape: (i) the need for high-quality, FAIR-compliant data to overcome fragmentation, proprietary restrictions, and inconsistencies; (ii) the shift toward collaborative, open-source modelling practices that enable multidisciplinary teams to share code, lower entry barriers, and ensure reproducibility; and (iii) the harmonisation of model outputs through the Open Energy Ontology (OEO), which provides explicit variable definitions and facilitates cross-model comparison.

The Helmholtz Association curates and sustains open-data sets and open-source models that adhere to FAIR principles and serve as benchmarks for the broader community. The present document provides a structured overview of these resources generated by the German Aerospace Center (DLR), Forschungszentrum Jülich (FZJ), and the Karlsruhe Institute of Technology (KIT), i.e. open-source modelling frameworks, energy-system models (including economic extensions), and auxiliary tools as well as the associated open databases. Each entry is summarised in a standardized scheme facilitating rapid discovery via the Helmholtz Research Software Directory (HRSD). By consolidating data stewardship, collaborative development, and ontological standardisation, the Helmholtz-backed resources empower researchers, industry, and policymakers to base decisions on robust, comparable, and transparent energy-systems analyses.

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1. Introduction

Energy is indispensable for modern economies and societies, yet its production and consumption continue to generate substantial climate and environmental impacts. As a result, the energy system occupies a central position in the transition toward a sustainable and resilient future. Transforming the technical infrastructure inevitably influences economic and social options, while society itself acts both as a driver of, and a potential obstacle to, this transition.

Recent developments have intensified the interaction among all economic sectors, largely because of the strong electrification of transport, heating, and industry. This electrification raises electricity demand even as total primary energy demand falls, thanks to improved energy efficiency. However, the increasing integration of sectors – combined with heightened awareness of societal effects – adds considerable complexity to the overall system.

The energy systems modelling community is responding to this complexity by creating comprehensive models and coupling strategies that preserve reasonable runtimes. These sophisticated computational tools are challenging to develop and apply, prompting researchers to collaborate more closely on three interrelated fronts:

1. **Data acquisition and quality** – The current data foundation for energy systems modelling remains fragile. Issues include limited comparability, poor documentation, proprietary restrictions, and the presence of missing, erroneous, outdated, or inconsistent records. Moreover, most datasets do not comply with the FAIR principles (Findable, Accessible, Interoperable, Reusable). Adopting FAIR standards (which includes open-data) would markedly accelerate data sharing and simplify its reuse (Wilkinson et al., 2016).
2. **Collaborative modelling practices** – Complex research questions can no longer be tackled by individual scientists. Instead, multidisciplinary modelling teams are required, and the sharing of codebases has become essential to lower entry barriers for new contributors. Over the past decade, the energy modelling community has embraced open-source development, fostering transparency and reproducibility.
3. **Harmonisation of model outputs** – Comparing results across different models has traditionally been difficult. The Open Energy Ontology (OEO) addresses this challenge by providing explicit definitions for key variables, thereby standardising both input and output data and facilitating cross model interpretation.

These advances – improved data stewardship, opensource collaborative modelling, and the adoption of common ontologies – make it easier for researchers, industry, and policymakers alike to base decisions on robust, comparable, and transparent results.

To address these issues, the Helmholtz Association creates, curates, and sustains high-quality open-data sets and open-source models whenever feasible. The resulting resources are valuable to the entire energy-modelling ecosystem and can serve as reference benchmarks for data and model comparison. Most of these provided data and models are compliant with the FAIR principles.

Hence, this report presents an overview of open-source models and data produced by Helmholtz partner institutions – the German Aerospace Center (DLR), Forschungszentrum Jülich (FZJ), and the Karlsruhe Institute of Technology (KIT). Funding for these developments is provided primarily by the Helmholtz Energy Systems Design Programme.

The document is organized into two principal parts (cf. Figure 1). The first part (Chapter 2) surveys the open-source models and frameworks, which are divided into three sub-sections: (1) basic modelling frameworks, (2) energy-system models and their extensions and applications for specific use cases, and (3) additional openly available tools, including so-called “input models”. Chapter 3 then describes the open energy-systems databases that have been assembled. Within this structure, we further differentiate between techno-economic energy-system models and those with a stronger economic orientation (cf. Figure 1). Figure 2 integrates already all considered models and data in this schema of Figure 1 and refers to the specific chapters.

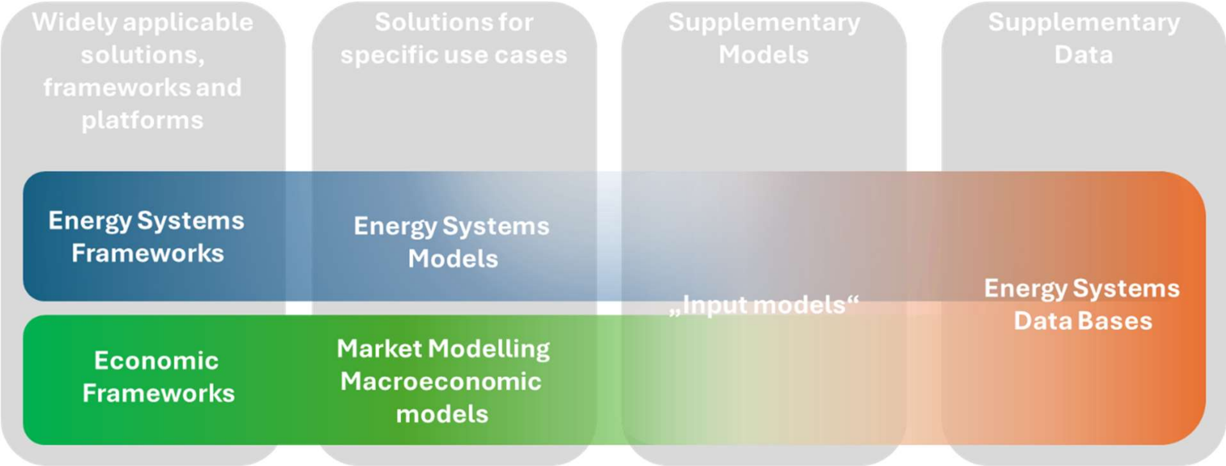

Figure 1: Overview of model categories

For each open model, tool or data set the report provides a concise "overview scheme" (Table 1). The scheme lists the name, a brief description, relevant tags, a link to the **Helmholtz Research Software Directory (HRSD)**, core references, and the principal partners involved. Hence, the HRSD is the cornerstone of all these open-source models. The header is colored according to the correspondent scheme in Figures 1 and 2: blue for energy-system frameworks or models, green for economic models, and orange for data-centric items.

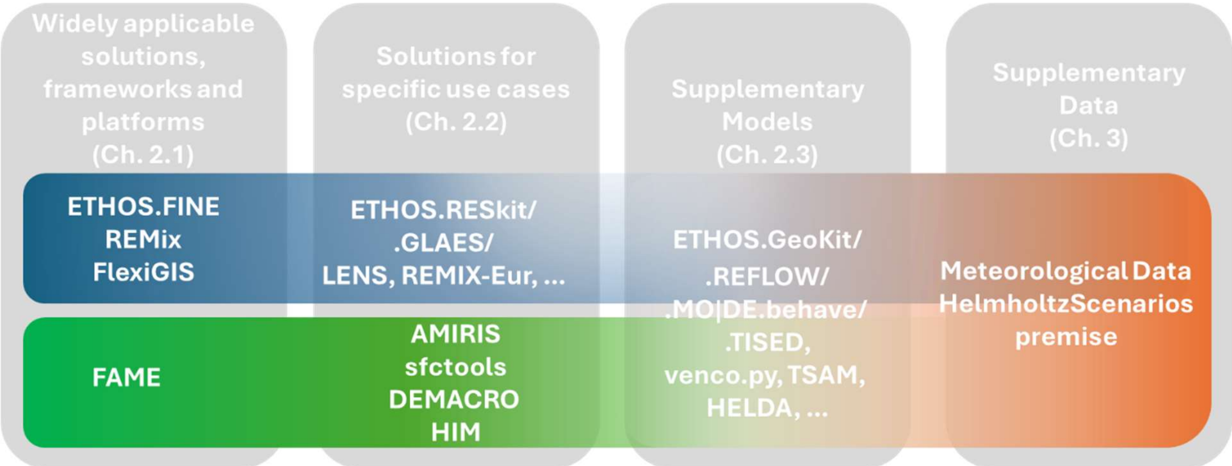

Figure 2: Overview of considered open-source models and data

The dedicated direct link to the HRSD (https://helmholtz.software) provides an easy and low-threshold access and allows a simple application of all models and frameworks. For some models, further information and issues are publicly available on platforms such as Zenodo, GitLab or GitHub. Hence, the HRSD offers a convenient entry point for further information on these tools or even other tools not included in this report. Detailed documentation is typically hosted in the individual repository.

Table 1: Overview scheme for all open models and data

Framework NAME **Short sentence or full form of abbreviation**	**Tags**
Short description	
Link to HRSD: https://helmholtz.software/software/XYZ **Main reference:** core reference **Core partners:** Institute	

This document and milestone report presents initial open-source solutions from the Helmholtz Energy System Design (ESD) Program – Topic 1. Similarly to our report, there is another report on more technically oriented models by Topic 2 (cf. Förderer et al., 2026).

2 Open-Source Models and Frameworks

Chapter 2 surveys the open-source models and frameworks, which are divided into three sub-sections: (1) basic modelling frameworks, (2) energy-system models and their extensions and applications for specific use cases, and (3) additional openly available tools, including so-called "input models".

2.1 Energy Systems Frameworks

2.1.1 REMix

REMix *REMix is a comprehensive optimization framework for complex energy systems*	**Framework Model**
The **REMix** framework is capable of capturing the complexities of various temporal, spatial, and technological scales and details in energy systems (Wetzel et al. 2024). This flexible tool enables researchers and practitioners to model a wide range of processes involved in the energy system, including extraction, storage, conversion, transfer, and demand for different energy carriers such as electricity, gases, or heat.	
Link to HRSD: https://helmholtz.software/software/remix **Repository:** https://gitlab.com/dlr-ve/esy/remix/framework **Main reference:** Wetzel, M., Ruiz, E.S.A., Witte, F., Schmugge, J., Sasanpour, S., Yeligeti, M., Miorelli, F., Buschmann, J., Cao, K.-K., Wulff, N., Gardian, H., Rubbert, A., Fuchs, B., Scholz, Y., Gils, H.C., 2024. REMix: A GAMS-based framework for optimizing energy systems models. JOSS 9, 6330. https://doi.org/10.21105/joss.06330 **Core partners:** DLR, University of Canterbury,	

REMix is a versatile and comprehensive framework for modeling energy systems, capable of capturing the complexities of various temporal, spatial, and technological scales and details (Wetzel et al. 2024). It allows to model a wide range of processes involved in the energy system. One of the key strengths of REMix is its ability to link various energy system components together, allowing users to analyze the interactions and interdependencies between different parts of the system. This includes modeling the flow of energy from primary sources (e.g., fossil fuels, renewable energy) through conversion processes (e.g., power plants, refineries) to end-use applications (e.g., transportation, industry, buildings).

