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Introducing the ETHOS energy transformation pathway optimization model suite

Jann Michael Weinand [a,*], Johannes Behrens [a,d], Julian Belina [a,d], Alicia Benitez [a], Arne Burdack [a,d], Shuying Chen [a,f], Kristina Dabrock [a,d], Mak Đukan [a], Philipp Dunkel [a,d], Jan Göpfert [a,d], Maxime Gorres [a], Thomas Grube [a], Noor Titan Putri Hartono [a], Heidi Heinrichs [a,b], Shitab Ishmam [a], Theresa Klütz [a], Patrick Kuckertz [a], David Neuroth [a], Olalekan Omoyele [a,d], Shruthi Patil [a], Tristan Pelser [a,d], Noah Pflugradt [a], Katharina Rieck [a,d], Andrew Ross [a], Thomas Schöb [a], Kai Schulze [a,d], Hawal Shamon [a], Maximilian Stargardt [a], Sandra Venghaus [a,c], Stefan Vögele [a,e], Henrik Wenzel [a,d], Christoph Winkler [a,d], Christina Wulf [a], Petra Zapp [a], Jochen Linßen [a]

[a] *Forschungszentrum Jülich GmbH, Institute of Climate and Energy Systems, Jülich Systems Analysis (ICE-2), Jülich, Germany*
[b] *University of Siegen, Chair for Energy Systems Analysis, Department of Mechanical Engineering, Siegen, Germany*
[c] *RWTH Aachen, Chair for Decision Analysis and Socio-economic Assessment, School of Business and Economics, Aachen, Germany*
[d] *RWTH Aachen University, Faculty of Mechanical Engineering, 52062 Aachen, Germany*
[e] *TU Freiberg, Chair for Energy Economics, Faculty of Business Administration, Freiberg, Germany*
[f] *Institute of Bio- and Geosciences - Agrosphere (IBG-3), Forschungszentrum Jülich GmbH, Jülich, Germany*

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ABSTRACT

Energy systems analysis requires a diverse set of tools to comprehensively evaluate complex transformation pathways. Robust assessments depend on methods for data generation and processing, renewable energy potential estimation, energy system optimization, as well as socio- and macroeconomic analysis. In this paper, we present for the first time a harmonized model suite – ETHOS – that integrates these functionalities within a consistent analytical framework. The ETHOS suite comprises tools ranging from automated data extraction using natural language processing to state-of-the-art renewable potential assessments and energy system optimization models, among others. We describe the individual components of the suite, outline their methodological foundations, explain how they can be accessed and applied, and summarize previous applications in scientific publications and flagship reports of the International Energy Agency. Looking ahead, all models within the ETHOS suite are intended to be developed as open-source software, fostering a broad research community and enabling holistic decision support for policymakers to advance the energy transition.

1. Introduction

To achieve the optimal transformation pathways to sustainable energy systems worldwide, planning tools such as energy system models are required [1]. These planning tools need to consider all relevant technologies and measures, as well as target criteria, from costs and environmental sustainability to justice [2]. Each energy system analysis begins with the collection of primary data, which may be based, for example, on official sources or crowdsourced public datasets. These data then have to be harmonized and further processed across multiple scenarios within a model formulation that employs a specific programming language and toolchain. In the case of mathematical optimization, a numerical solver is used to generate the model outputs. If the project is open source, the model code and data are typically hosted in a public archive. In the final step, the model outputs are interpreted and published [3]. Interactions with stakeholders for policy design usually take place after the publication of results, or as human-in-the-loop frameworks to enhance the real-world feasibility of the modeled solution

* Corresponding author.
E-mail address: j.weinand@fz-juelich.de (J.M. Weinand).

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spaces [4]. The holistic assessment of energy systems and all influencing factors typically requires the linking or integration of various models [5]. A prominent example is the application of models to determine the techno-economic potential of renewable energy plants, e.g., based on minimum distance restrictions and technical considerations, and the integration of the resulting data in energy system transformation studies [6].