The framework also enables users to characterize each process with relevant indicators such as costs or CO_2 emissions, providing a comprehensive understanding of the economic and environmental implications of different energy system configurations. The mathematical core of REMix supports both integer and continuous decision variables, allowing for a high degree of flexibility in modeling different types of energy system decisions.

The objective function in REMix can include one or more indicators, such as minimizing costs or reducing CO_2 emissions, enabling users to optimize the energy system design based on specific goals or priorities. This makes it an ideal tool for evaluating different energy policy scenarios, assessing the impact of new technologies or infrastructure investments, and identifying trade-offs for example between ecological, economic, and resilience indicators using multi-criteria optimization.

REMix can be applied to model energy system infrastructures at various scales, from regional to continental systems, and can be used to analyze both economic dispatch and capacity expansion planning. This includes evaluating the optimal operation of existing energy infrastructure, as well as planning for future capacity expansions or upgrades to meet changing energy demand or policy requirements. So far, the focus of REMix application is on large models with high spatial and technological resolution.

REMix supports multi-year analyses with and without temporal foresight. With that, the framework is particularly well-suited for researching the transformation of energy systems towards a climate-neutral energy supply, which is a critical goal for many countries and regions around the world. By modeling different scenarios and pathways for achieving this goal, REMix can help policymakers, researchers, and industry stakeholders to identify the most effective strategies for reducing greenhouse gas emissions and promoting sustainable energy development.

Some potential applications of REMix include:

1. **Energy policy analysis**: REMix can be used to evaluate the impact of different energy policy scenarios on the energy system, including the effects of carbon pricing, renewable portfolio standards, or energy efficiency targets.
2. **Infrastructure planning**: The framework can help planners and investors to identify optimal locations and designs for new energy infrastructure, such as wind farms, solar parks, or transmission lines.
3. **Technology assessment**: REMix can be used to evaluate the potential benefits and challenges of emerging energy technologies, such as hydrogen fuel cells, advanced nuclear power, or carbon capture and storage.

The latest version of REMix has been published open source (Wetzel et al., 2024). Recent applications focus on the planning of hydrogen infrastructure in Europe (Wetzel et al., 2023, 2026), the assessment of the economic potential of Carnot Batteries (cf. Nitsch et al., 2024), the exploration of large scenario spaces (Frey et al., 2025), model speed-up strategies (Wetzel et al., 2025), and resilience analysis (Alé et al., 2026). Earlier versions have been used in comprehensive model comparisons (Gils et al., 2022a, 2022b), the assessment of sector coupling (Gils et al., 2021; Wulff et al., 2025), electricity grid (Cao et al., 2021) and energy storage (Moser et al., 2020), energy policy analysis (Sasanpour et al., 2021), the evaluation of model speed-up strategies (Cao et al., 2019) and many others. REMix-Eur, which is focusing on Europe (Gils et al., 2025), is not open source, yet.

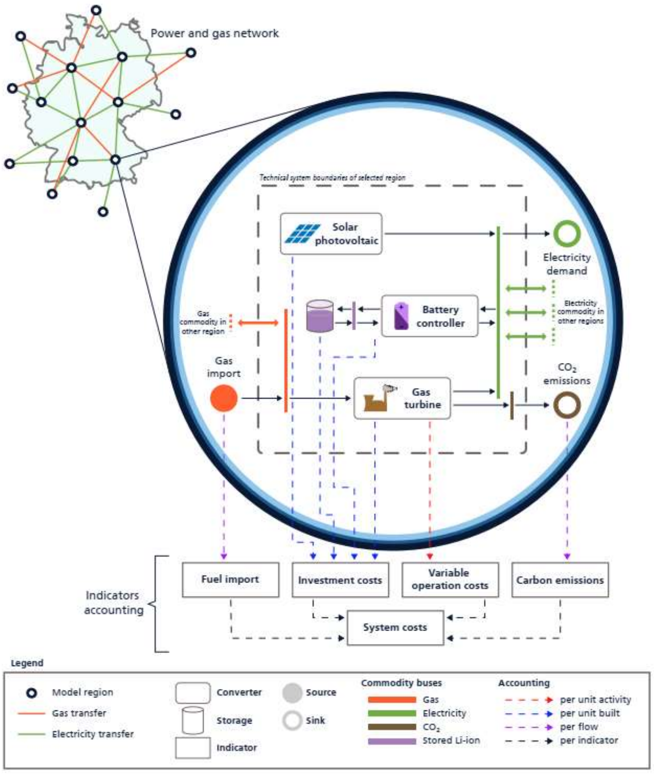

Figure 3: Outline of the REMix Framework (Source: DLR-VE)

2.1.2 ETHOS.FINE

ETHOS.FINE *Framework for Integrated Energy Systems Assessment*	**Framework Model**

ETHOS.FINE enables the users to model, optimize and assess energy systems with multiple regions, commodities, time steps and investment periods. The target of optimization is the minimization of the net present value.

Link to HRSD: https://helmholtz.software/software/ethosfine-framework-for-integrated-energy-system-assessment
Repository: https://github.com/FZJ-IEK3-VSA/FINE
Main reference:
Klütz, T., Knosala, K., Behrens, J., Maier, R., Hoffmann, M., Pflugradt, N., Stolten, D., 2025. ETHOS.FINE: A Framework for Integrated Energy System Assessment. JOSS 10, 6274. https://doi.org/10.21105/joss.06274
Core partners: FZJ

ETHOS.FINE enables the users to model, optimize and assess energy systems with multiple regions, commodities, time steps and investment periods (Klütz et al., 2025). To set up an energy system model, the modeler can combine components from various object classes. These classes consist of sources and sinks that can be used to depict imports and demands, conversion processes to model, e.g., powerplants, transmissions to connect different nodes or regions that enable the exchange of energy carriers, and storages for balancing the system over time (see Figure 4). The generic, objectoriented- implementation supports arbitrary spatial scales and any number of regions – from the local level, e.g., individual buildings, to the regional level, e.g., districts or industrial sites, to the national and international levels.

To reduce model complexity, the modelers can use the built-in aggregation methods for the aggregation of the spatial and technological resolution (Patil et al., 2022) or for the aggregation of the temporal resolution using the built-in python package tsam (Hoffmann et al., 2022),which supports the aggregation of time steps to typical periods, the segmentation of the time series and the combination of both. Transformation pathways can be investigated by considering multiple investment periods in a perfect foresight approach. Additionally, the framework allows the stochastic optimization for a single year optimization with multiple sets of input parameters to find more robust energy system designs.

Recent applications include analyses of the impact of weather conditions on the optimal location selection for direct air capture (Wenzel et al., 2025), the impact of foresight horizons on decarbonization trajectories (Maier et al., 2025), and participatory mapping of local cost potentials for green hydrogen in sub-Saharan Africa (Winkler et al., 2025).

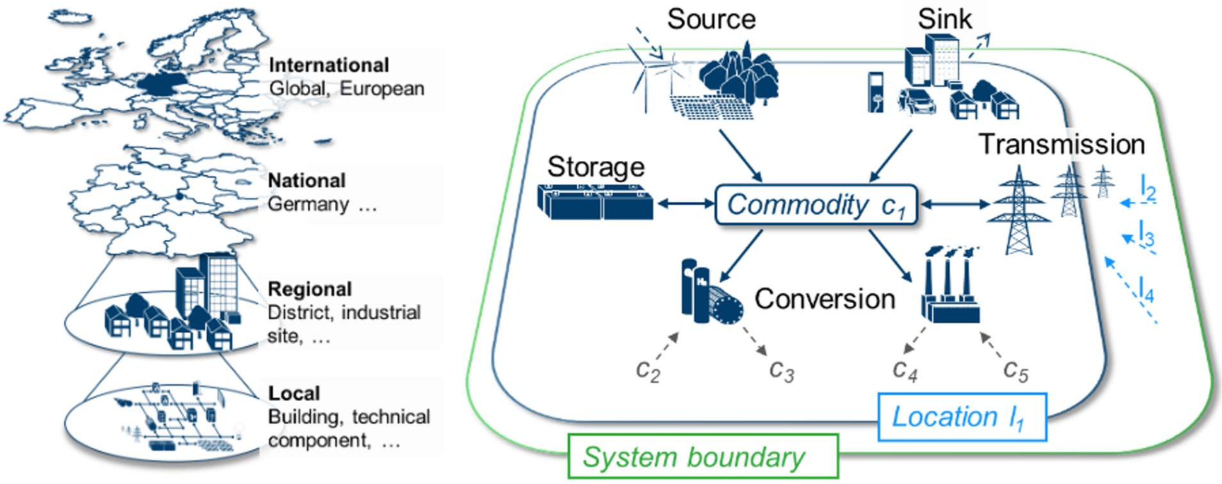

Figure 4. Application cases and outline of the framework ETHOS.FINE (Source: FZJ-ICE-2)

2.1.3 FlexiGIS

FlexiGIS *Flexibilisation in Geographic Information Systems*	**Framework Model**

The **FlexiGIS** framework for developing linear optimisation models of urban systems consists of a collection of mutually compatible source codes required for a particular model, which can be combined in a modular way. This modular structure allows the reuse of the same modelling concepts and associated source codes to address different research questions, all based on a common set of model features.

Link to HRSD: https://helmholtz.software/software/flexigis

Main reference:

Alhamwi, A., Medjroubi, W., Vogt, T., Agert, C., 2017. GIS-based urban energy systems models and tools: Introducing a model for the optimisation of flexibilisation technologies in urban areas. Applied Energy 191, 1–9. https://doi.org/10.1016/j.apenergy.2017.01.048

Core partners: DLR

FlexiGIS (Flexibilisation in Geographic Information System) is a framework for developing linear optimisation models of urban systems (Alhamwi et al., 2017). The framework consists of a modular collection of mutually compatible source codes required for a particular model, which allows address different research questions in a flexible way, all based on a common set of model features. The software combines three main components: data processing, simulation of energy supply and demand, and system optimization. Together, these modules generate data-driven recommendations to support sustainable and efficient urban energy planning.