When linking models, it is essential to ensure that all assumptions and parameter values in the models are consistent and harmonized. Furthermore, although initial limited efforts have been made [7], there are currently no standardized FAIR [8] data sources for energy system analysis. This often results in data and models being combined that were not originally intended to be linked. To avoid potential problems, an open model suite that is designed to be interconnected and consistent in terms of assumptions and data could provide a solution.

There are already several prominent energy system frameworks and models available as open source, such as PyPSA [9], oemof [10], and Calliope [11]. PyPSA also has standardized links to other tools such as atlite [6] for determining renewable potential or ETHOS.tsam [12] for time series aggregation. However, to the authors' knowledge and based on a review of 152 potentially relevant studies[1], there is still no coherent, coordinated model suite for energy system analysis that harmonizes data collection, system optimization, and further ex-post analyses. The only examples in the literature are suites that optimize combined heat and mass integration in urban and industrial systems [13], suites for model-inter-comparisons [14–16], and suites that generate flexible model regions for energy system models [17].

Therefore, the objective of our article is to provide one of the first fully open-source model suites for energy system analysis with the *Energy Transformation PatHway Optimization Suite* (ETHOS). In this article, we present all already existing open-source modules of ETHOS as well as others that are currently planned for release. In addition, we show which interfaces already work properly and which of them are to be automated in the future.

The article is structured as follows: Section 2 provides an overview of the ETHOS model suite and its model groups. Section 3 describes the most important models in the suite and presents their potential applications, as well as selected use cases. Section 4 explains the model instances of the optimization frameworks and the interfaces of the models that have been successfully implemented and those that are potentially possible. Section 5 discusses the work and presents conclusions.

2. The ETHOS Model Suite

The purpose of the ETHOS model suite is that it develops quantitative and qualitative energy system transformation scenarios as a basis for discussion and decision-making by policymakers aimed at demonstrating societal feasibility, while ensuring techno-economic effectiveness. The quantitative assessment of transformation pathways for global energy systems is based on techno-economic simulation and optimization models with a temporal resolution and timeframe ranging from sub-hourly to decades, where model parameters are iteratively refined based on insights gained in socio-economic analyses. ETHOS combines various modules (see Fig. 1) from renewable potential assessment, load profile generators and grid planning to technology evaluation with Life Cycle Sustainability Assessment (LCSA). The suite focuses on holistic energy system optimizations, which are regionalized using detailed infrastructure models, considering socio-economic impacts and societal feasibility.

At the core of the model suite are integrated hourly energy system optimization models. These models use inputs from surrounding components, including techno-economic data and renewable resource potentials, and are coupled with other components, such as macroeconomic assessment frameworks. Their outputs, in turn, feed into subsequent analyses, including sustainability assessments. The following sections describe the linked components and their interactions in greater detail.

In addition to numerous scientific publications, the ETHOS model suite has also been used in wide-ranging policy and public information events on cost-effective German [23] and European [24] energy system transformation strategies, as well as to support several major reports by the International Energy Agency (IEA) in recent years. The latter include the latest Global Hydrogen Reviews [25–27], the Latin America Energy Outlook [28], as well as reports on the reconstruction of the Ukrainian energy system [29,30].

In the following, we focus on the modules of the ETHOS suite that 1) are already openly available or 2) have already been published in journals and are scheduled for open-source release. We will also present the existing model instances and model interfaces.

3. Open-source Modules and Applications

In this section, we divide the description of the modules of the ETHOS model suite as follows (see Table 1 and Fig. 2): first, we describe the modules for data provision to the frameworks and models (Section 3.1). Then, for the frameworks and models, we distinguish between modules for determining the techno-economic and socially feasible global renewable energy potential (Section 3.2), modules for determining optimal energy system designs and transformation pathways (Section 3.3), and modules for socio-economic analysis of energy systems (Section 3.4). The model instances, based on the modules described in this section, are presented in the next Section 4. Table 1 also provides an overview of all modules, including links to the repositories and key journal publications.