FlexiGIS is designed to model urban systems for research in the field of energy system modelling. It regularly processes publicly available datasets to map, classify, and model urban energy infrastructures, with a particular focus on georeferenced data. These datasets may include building areas, road networks, or land-use information. FlexiGIS enhances these datasets with modelled information, such as the electricity demand of individual buildings, by considering factors like building age or demographic data. Within its optimisation environment, the software can determine the most cost-effective deployment of different technologies while ensuring security of supply in urban areas. Constraints on technologies – such as limited expansion space are included as boundary conditions. By mapping and evaluating different development scenarios for urban energy systems, FlexiGIS makes it possible to quantify both the degree of regional self-sufficiency and the flexibility potential of cities.

Thanks to its transferability, FlexiGIS provides global support for the development and implementation of strategies for sustainable urban energy systems.

The FlexiGIS framework to model urban energy systems is developed for more than 10 years. Recently, there were new features selected and developed, for instance, the modeling of urban street lightning infrastructure (Alhamwi et al., 2021), synthetic grid infrastructure for power, heat and gas grids (Alhamwi et al., 2022) and the data-driven classification of so-called urban energy units (Blanco et al., 2024).

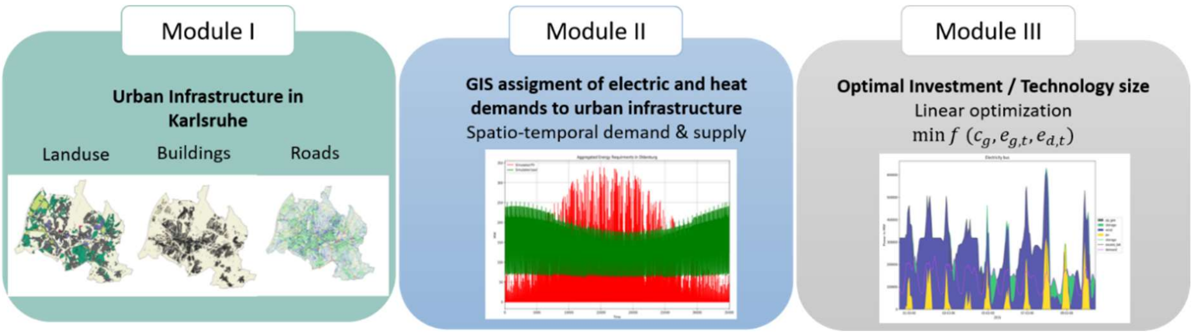

Figure 5: FlexiGIS can be used to map urban infrastructures (Module I) and to simulate and geographically allocate urban energy requirements (Module II). Another component of FlexiGIS is the determination of the most economically cost-effective deployment planning for different technologies (Module III) (Source: DLR-VE)

2.2 Solutions for specific use cases

2.2.1 LENS

LENS ***Long-term Energy Scenario Tool***	**Preprocessing Model**
The LENS Framework is a software tool for quantitatively constructing and analysing complete energy scenarios. The scope of analysis ranges from various demand drivers and sectoral useful and final energy consumption to primary energies, installed capacities and emissions on the supply side.	
Link to HRSD: https://www.dlr.de/de/ve/forschung-und-transfer/infrastruktur/modelle/lens **Main reference:** Non yet **Core partners:** DLR	

LENS Framework is a software tool developed at the DLR Institute of Networked Energy Systems that can be used to quantitatively construct and analyse complete energy scenarios. The scope of analysis ranges from various demand drivers and sectoral useful and final energy consumption to primary energies, installed capacities and emissions on the supply side.

LENS has interfaces for linking with other models (e.g. REMix (cf. Chapter 2.1.1) and AMIRIS (cf. Chapter 2.2.6)) so that the results of more complex system and market modelling can be integrated in the future. Interfaces for the further assessment of scenarios (for example with FRITS - Framework for impact assessment of transformation scenarios, cf. Harpprecht et al., 2024), particularly with regard to life cycle-based environmental effects and (critical) resource requirements, were also taken into account during software development.

LENS is used at the German Aerospace Center for national and international bottom-up scenario analyses as well as for detailed analyses of the industrial sector. Since 2024, a first coupled stakeholder-based workflow using LENS has also been developed.

LENS was planned from the outset as an open-source tool for scenario development. It is designed for a broad user base in terms of its clear and professional software architecture and structure, documentation and existing instructions, as well as its implementation as a Python package on GitLab. The creation of different sectoral, regional or national scenario models based on the framework was tested with initial case studies.

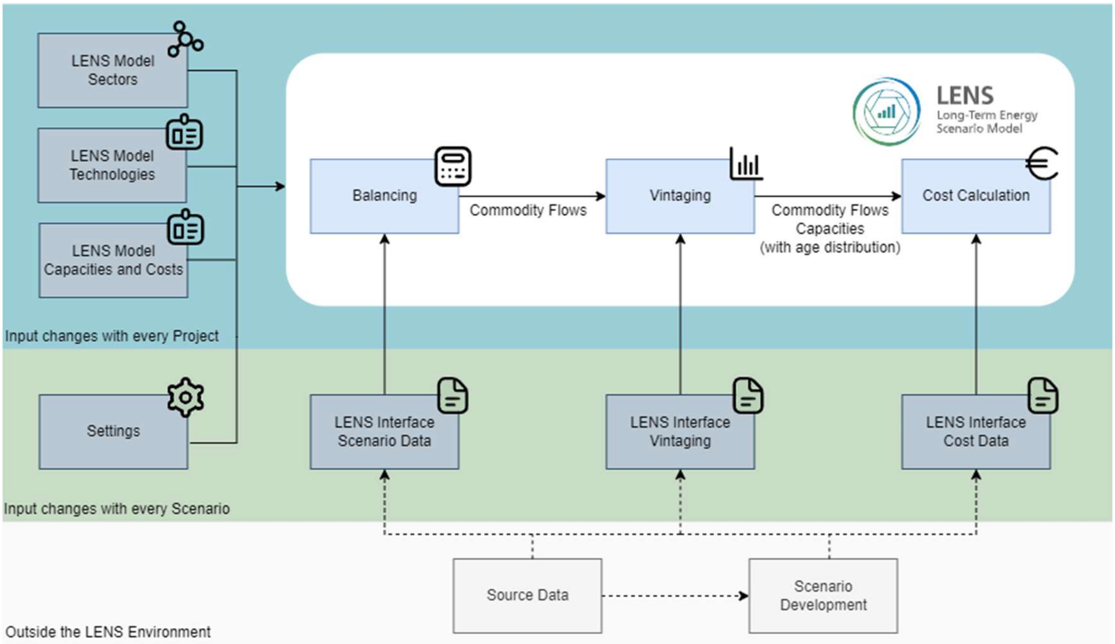

Figure 6: Outline of LENS Framework (Source: DLR-VE)

2.2.2 ETHOS.RESkit

ETHOS.RESkit *Renewable Energy Simulation toolkit for Python*	**Preprocessing Model**
ETHOS.RESKit aids with the broad-scale simulation of renewable energy systems, primarily for the purpose of input generation to Energy System Design Models.	
Link to HRSD: https://helmholtz.software/software/ethosreskit **Main reference:** Peña-Sánchez, E.U., Dunkel, P., Winkler, C., Heinrichs, H., Prinz, F., Weinand, J., Maier, R., Dickler, S., Chen, S., Gruber, K., Klütz, T., Linßen, J., Stolten, D., 2025. Towards high resolution, validated and open global wind power assessments. https://doi.org/10.48550/ARXIV.2501.07937 **Core partners:** FZJ	

ETHOS.RESKit is a highperformance- simulation toolkit for large-scale renewable energy systems, designed to generate inputs for energy system design models (Peña-Sánchez, Dunkel, Winkler et al., 2025). It includes simulators for onshore and offshore wind, solar PV, and concentrated solar power, plus utilities for weatherdata- manipulation. Although simulations run at the level of individual units, the tool is optimized for speed and can simulate millions of turbines or PV/CSP systems in minutes depending on hardware.

ETHOS.RESkit can generate synthetic windturbine power curves and provides access to the latest PV module databases from Sandia and the California Energy Commission. The toolkit is configurable to use different climate model datasets and supports adjustments to align results with national capacityfactor averages. Designed with flexible, modular architecture, ETHOS.RESKit enables scalable, fast simulations across large numbers of individual units.

2.2.3 ETHOS.GLAES

ETHOS.GLAES *Geospatial Land Availability for Energy Systems*	**Preprocessing Model**
ETHOS.GLAES is a framework for conducting land eligibility analyses and is designed to easily incorporate disparate geospatial information from a variety of sources into a unified solution.	
Link to HRSD: https://helmholtz.software/software/ethosglaes **Main reference:** Ryberg, D., Robinius, M., Stolten, D., 2018. Evaluating Land Eligibility Constraints of Renewable Energy Sources in Europe. Energies. https://doi.org/10.3390/en11051246 **Core partners:** FZJ	

ETHOS.GLAES is a framework for landeligibility- analyses that integrates diverse geospatial data into a single, consistent workflow. Its primary function is to identify areas within a region that are eligible for a specific purpose, for example, siting a wind turbine (Ryberg et al., 2018). Although developed with distributed renewable energy applications in mind – such as onshore wind and openfield- solar parks – ETHOS.GLAES can be applied wherever a constrained indication of land is needed.

Outside Europe, ETHOS.GLAES supplies the analysis framework but requires users to provide the underlying datasets. Built on the Geospatial Data Abstraction Library (GDAL), ETHOS.GLAES can ingest any geospatial format GDAL supports, including common GIS files like .shp and .tif, offering high flexibility to incorporate projectspecific constraints while maintaining a consistent methodology across studies.