To ensure interoperability between individual modules while enabling their flexible composition into data-driven workflows for complex research questions, the ETHOS model suite is based on a modular workflow concept [69]. This approach supports detailed, machine-actionable descriptions of both data and software components and promotes their flexible and sustainable reuse. Instead of relying on rigid, domain-wide interface standards or ad-hoc integration scripts, ETHOS emphasizes the reuse of collaboratively developed transformation functions that can be dynamically deployed and jointly evolved. These functions enable the application-specific integration of heterogeneous data and modules into complex workflows. By leveraging workflow managers, modules can be easily coupled, exchanged, or extended, ensuring interoperability within ETHOS and with external research software ecosystems.

3.1. Data and Metadata

Energy system analyses require a large amount of data on current and future costs, efficiencies, availability, and much more for potential technologies, measures, and materials. This involves making many assumptions that can sometimes have a substantial impact on the results of the energy system transformation. Many energy system models rely on data from sources such as the International Renewable Energy Agency [70] or the Danish Energy Agency [71], which is often not automatically accessible but must be extracted from PDF files or similar sources. Furthermore, it is not always clear where the data used in energy system analyses comes from and for which application or scenario it is valid. In the following, we present modules of the ETHOS model suite that are designed to ensure the transparency and accuracy of data through automatic data extraction and metadata description.

3.1.1. Metadata Schema for Software and Data

In energy systems research, the sharing, integration, and processing of software and data pose pressing challenges. An evaluation of wind

[1] Search query *TITLE-ABS-KEY("Energy system" and ("model suite" OR "suite")) AND (LIMIT-TO(DOCTYPE,"ar"))* in Scopus on November 5, 2025.

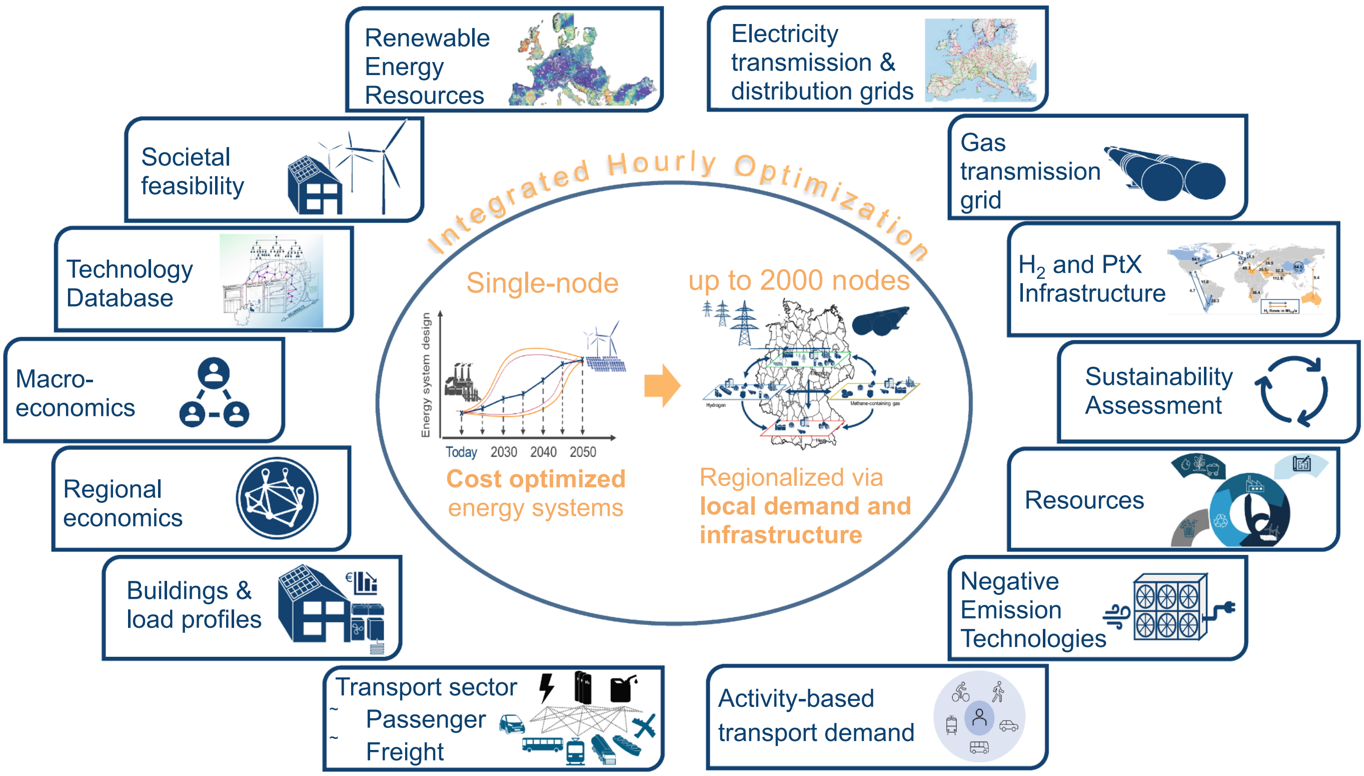

Fig. 1. A selection of the most important topics covered by the modules of the ETHOS model suite. This article only deals in detail with the modules that 1) are already openly available or 2) have already been published in journals and are scheduled for open-source release. The illustrations in the figure were taken from various previous publications[18–22].

resource assessments [72], for example, showed that up to 90% of studies are insufficiently reproducible due to missing data provision and a lack of transparency. Beyond harmonizing data collection, data processing must therefore be designed in an efficient, transparent, and sustainable manner to support reproducible model-based analyses.

To enable an overarching integration of data and software within such analyses, both must be described unambiguously in terms of their interfaces and underlying data models. Metadata schemas are required to capture all information considered relevant by the energy systems domain in a well-structured and machine-actionable format. Ontologies and controlled vocabularies provide the necessary linguistic basis to ensure that these metadata descriptions are not only formally standardized but also semantically unambiguous.

For this purpose, the ETHOS.DataDesc framework [31,32] was developed, which enables the detailed and machine-actionable description of data models in both software interfaces and datasets. The DataDesc metadata schema focuses on formally describing contents, formats, value ranges, and structural properties of data models, thereby allowing data provided by external sources to be systematically compared with the requirements of model interfaces. By making such information explicit, DataDesc supports the transparent ingestion of heterogeneous data into ETHOS workflows and promotes the FAIRness of research software and data.

Based on these metadata descriptions, DataDesc enables the identification of required data transformations when datasets and software interfaces are not directly compatible. These transformations can be implemented in a modular and reusable manner using dedicated data processing components. Within ETHOS, this approach is exemplified by CuCoPy [73], which provides reusable workflows for currency conversion and cost harmonization and can be flexibly integrated into data ingestion pipelines. In addition to supporting data integration, DataDesc metadata can also be used to automate and document interfaces between individual components of the ETHOS model suite, facilitating their composition into transparent and reproducible workflows.

Examples of this approach include our open-source workflows for wind power [44] and rooftop photovoltaic potential assessments based on satellite imagery [43], which are described in the section on renewable potential assessments.

3.1.2. Quantitative Information Extraction from Text

To support energy system modelers in researching techno-economic data, we use natural language processing methods to automatically identify and extract quantitative information from scientific literature [74]. As part of ETHOS, this functionality is bundled in a framework called Quinex [34] (short for Quantitative Information Extraction).

Quinex builds on lightweight large language models that are specifically trained on extracting quantitative information from scientific literature. Quinex outperforms similar lightweight systems for quantitative information extraction and also provides qualitative improvements, such as capturing implicit properties and detailing critical qualifiers such as the spatio-temporal scope. Quinex is trained on large heuristically created datasets [33] from Wikipedia and Wikidata as well as human-labeled data from various scientific domains including energy systems analysis. This broad training data enables small models to achieve robust performance across domains. Quinex's domain-agnostic design and low computational requirements make large-scale literature analysis accessible to a broad audience. The framework is openly available as a Python package (https://pypi.org/project/quinex/, https://github.com/FZJ-IEK3-VSA/quinex), as are the underlying language models (https://huggingface.co/JuelichSystemsAnalysis).