2.2.4 ETHOS.HiSim

ETHOS.HiSim *Household Infrastructure and Building Simulator*	**Preprocessing Model**
HiSim is a Python package for simulation and analysis of household scenarios and building systems using modern components as alternative to fossil fuel-based ones.	
Link to HRSD: https://helmholtz.software/software/hisim **Main reference:** Rieck, K., Dabrock, K., Pflugradt, N., Weinand, J.M., Stolten, D., 2025. Large-scale quantification of the future self-covered heat demand using a nationwide residential building database. Energy 317, 134622. https://doi.org/10.1016/j.energy.2025.134622 **Core partners:** FZJ, Hochschule Emden/Leer, 4ward Energy	

The goal of this package is to enable a free fast to implement investigation of different building energy system strategies considering the many load profiles, physical conditions and alternative components from fossil fuel sources. It features a timestep simulation engine and an extensible integration framework. The package supports generation of load profiles for electricity and heating demand, models electricity generation, and implements smart control strategies for modern components including heat pumps, batteries, electric vehicles, and thermal energy storage (Rieck et al., 2025).

ETHOS.HiSim models building energy systems as collections of discrete components. Current modules include building, PV system, battery, seasonal hydrogen storage, gas heater, weather, and occupancy load profiles. The discrete components define the entirety of a designed building energy system. The package is designed to enable rapid, loweffort exploration of alternative building energy strategies across diverse load profiles, environmental conditions, and component choices, including fossilfuel options. Users can also create and integrate their own custom components into the framework.

2.2.5 ETHOS.PeNALPS

ETHOS.PeNALPS *Petri Net Agent-based Load Profile Simulator*	**Preprocessing Model**
ETHOS.PeNALPS (Petri Net Agent based Load Profile Simulator) is a Python library for the simulation of load profiles of plants of industrial manufacturing processes.	
Link to HRSD: https://helmholtz.software/software/ethospenalps **Main reference:** Belina, J., Pflugradt, N., Stolten, D., 2024. ETHOS.PeNALPS: A Tool for the Load Profile Simulation of Industrial Processes Based on a Material Flow Simulation. JOSS 9, 6358. https://doi.org/10.21105/joss.06358 **Core partners:** FZJ	

ETHOS.PeNALPS (Petri Net Agent-based Load Profile Simulator) (Belina et al., 2024) simulates the load profiles of industrial manufacturing systems. It enables the modeling of individual industrial manufacturing systems as well as entire industrial sectors – such as steel, cement, or glass production – on a national scale. It provides a set of generic building blocks that can be used to model industrial manufacturing systems.

The structure of ETHOS.PeNALPS can be seen in Figure 7. The tool conceptualizes industrial manufacturing systems as networks of work systems that are interconnected via material flows. The manufacturing systems are built from generic nodes that are displayed at the top of Figure 7. Each work system of the manufacturing system is represented as an autonomous agent capable of communication with other agents to which it is linked through material dependencies. This agent-based communication allows for the synchronization of inputs and outputs across the system, resulting in the creation of a just-in-time (JIT) production schedule.

In order to start the simulation, a set of production orders have to be passed to the manufacturing system. During the simulation the energy demand of the system is attributed to both the activity of the individual work systems and the associated material flows. Fluctuations in activity can then lead to fluctuations in energy demand. ETHOS.PeNALPS is an open-source Python-based software package, available via the conda-forge channel or for development use directly from its GitHub repository[1].

[1] https://github.com/FZJ-IEK3-VSA/ETHOS_PeNALPS

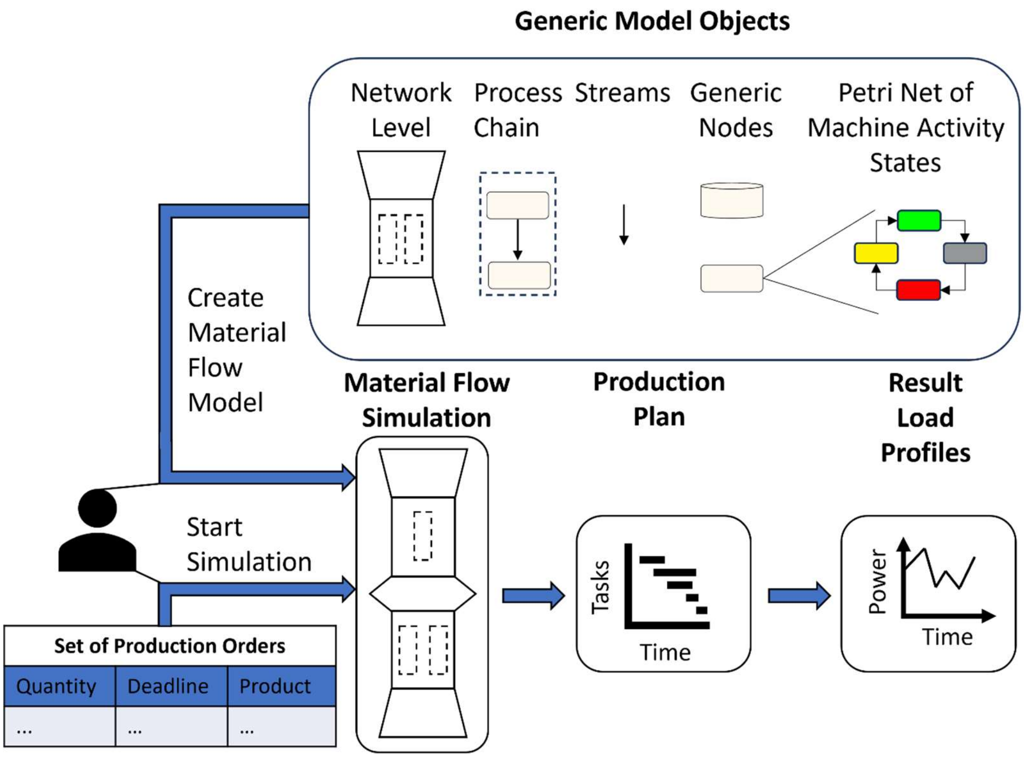

Figure 7: Structure and Application of ETHOS.PeNALPS (Belina et al., 2024)

2.2.6 AMIRIS

AMIRIS ***AMIRIS** is an agent-based electricity market model*	**Economic Model**
AMIRIS is the open Agent-based Market model for the Investigation of Renewable and Integrated energy Systems. It aims at enabling scientists to dissect the complex questions arising with respect to future energy markets, their market design, and energy-related policy instruments.	
Link to HRSD: https://helmholtz.software/software/amiris **Main reference:** Christoph Schimeczek, Kristina Nienhaus, Ulrich Frey, Evelyn Sperber, Seyedfarzad Sarfarazi, Felix Nitsch, Johannes Kochems, A. Achraf El Ghazi (2023), AMIRIS: Agent-based Market model for the Investigation of Renewable and Integrated energy Systems, Journal of Open Source Software, 5041, doi: 10.21105/joss.05041 **Core partners:** DLR	

AMIRIS is an open-source, agent-based model for electricity markets that was specifically developed to analyse the complex interdependencies between market actors, support policies and market design and technology in future energy systems. The framework enables the endogenous calculation of electricity prices by simulating the strategic bidding behaviour of different participants in the electricity market, taking into account uncertainties, limited information and support mechanisms. Market actors and entities, are represented in six main categories of agents: market places, power plant operators, flexibility providers, demand and supply traders, policy and information agents, providing e.g. forecast time series. Besides of, e.g, hourly electricity prices, outputs comprise, e.g., sold energy volumes, support costs as well as financial flows between the representing agents.

AMIRIS has been applied to assess refinancing perspectives of renewable energy sources (Kochems et al., 2024), the economic potentials of demand response (Kochems, 2024), impacts of cold doldrums on European electricity trading (Nitsch et al., 2023) as well as the integration of energy communities into the overall energy system (Sarfarazi et al., 2024). Further analyses were conducted on the economic potentials of flexibility options, such as Carnot batteries (Nitsch et al., 2024b), battery storage systems (Nitsch, 2025), heat-pumps (Sperber et al., 2025; Sperber, 2025) and last but not least on dispatch planning strategies in agent-based electricity market simulations to counter "avalanche effects" resulting from competition (Schimeczek et al., 2026).

In order to answer this wide variety of research questions AMIRIS has been coupled with a large number of different models, including energy system and grid models like REMix, E2M2, TANGO, and EMLabpy. AMIRIS provides an UrlModelService for flexible and easy coupling with any other model APIs, like, e.g., machine-learning based forecasts (Nitsch et al., 2024a).

AMIRIS is based on the in-house developed FAME framework (Schimeczek et al., 2023) and characterized by a consistent pursuit of open science and FAIR principles. For reasons of validation modeling results are subjected to backtesting like in (Nitsch et al., 2021).

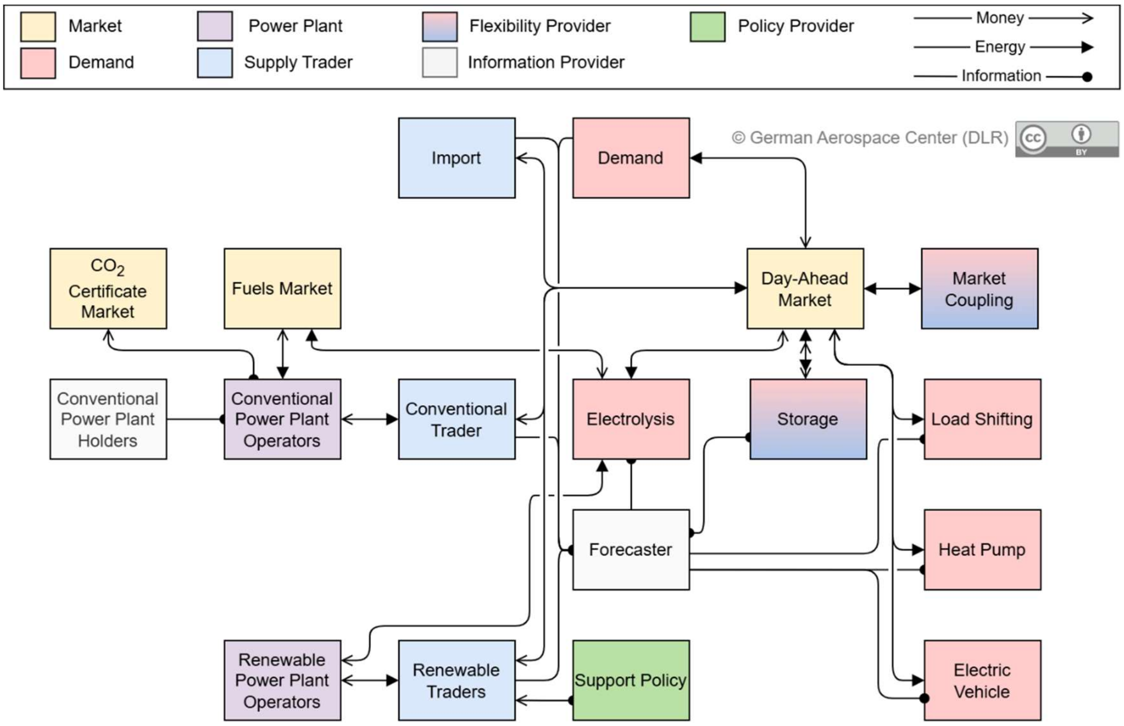

Figure 8: Outline of AMIRIS (Source: DLR-VE)