Furthermore, to facilitate the sharing, reuse and integration of energy technology data, a controlled-access techno-economic database is being developed. In this database, data will be described using the Open Energy Ontology [75] (OEO) as a community-driven terminology standard. Meanwhile, Quinex is being extended to automatically populate the database.

Table 1
Major modules of the ETHOS suite that 1) are already openly available or 2) have already been published in journals and are scheduled for open-source release.

Category	ETHOS Model	Short description	Repository	Journal Publications
Data & Metadata	DataDesc	Metadata schema for software and data	https://github.com/FZJ-IEK3-VSA/DataDesc	[31,32]
Data & Metadata	Quinex	AI-based extraction of quantitative information from text	https://github.com/FZJ-IEK3-VSA/ETHOS.quinex	[33,34]
Data & Metadata	LoadProfile-Generator	Generation of load profiles for residential buildings	https://github.com/FZJ-IEK3-VSA/LoadProfileGenerator	[35,36]
Data & Metadata	PeNALPS	Generation of load profiles for industrial sites	https://github.com/FZJ-IEK3-VSA/ETHOS_PeNALPS	[37]
Data & Metadata	BUILDA	Provision of spatially explicit building data	https://github.com/FZJ-IEK3-VSA/ethos-builda-client	[38,39]
Renewable Energy Potential Assessment	GeoKit	Analysis and Processing of Geodata	https://github.com/FZJ-IEK3-VSA/geokit	[40]
Renewable Energy Potential Assessment	GLAES	Land eligibility assessment for energy technologies	https://github.com/FZJ-IEK3-VSA/glaes	[41]
Renewable Energy Potential Assessment	RESKit	Simulation of globally validated generation profiles and costs for energy technologies	https://github.com/FZJ-IEK3-VSA/RESKit	[20,42]
Renewable Energy Potential Assessment	PASSION	AI-based assessment of rooftop potentials worldwide	https://github.com/FZJ-IEK3-VSA/PASSION	[43]
Renewable Energy Potential Assessment	REFLOW	Provision of a workflow manager for potential assessments	https://github.com/FZJ-IEK3-VSA/ethos.REFLOW	[44,45]
Energy Systems Design	tsam	Time series aggregation for energy systems analyses	https://github.com/FZJ-IEK3-VSA/tsam	[12,46–48]
Energy Systems Design	spagat	Spatial aggregation for energy systems analysis	https://github.com/FZJ-IEK3-VSA/FINE/tree/master/fine/aggregations	[49]
Energy Systems Design	HiSim	Simulation of building energy systems	https://github.com/FZJ-IEK3-VSA/HiSim	[50]
Energy Systems Design	FINE	Facilitated energy system model set-up via standardized framework	https://github.com/FZJ-IEK3-VSA/FINE	[51]
Socioeconomics	DEMARCO	Macro-economic assessment of energy systems	Release planned	[52–54]
Socioeconomics	MODE.behave	Assessment of mobility behavior	https://github.com/FZJ-IEK3-VSA/mode_behave	[55]
Model Instance	FineBuildings	Optimization of building energy systems at arbitrary locations	Release planned	[56–59]
Model Instance	FineRegions	Optimization of German municipalities	Release planned	[60,61]
Model Instance	NESTOR	Optimization of one-node national energy systems	Release planned	[62–65]
Model Instance	Infrastructure	Optimization of multi-node energy infrastructure	Release planned	[66]
Model Instance	FineEurope	Optimization of the European energy system (multi-node)	Release planned	[67]

3.1.3. *Load Profile Generation*

Load profiles are time series that represent the energy demand of individuals, devices, or facilities over time. In energy systems, accurately capturing and anticipating demand through load profiles is essential for ensuring the alignment of energy supply and demand. These profiles are critical inputs for evaluating and designing flexibility measures, including energy storage systems, demand-side management, flexible generation technologies, oversizing unflexible energy supply technologies, and energy imports. Load profiles provide detailed insights into consumer behavior patterns. As a result, empirically measured load profiles are often considered sensitive data, which limits their availability for research and development purposes.

In addition, many energy system analyses require load profiles for hypothetical or future scenarios where no measured data exists. This makes it necessary to generate load profiles through alternative methods such as occupancy behavior simulation [76]. Artificial load profiles offer two key advantages: they can be freely shared as open data, and they can be tailored to represent prospective scenarios. To support this need, the ETHOS platform offers two tools for load profile generation. The ETHOS.LoadProfileGenerator simulates electricity demand profiles for private households, while ETHOS.PeNALPS focuses on simulating load profiles for industrial manufacturing processes.

LoadProfileGenerator. The LoadProfileGenerator [35] is an agent-based residential demand model designed to generate high-resolution load profiles for individual households. It is based on a desire-driven approach that uses a psychological model to simulate daily activities of each occupant. These activities are linked to devices, whose load is then aggregated to create the household load profile. By modeling each occupant and device individually, the LoadProfileGenerator can account for various constraints such as time limits and concurrent device usage, resulting in realistic and internally consistent energy demand patterns. The LoadProfileGenerator offers highly detailed household configuration options, including every device and behavioral trait of the occupants. To simplify usage, it provides a set of predefined households representative of the German population, which can be simulated directly or adapted as needed.

The model has been applied for many different purposes, for example assessing methods for electric vehicle charging [77] and optimal sizing and operation of photovoltaic systems [78,79]. In future work, it will serve as a foundation for simulating occupant behavior and energy demands for entire cities.

The LoadProfileGenerator is fully open-source (https://github.com/FZJ-IEK3-VSA/LoadProfileGenerator). Precompiled executables are available for both Windows and Linux (https://www.loadprofilegenerator.de/download). They include a graphical user interface for household configuration, and a command line tool for simulation. Additionally, a Python wrapper library is available via PyPI (https://pypi.org/project/pyloadprofilegenerator/).

PeNALPS. ETHOS.PeNALPS [37] (Petri Net Agent-based Load Profile Simulator) simulates the load profiles of industrial manufacturing systems. It enables the modeling of individual 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.

PeNALPS conceptualizes industrial manufacturing systems as networks of work systems that are interconnected via material flows. Each work 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 production schedule.