2.2.7 sfctools

sfctools ***modeling suite for ABM-SFC modeling***	**Economic Model**
sfctools is a modeling suite for agent-based, macroeconomic and stock-flow consistent (ABM-SFC) modeling written in Python. It concentrates on agents in economics and provides a graphical model design interface.	
Link to HRSD: https://helmholtz.software/software/sfctools **Main reference:** Baldauf, T., 2023. sfctools - A toolbox for stock-flow consistent,agent-based models. JOSS 8, 4980. https://doi.org/10.21105/joss.04980 **Core partners:** DLR, University of Pisa	

sfctools is a specialized software framework for modeling economic systems, based on the combination of agent-based models (ABM) and stock-flow consistent (SFC) approaches (Baldauf, 2023). It enables transparent and consistent modeling of complex economic systems. sfctools is especially suited for studying macroeconomic dynamics and analyzing the impact of policy measures on economic agents. It focuses on representing economic actors and provides tools to create new models and manage fundamental economic data structures such as financial balance sheets. The primary focus of sfctools is on economic applications, making it particularly well-suited for modeling interactions between households, firms, banks, and government institutions in small to medium-sized economic models.

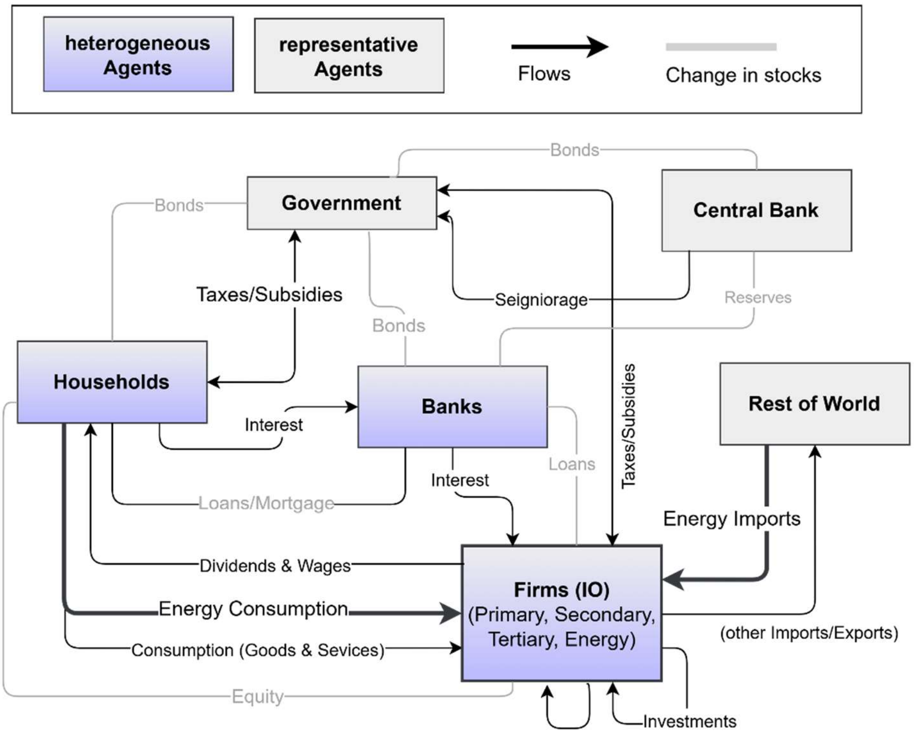

Figure 9: Outline of sfctools (Baldauf et al., 2026)

2.2.8 DEMACRO

DEMACRO *A Macroeconomic Assessment Suite*	**Economic Model**
DEMACRO provides a suite of specialized models that use diverse methodologies for forecasting, scenario analysis, and macroeconomic projections.	
Link to HRSD: https://helmholtz.software/software/demacro **Main reference:** Raseta, M., Ross, A.G., Vögele, S., 2025. Macro-level implications of the energy system transition to net-zero carbon emissions: Identifying quick wins amid short-term constraints. Economic Analysis and Policy 85, 1065–1078. https://doi.org/10.1016/j.eap.2025.01.011 **Core partners:** FZJ	

DEMACRO includes a suite of specialized models designed for macroeconomic impact analysis. These models cover a range of methodologies, including a computable general equilibrium model with Neo Keynesian and behavioural features (Ross et al., 2024a, 2024b), an econometric non-equilibrium model (Ross et al., 2025; Raseta et al., 2024), and a state-of-the-art agent-based (stock-flow consistent) model that has been validated for both forecasting and scenario analysis (Ross, 2026a). In addition, DEMACRO incorporates a disequilibrium input-output (IO) model (Raseta et al., 2025). Together, these models provide a comprehensive framework for analyzing various macroeconomic scenarios. The disequilibrium IO component, PyMacroIO (Ross, 2026b), is described below, along with its main features and current applications.

This framework captures the macroeconomic impacts of energy transition pathways, as well as other non-energy scenarios and shocks, with high sectoral and employment detail. It is built on a Leontief IO structure (with alternative specifications, such as CES, available), using recent, detailed German economic data. The framework explicitly distinguishes between intermediate and final demands, inventory dynamics, and sectoral production constraints. Unlike standard IO models, it allows for temporary mismatches between supply and demand, reflecting real-world frictions and bottlenecks during periods of rapid structural change. The labor market is modeled explicitly, with sector-level hiring and firing subject to legal and institutional adjustment constraints. This enables the model to capture occupational and skills-based employment effects.

This design facilitates the simulation of detailed, time-dependent output and employment responses under user-defined transformation scenarios, making the approach especially well-suited for analyzing the short-run, sector-specific consequences of large-scale economic transitions.

Current applications (Raseta et al., 2025) include a soft link to an energy system optimization model to assess the potential short-term impact of the energy transition on the overall economy, specifically in terms of output and employment disaggregated by labor market skill category.

2.2.9 HIM

HIM *Hydrogen Investment Model*	**Economic Model**
HIM is an agent-based model for investment decisions in the German electricity and green hydrogen sectors.	
Link to HRSD: https://helmholtz.software/software/him **Main reference:** Jesse, B.-J., Kramer, G.J., Rhoden, I., Koning, V., 2026. Exploring the scale-up of a green hydrogen industry: An agent-based modeling approach. International Journal of Hydrogen Energy 198, 152695. https://doi.org/10.1016/j.ijhydene.2025.152695 **Core partners:** FZJ, Utrecht University	

HIM is an agent-based model for investment decisions in the German electricity and green hydrogen sectors. The model was designed to explore how a green hydrogen industry can scale up by explicitly representing heterogeneous market actors and their investment decisions in coupled electricity, hydrogen, and electrolyzer markets (Jesse et al., 2026).

The model represents distinct agent classes, e.g., electricity producers, electrolyzer investors, hydrogen buyers, and possibly policy actors, that interact through market prices and investment signals. Agents make decentralized, boundedrational investment decisions based on technoeconomic conditions, expectations, and local constraints.

Electricity, hydrogen production, and electrolyzer capacity markets are coupled: electricity supply and prices affect electrolyzer operation and profitability, while electrolyzer demand feeds back into electricity markets. HIM captures dynamic feedback as agents update strategies and investments over time, producing pathdependent scaleup trajectories.

Primary outputs are timeresolved deployment trajectories (installed electrolyzer- capacity), hydrogen production, market prices, and indicators of industry scale-up under different assumptions. The model is used to test how stakeholder behavior, market conditions, and policy interventions influence the pace and feasibility of green hydrogen expansion. An overview of the model setup can be found in Figure 10.

The model is intended as a tool to compare policy and market scenarios and to identify barriers and enablers for industry growth.

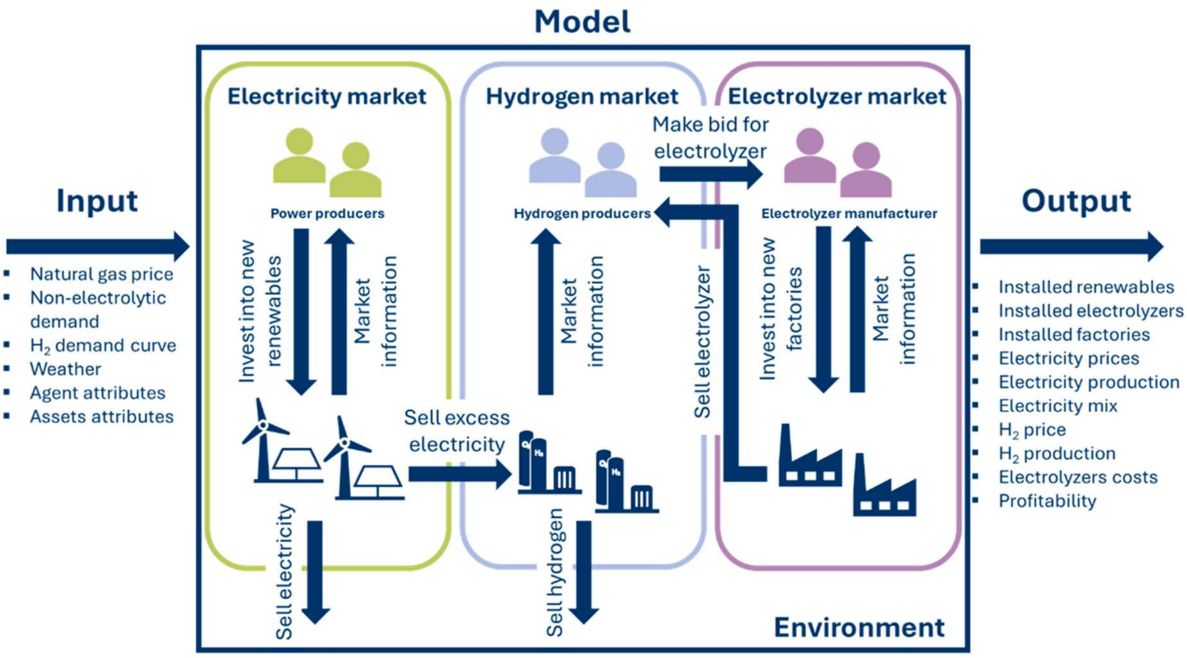

Figure 10. Overview of HIM (Jesse et al., 2026)

2.3 Supplementary Models and Tools

2.3.1 ETHOS.GeoKit

ETHOS.GeoKit *Geospatial Land Availability for Energy Systems*	**Preprocessing Model**
ETHOS.GeoKit is a Python toolkit designed to efficiently handle geospatial data and spatial operations.	
Link to HRSD: https://helmholtz.software/software/geokit **Main reference:** Ishmam, S., Belina, J., Winkler, C., Weinand, J.M., Pflugradt, N., Heinrichs, H., Linßen, J., 2026. ETHOS.GeoKit: A Python Toolkit for Analyzing and Altering Geospatial Data for Energy Systems Modeling and Beyond. https://doi.org/10.2139/ssrn.6299208 **Core partners:** FZJ	

ETHOS.GeoKit is a compact, Pythonbased toolkit designed to simplify the preprocessing, harmonization, and combined analysis of vector and raster geospatial data for scientific modeling, with a particular focus on -energysystem and -renewableresource- workflows (Ishmam et al., 2026). The library wraps and abstracts GDAL/OGR functionality into a small set of composable Python modules and userfacing classes so that users can load, reproject, warp, rasterize, polygonize-, and otherwise mutate geospatial datasets, making it more applicable to non-experts in geospatial data processing.

Originally derived from the Geospatial Land Eligibility for Energy Systems model ETHOS.GLAES (see Section 2.2.3), which was designed for rapid landeligibility assessments in renewable energy applications, ETHOS.GeoKit has since evolved into a versatile and broadly applicable GIS toolkit. Its capabilities extend well beyond landsuitability analysis, making it a robust foundation for a wide range of geospatial workflows.

2.3.2 ETHOS.REFLOW

ETHOS.REFLOW *Renewable Energy potentials workFLOW manager*	**Preprocessing Model**
ETHOS.REFLOW helps researchers to conduct transparent and reproducible renewable energy resource analyses by providing a framework for automating tasks in the workflow.	
Link to HRSD: https://helmholtz.software/software/ethosreflow **Main reference:** Pelser, T., Weinand, J.M., Kuckertz, P., Stolten, D., 2025. ETHOS.REFLOW: An open-source workflow for reproducible renewable energy potential assessments. Patterns 6, 101172. https://doi.org/10.1016/j.patter.2025.101172 **Core partners:** FZJ	

ETHOS.REFLOW is an opensource Python workflow tool that automates -renewableenergy- potential assessments to ensure transparency and reproducibility (Pelser et al., 2025). Built on Spotify's Luigi workflow manager package, it streamlines the full analysis chain — data acquisition, preprocessing, land/sea eligibility screening, technology siting, simulation, and visualization — while allowing users to plug in their preferred data sources and tools (e.g., ArcGIS, QGIS, ETHOS.RESKit, PyPSA). Workflows are configured via settings files describing the study region, exclusion rules, technology specs, which reduces the need to edit code. ETHOS.REFLOW supports parallel processing and containerized execution, produces detailed logs and machinereadable- reports, and makes it easy to rerun or compare alternative workflows to improve collaboration and methodological transparency.

2.3.3 ETHOS.MO|DE.behave

ETHOS. MO|DE.behave *A python package for discrete choice modeling*	**Preprocessing Model**
ETHOS.MO|DE.behave is a Python-based software package for the estimation and simulation of discrete choice models. The purpose of this software is to enable rapid quantitative analysis of survey data on choice behavior, utilizing advanced discrete choice methods.	
Link to HRSD: https://helmholtz.software/software/ethosmodebehave **Main reference:** Reul, J.P., Grube, T., Linßen, J., Stolten, D., 2023. MODE.behave: A Python Package for Discrete Choice Modeling. JOSS 8, 5265. https://doi.org/10.21105/joss.05265 **Core partners:** FZJ,	

ETHOS.MO|DE.behave is a Python package for the estimation and simulation of discrete choice models. It enables fast quantitative analysis of survey data on decision making using modern discrete choice methods. The package includes estimation routines for standard multinomial logit and mixed logit models with nonparametric distributions, tools for visualizing estimation and simulation results, and prebuilt simulation methods tailored to transportation research.

ETHOS.MO|DE.behave has been used primarily in transportation research (Reul et al., 2022, 2023) but is a general framework for rapid quantitative analysis of choice behavior based on discrete choice theory. A common workflow for analyzing survey data is:

1. Prepare data: convert survey responses to the repository's required long format.
2. Specify model: choose attributes and set model parameters.
3. Estimate model: fit a multinomial or mixed logit model.
4. Analyze and visualize: inspect estimated parameters and simulation outputs.

ETHOS.MO|DE.behave aims to make discrete choice methods – especially mixed logit models with nonparametric designs, which are often poorly documented – more accessible to researchers interested in choice modeling.

2.3.4 venco.py

venco.py **Preprocessing Model**

translating charging patterns by electric vehicle to electricity load flexibilities

A tool to derive battery electric vehicle energy demands from given trip data. venco.py provides normalized, aggregated electric vehicle fleet demand profiles for two cases: Uncontrolled charging and a technical (mobility-constrained) potential for controlled charging including vehicle-to-grid

Link to HRSD: https://helmholtz.software/software/vencopy

Repository: https://gitlab.com/dlr-ve/esy/vencopy/vencopy

Main Main reference:

Miorelli, F., Wulff, N., Fuchs, B., Gils, H.C., Jochem, P., 2025. venco.py: A Python model to represent the charging flexibility and vehicle-to-grid potential of electric vehicles in energy system models. JOSS 10, 6896. https://doi.org/10.21105/joss.06896

Core partners: DLR

The venco.py simulation model is a bottom-up approach designed to estimate the load shifting and vehicle-to-grid (V2G) potential of battery electric vehicles (BEVs) based on mobility demand data and techno-economic assumptions. This open-source tool (Miorelli et al., 2025) allows researchers to analyze the energy demand and flexibility of EV fleets within the context of energy systems, providing valuable insights for optimizing the integration of EVs into the grid.

The model uses a modular structure, enabling users to configure various assumptions about charging infrastructure, vehicle fleet characteristics, and plugging behavior. This flexibility allows researchers to explore a wide range of scenarios, from different types of charging infrastructure (e.g., slow, fast, or high-power charging) to varying vehicle fleet compositions (e.g., BEV, plug-in hybrid electric vehicles, or fuel cell electric vehicles). Additionally, users can specify the technical characteristics of the vehicle fleet, such as battery capacity, charging power, and efficiency.

One of the key features of venco.py is its ability to model both controlled and uncontrolled charging strategies. Controlled charging strategies include load shifting, where EVs are charged during off-peak hours to reduce strain on the grid, and V2G, where EVs can supply energy back to the grid when needed. Uncontrolled charging scenarios simulate a situation where vehicles begin charging as soon as a charging opportunity becomes available, without any external control or optimization.

The model generates several key outputs, including:

1. **Battery drain profiles**: These profiles show the expected state of charge (SoC) of each vehicle over time, taking into account factors like driving patterns, charging opportunities, and vehicle efficiency.
2. **Charging and discharging capacity profiles**: These profiles indicate the amount of energy that can be charged or discharged by each vehicle at any given time, considering constraints like charging power, battery capacity, and grid availability.
3. **Minimum and maximum battery energy levels**: These outputs provide information on the expected minimum and maximum SoC of each vehicle over a given period, helping to identify potential issues with charging infrastructure or vehicle fleet management.
4. **Uncontrolled charging profiles**: These profiles simulate a scenario where vehicles charge as soon as possible, without any external control or optimization, providing insights into the potential impact of uncontrolled charging on the grid.

These outputs can be used as input constraints in other models to determine optimal charging strategies and represent EV demand endogenously. For example, energy system optimization models can use the battery drain profiles and charging capacity profiles to optimize the charging schedule for a fleet of EVs, while agent-based electricity market models can utilize the uncontrolled charging profiles to simulate the behavior of EV owners in response to changing market conditions.

The venco.py model has been designed to be highly flexible and adaptable, allowing users to easily integrate it with other modeling tools and frameworks. Its output profiles are generic and versatile, making it an ideal tool for addressing a wide range of research questions across multiple modeling domains, including:

1. **Energy system optimization models:** venco.py can provide detailed information on EV energy demand and flexibility, enabling the development of more accurate and effective optimization strategies.
2. **Agent-based electricity market models:** The model's output profiles can be used to simulate the behavior of EV owners in response to changing market conditions, providing insights into the potential impact of EVs on the grid.
3. **Transportation planning models:** venco.py can help transportation planners understand the energy demand implications of different transportation scenarios, enabling more informed decisions about infrastructure development and urban planning.

By providing a comprehensive understanding of EV energy demand and flexibility, venco.py can help researchers and policymakers develop more effective strategies for integrating EVs into the energy system, reducing greenhouse gas emissions, and promoting sustainable transportation.

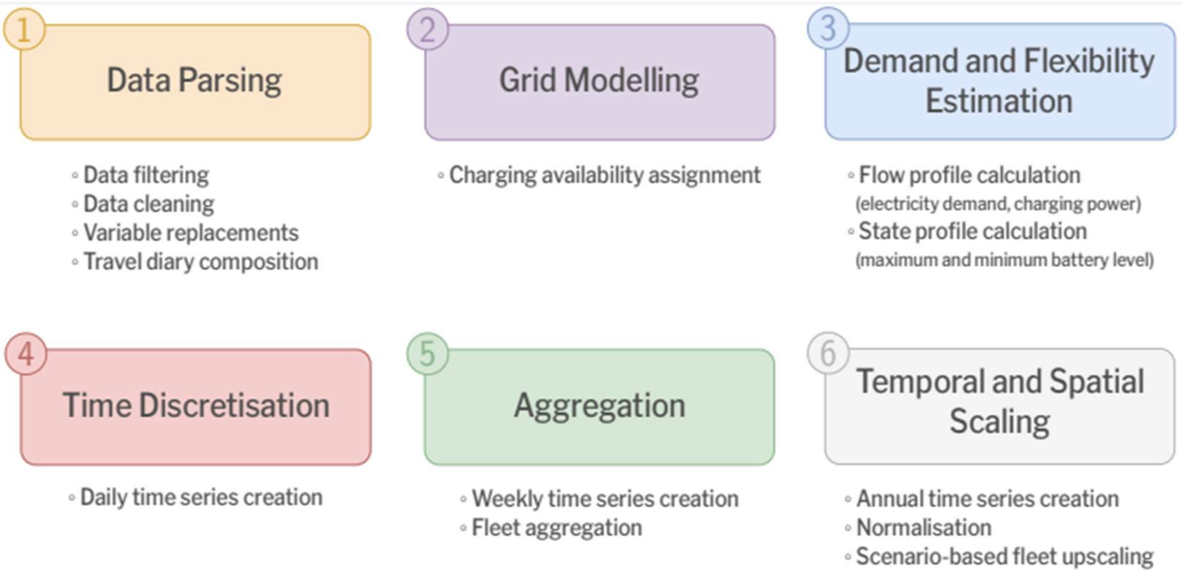

Figure 11: Outline of venco.py (Miorelli et al., 2025)

2.3.5 TSAM

TSAM *Time Series Aggregation Module*	**Preprocessing Model**
tsam is a python package which uses different machine learning algorithms for the aggregation of time series	
Link to HRSD: https://helmholtz.software/software/tsam **Repository:** https://github.com/FZJ-IEK3-VSA/tsam **Main Main reference:** Hoffmann, M., Kotzur, L., Stolten, D., 2022. The Pareto-optimal temporal aggregation of energy system models. Applied Energy 315, 119029. https://doi.org/10.1016/j.apenergy.2022.119029 **Core partners:** FZJ	

tsam is a python package which uses different machine learning algorithms for the aggregation of time series (Kotzur et al., 2018a, 2018b). The data aggregation can be performed in two freely combinable dimensions: By representing the time series by a user-defined number of typical periods or by decreasing the temporal resolution. tsam was originally designed for reducing the computational load for large-scale energy system optimization models by aggregating their input data, but is applicable for all types of time series, e.g., weather data, load data, both simultaneously and other arbitrary groups of time series (Hoffmann et al., 2021, 2022).

2.3.6 ETHOS.TISED

ETHOS.TISED *Time Series Downscaler*	**Preprocessing Model**
ETHOS.TISED (TIme SEries Downscaler) is a python package that utilizes the non-dimensionalization of solar irradiance and time with statistical parameters matching to increase the temporal resolution of Global Horizontal Irradiance (GHI).	
Link to HRSD: https://helmholtz.software/software/ethostised **Repository:** https://github.com/FZJ-IEK3-VSA/ETHOS.TISED **Main reference:** Omoyele, O., Hoffmann, M., Weinand, J.M., Larrañeta, M., Linßen, J., Stolten, D., 2026. A high-resolution downscaling approach for solar irradiance using statistical parameter matching. Renewable Energy 256, 124551. https://doi.org/10.1016/j.renene.2025.124551 **Core partners:** FZJ	

ETHOS.TISED is a Python library for global downscaling of Global Horizontal Irradiance (GHI) from one hour resolution to one minute for energy system applications (Omoyele et al., 2026). The package utilizes the non-dimensionalization of solar irradiance and time with statistical parameters matching to increase the temporal resolution of GHI.

2.3.7 HELDA

HELDA[2] *Helmholtz MCDA Tool*	**MCDA Model**
HELDA is an operational, scientific application for applying different Multi Criteria Decision Analysis (MCDA) methods , featuring a user-friendly interface, uncertainty analysis, comprehensive graphical representations, and a plug in that enables interactive stakeholder integration over the internet.	
Link to HRSD: https://helmholtz.software/software/helda **Link to HELDA:** https://www.mcda-helmholtz.de/64.php **Main reference:** Mesa Estrada, L., Haase, M., Müller, T. (2026): Development and application of HELDA: a multi-criteria decision analysis tool tailored for sustainable energy system transformations (submitted to Expert systems with Applications) **Core partners:** KIT, FZJ, DLR	

In terms of decision-support methods, HELDA offers a broad suite of aggregation techniques. Users can employ classic approaches such as weighted sum, weighted product, weighted rank, TOPSIS, and VIKOR, as well as define custom expressions. The package also includes the PROMETHEE I and II methods and ELECTRE III, both of which represent recently added capabilities. For assigning importance to criteria, HELDA supports AHP, SWING, SMART, and relative weighting by sliders, while also introducing a deck-of-cards method and direct absolute weighting as fresh alternatives.

The plugin for online surveys facilitates the interaction between stakeholders and the decision models created in HELDA. The plug-in can automatically create surveys using a (pre-)defined list of stakeholders' categories and the criteria available in the evaluation matrix in HELDA. Once the survey is created, the plug-in displays a QR code and a link that stakeholders can scan to access the survey. Stakeholders can express their preferences regarding selection and weighting of decision criteria. To collect the preferences, the platform LimeSurvey is used. The stakeholders or survey participants

[2] HELDA is freely available for research and teaching (CC-BY-NC-ND) but not open source.

submit their responses, and these are in turn sent to HELDA in real-time which allows that the elicited preferences can directly be observed in HELDA.

The software is equipped to address uncertainty in both performance data and criteria weights. It does so by allowing users to specify probability distributions and run Monte Carlo simulations, thereby quantifying the impact of stochastic variations. Complementary sensitivity analyses can be performed to explore how changes in the underlying data influence the final rankings.

Visualization is a central component of HELDA's user experience. The platform can display weighting set analyses for individual or multiple stakeholders, rank alternatives from best to worst (including uncertainty bands when applicable), and generate stability graphs that illustrate the sensitivity of results to variations in values, weights, and – soon – to thresholds and alternatives. A dominance graph is also available to depict pairwise dominance relationships among the options under consideration.

Overall, HELDA extends the original MCDA Tool KIT into a more versatile, stakeholder-oriented environment for sustainability evaluation, combining an expanded methodological toolbox with robust uncertainty handling and rich graphical output.

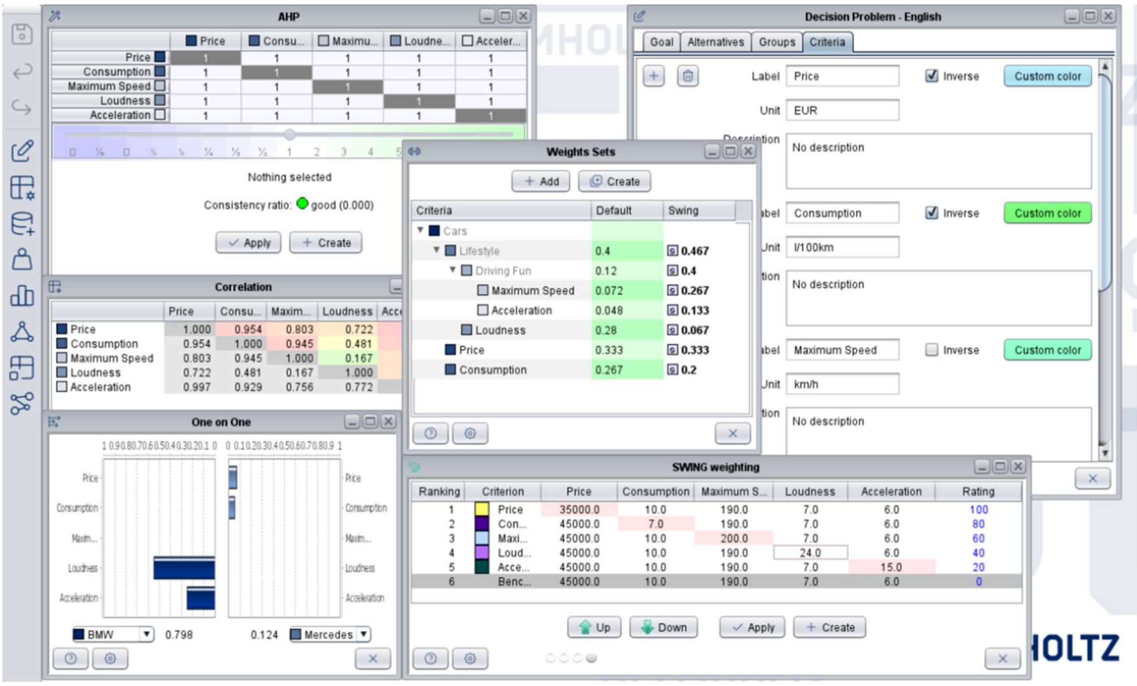

Figure 12: Example of the comprehensive HELDA user interface (Source: KIT-ITAS)

3 Open Data Sets for Energy System Models

Providing divers energy data openly for researchers and other stakeholders is crucial for improving the decision-making process in the transition to a low-carbon economy. Especially energy systems modeling profits from this trend and as it enables the creation of accurate, reliable, and transparent models in these more complex and decentralized energy systems of tomorrow. Open data provides the necessary foundation for modeling these systems efficiently by making available a wide range of datasets, including historical weather patterns, energy demand and supply profiles, grid infrastructure, and technology costs.

With open data, researchers and analysts can develop robust models that account for uncertainties and variability in energy systems, allowing them to:

1. **Improve forecasting accuracy**: By leveraging large datasets, models can better predict energy demand, renewable energy output, and other key variables.
2. **Optimize system design**: Open data enables the evaluation of different scenarios, identifying the most effective and efficient ways to integrate variable renewables, energy storage, and other low-carbon technologies.
3. **Enhance policy-making**: Transparent and accessible data facilitates the development of evidence-based policies, ensuring that decisions are grounded in reality rather than assumptions.
4. **Foster collaboration and innovation**: Open data promotes knowledge sharing and cooperation among stakeholders, driving innovation and accelerating the transition to a sustainable energy future.

Helmholtz is contributing to this undertaking considerably and mainly in accordance with the FAIR principles, i.e. findable, accessible, interoperable, and reusable. In the following Section 2.1 core contributions are shown. Further data can be found by the following repositories of the two main contributing institutions:

1. Jülich-ICE2 Data: https://data.fz-juelich.de/dataverse/ICE-2
2. DLR-VE Data: https://zenodo.org/communities/dlr-ve/records?q=&l=list&p=1&s=10&sort=newest

Helmholtz will continue to publish further energy data, mainly in collaboration with further relevant stakeholder in the research community, e.g. on the Open Energy Database (https://nfdi4energy.uol.de/service/open-energy-database).

Following the FAIR principles all the data sets will be made available in the data catalog of the open energy platform (https://www.openenergyplatform.org). Data originating from these Helmholtz programs are annotated with a specific Helmholtz metadata module. The general principles of the catalog are explained in Hellmann and Hoyer-Klick (2024). These data sets are available here: https://moss.openenergyplatform.org/?HGFProgram=ESD&HGFTopic=TOPIC+1.

The catalog will continuously updated as new data is published. We use the Open Energy Metadata to document the data sets und their data schema semantically.

3.1 Meteorological Data

Meteorological data for energy systems analysis	**Data**
Helmholtz offers highly resolved data for Germany and Europe, including satellite-based solar radiation data. This data is used for energy system modeling, including cost-potential-curves for renewable electricity generation. Geographical downscaling of wind speed data and future electricity demand considering climate change are also available. These datasets are publicly available on platforms like Zenodo.	
Link to HRSD: none **Main reference:** Schroedter-Homscheidt, M., Azam, F., Betcke, J., Hanrieder, N., Lefèvre, M., Saboret, L., Saint-Drenan, Y. -M., 2022. Surface solar irradiation retrieval from MSG/SEVIRI based on APOLLO Next Generation and HELIOSAT-4 methods. metz 31, 455-476. https://doi.org/10.1127/metz/2022/1132 **Core partners:** DLR, Meteodat	

Meteorological data for energy systems analysis has a long history in Helmholtz. The DLR started already in the late 1990ies to give highly resolved data for solar and wind potentials for Germany and Europe. For solar energy, this is based mainly on satellite data (Broesamle et al., 2001) and continued with most recent method improvements as regular service on behalf of European Commission as part of the Copernicus Service (https://ads.atmosphere.copernicus.eu/datasets/cams-gridded-solar-radiation?tab=overview; Schroedter-Homscheidt et al., 2022). The integration of the new, specifically for energy system analysis studies generated, CAMS gridded radiation dataset into the PyPSA/atlite library was prepared. Furthermore, continuous method evolution takes place e.g. providing recently a first time-and space-resolving uncertainty model for the CAMS Radiation Service (Lezaca Galeano et al., 2025). Geospatially resolved and meteorological data for energy system analysis contains mainly three fields: (1) spatial highly resolved cost-potential-curves for renewable electricity generation by solar and wind, (2) geographical downscaling of energy potentials, and (3) future electricity demand considering climate change and the electrification of residential heating and cooling. These data domains are shortly explained in the following.

First **cost-potential-curves for renewable electricity generation by solar and wind in Europe** have a long tradition and are of high relevance for energy systems models. These geospatial curves distinguish between different levelized costs of electricity (LCOE) categories based on resource qualities and geographical location, providing a detailed assessment of renewable electricity generation potentials. Each LCOE category has its own generation time series, covering various technologies such as PV rooftop, PF open area, wind onshore, wind offshore, and CSP units. While some data is already available, further data is currently undergoing a standard process for FAIR data publication at DLR. This data set includes data from reanalysis, detailed modeling (such as downscaled wind speeds), satellite image-based irradiance modeling, and observations. The data can be used to test and demonstrate the usefulness of more geographically detailed modeling approaches for energy system analysis.

For some analysis the granularity is not precise enough and an ex-post downscaling is necessary. Correspondingly, a **geographical downscaling of wind speed data** of the widely used ERA5 data set has been developed using a machine learning approach that considers topographic influences and can be used by other stakeholders (cf. Hu et al., 2023a). This method addresses the limitations of traditional downscaling methods, which either require high computational effort or focus on wind speed distributions rather than time series. The resulting downscaled wind speed data are publicly available on Zenodo (Hu et al., 2023b).

Another important data set is the **future electricity demand for Europe**, which was developed using a **Temperature Response Function** approach considering climate change (cf. Hu et al., 2024a). This method enables the construction of electricity demand time series from temperature data, taking into account the influence of ambient air temperature on electricity demand due to heat pumps, direct electrical heating, and cooling. The data set includes electricity demand time series for European countries from 2023 to 2100 and is available on Zenodo (Hu et al., 2024b).

3.2 Helmholtz Scenarios 2024

Helmholtz Scenarios 2024 **Data**

Integrative Scenarios for a carbon neutral German energy system in 2045

The Helmholtz Energy Scenarios 2024 are based on an integrative approach considering energy technical, ecological, economic, institutional, organizational, and social aspects including their interactions. The approach essentially consists of two elements: (1) the development of so-called socio-technical energy scenarios and (2) the assessment of the effects of these energy scenarios with regard to sustainability indicators. This approach extends the current decision-making basis for improving sustainable transformations of energy systems.

Link: https://energy.helmholtz.de/en/translate-to-englisch-forschungshighlights/translate-to-englisch-die-energiewende-integrativ-denken

Main reference:

Poganietz, W.-R., Kopfmüller, J., Stelzer, V., Jochem, P., Naegler, T., Kullmann, F., Ross, A., Vögele, S., 2024. Integrative Considerations on Energy Transition (Policy Brief). Helmholtz Energy, Berlin.

Core partners: KIT, FZJ, DLR

Helmholtz developed an integrative scenario approach that considers technical, ecological, economic, institutional, and social aspects (Poganietz et al., 2024). The approach essentially consists of two elements: 1) the development of so-called socio-technical energy scenarios and 2) the assessment of the effects of these energy scenarios with regard to sustainability indicators. The aim is to improve the decision-making basis for the sustainable transformation of the energy system, i.e. extending current methods for energy scenarios.

Key findings include the need for systematic consideration of population and economic development, as well as the importance of electrification of production and transportation processes. This requires spatial and temporal flexibility in the electricity sector, supplemented by defossilized hydrogen. The transformation of the heating sector requires a concerted interplay between energy-efficient building refurbishment, changes in energy sources, and grid expansion. To achieve a climate-neutral energy sector, an infrastructure for effective CO_2 management is essential, and non-climate-related environmental effects must also be considered. The macroeconomic effects of transformation strategies can lead to increased domestic value added but may also result in additional burdens on low-income households, depending on socio-economic boundary conditions. The success of a sustainable transformation depends on the internalization of external costs, which is influenced by political and economic developments, as well as the innovative capacity of the system. Overall, the analysis highlights the complexity of the energy system transformation and the need for a comprehensive and integrated approach to achieve a sustainable future.

3.3 Environmental impact assessment

PRospective EnvironMental Impact AsSEssment (premise) (contribution) **Environmental impact assessment**	**Data**
premise is a Python package for prospective life-cycle assessment that projects the ecoinvent 3 database forward using scenarios from Integrated Assessment Models (IAMs). By adjusting energy-policy pathways, emerging technologies, market shares and efficiencies, it updates selected sectors (e.g., energy supply, transport, fuels, industry) while leaving the rest of the database unchanged unless explicitly mapped. Results are specific to the chosen IAM, scenario, year and ecoinvent version. The tool enables rapid assessment of future energy-system impacts and comparison of policy options. It ships with a library of IAM scenarios and utilities for building custom ones, and it is designed for reproducibility and ease of use. Although built on the Brightway framework, its outputs can be exported to Activity Browser, SimaPro, OpenLCA or any Python-based LCA workflow.	
Link: https://github.com/polca/premise **Main reference:** Sacchi, R., Terlouw, T., Siala, K., Dirnaichner, A., Bauer, C., Cox, B., Mutel, C., Daioglou, V., Luderer, G., 2022. PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renewable and Sustainable Energy Reviews 160, 112311. https://doi.org/10.1016/j.rser.2022.112311 **Core partners:** DLR, ETHZ, PSI	

Most models assess CO_2 or greenhouse gas emissions, although other types of emissions from energy supply or energy-intensive sectors can also have major impacts for the environment and human health, such as toxic or particulate matter emissions. Comprehensive life-cycle based assessments are thus key to gain a full picture of climate and non-climate effects of energy scenarios.

We contributed to the open-source tool *premise* (Sacchi et al., 2022) which enables a life-cycle based environmental impact assessment of detailed, regionalized and technology-rich scenarios. Specifically, we developed models for future cement (Müller et al., 2024) and steel production (Harpprecht et al., 2025b) considering a transition to novel, e.g., hydrogen-based or electrified, technologies. These models have been published in open access zenodo repositories (Müller et al., 2023; Harpprecht et al., 2025a) and have also been integrated into *premise.*

3.4 Truck flow data for German motorways

Hourly resolved truck flow and rest stop data on the German road network *Road freight transport; Infrastructure planning*	**Data**
The dataset contains hourly resolved traffic flows as well as spatio-temporally resolved data on break and rest stops of trucks on the German road network. The high spatial and temporal resolution of the traffic flows on the road network allow for planning and sizing of road infrastructure such as road capacities as well as capacities of rest/charging/fueling stop locations.	
Link: https://zenodo.org/records/17910128 **Main reference:** Jungblut, E. (2025). Hourly resolved truck flows and rest stops on the German road network [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17910128 **Core partners:** FZJ	

The allocation of (truck) traffic flows to the road network is necessary for future infrastructure planning. Information about hourly truck flows is available for Germany in the form of data collected by automated counting loops on freeways and federal roads. However, planning fueling and charging infrastructure along major highways requires additional information about spatio-temporal patterns of break and rest times. This can be achieved by considering route information for freight origin-destination pairs.

Currently, information on freight flows between regions in Europe is available as yearly data on NUTS-3 spatial resolution. This resolution is not sufficient for infrastructure planning.

In this dataset, road freight transport data from publicly available sources was disaggregated spatially and temporally (Jungblut, 2025). Spatial resolution for Germany was increased from NUTS-3 (401 regions) to municipality association level (4620 regions) which lies in between LAU1 and LAU2 level. Temporal resolution was increased from yearly freight flows to hourly freight flows based on traffic count data for motorways and federal roads in Germany. In total, freight flows between a total of 4957 analysis zones in Germany and its neighboring countries are used. For each origin-destination pair the respective shortest path in the road network is calculated. Freight volumes are allocated to individual truck trips by considering distance specific loading factors and empty travel shares.

5. Conclusions and Outlook

This report gives an overview of open-source models and data produced by Helmholtz partner institutions. Other researchers may make use of these models and data for making our research community faster, more reliable, and comprehensive. Further collaborations with other research institutions are highly welcome.

For the years to come we plan to extend each model and improve the interconnectivity of all data and models. A vision is to establish a "**Suite of networked models**", which allows a flexible integration of different models and modules as well as data. Such models would allow highly competent analyses of our highly sector coupled energy system. It would make a carbon neutral future energy system more reliable. To realize this vision, we are searching for relevant partners all over the world, support broader open-science initiatives, including the development of shared databases and the adoption of the Open Energy Ontology (cf. Booshehri et al., 2021).

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