The energy demand of the system is attributed to both the activity of

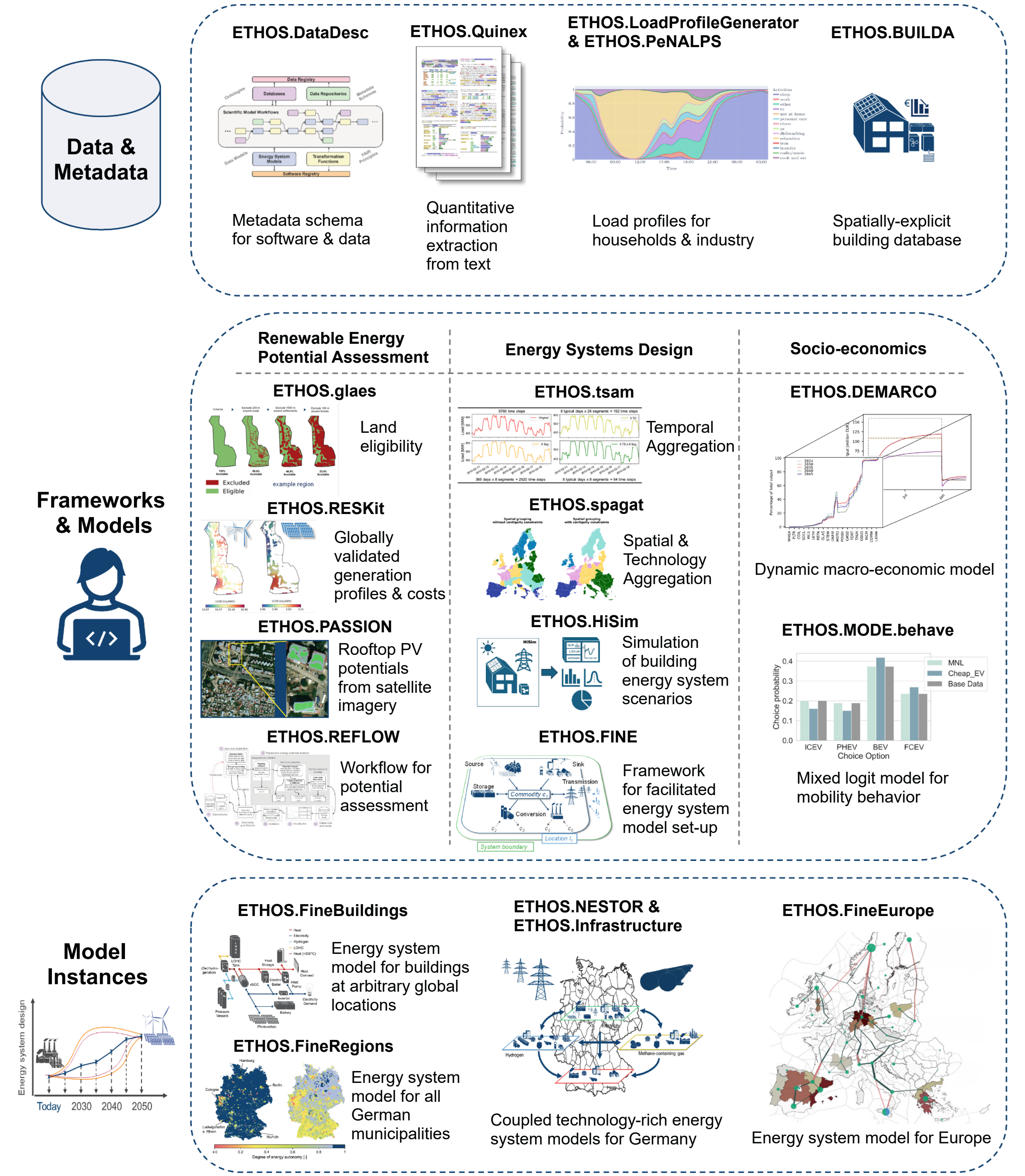

Fig. 2. Overview of the major modules of the ETHOS suite, categorized into "Data & Metadata", "Frameworks & Models" and "Model Instances". The modules are either 1) already openly available or 2) have already been published in journal articles and are scheduled for open-source release. The illustrations in the figure were taken from various previous publications[2,24,32,34,36,43,44,49,50,53,55,58,60,68].

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 [37].

3.1.4. Building Database

The building database ETHOS.BUILDA provides building data for the

German building stock at the level of individual buildings. Data includes both geometric information, such as the building footprint and the height, as well as information about, for example, building type, size class, construction year, TABULA types, and heating systems. The footprint polygons were retrieved from official 3D building datasets and OpenStreetMap data [38]. The building footprint data was then enriched with further attributes, using both the aforementioned data sources as well as additional sources, such as the German census. Furthermore, machine learning models were trained in order to impute missing values for attributes, such as height [38], size class and construction year [39]. Using this approach, a complete building dataset for Germany was created.

The data is made available through a Rest-API (https://ethos-builda.fz-juelich.de/), which allows the targeted retrieval of buildings of selected types and for areas. Furthermore, a ready-made Python client (https://github.com/FZJ-IEK3-VSA/ethos-builda-client) is available, which is especially useful for integration in Python-based workflows. Furthermore, database extracts in CSV-format can be downloaded from Zenodo (https://doi.org/10.5281/zenodo.11845991, https://doi.org/10.5281/zenodo.12069754).

The database is a valuable resource for large-scale simulation studies of the German building stock and provides the data necessary to parametrize building models such as ETHOS.HiSim (https://github.com/FZJ-IEK3-VSA/HiSim). This makes it possible to conduct bottom-up studies of, for example, self-sufficiency rates of building energy systems [50]. In the future, data from ETHOS.BUILDA could be used in workforce demand analyses for building envelope refurbishments or for city simulations. The database will be extended to include the buildings of further countries in the future.

3.2. Renewable Energy Potential Assessment

Future greenhouse gas-neutral energy systems will be based on renewable energies for electricity and heat supply. To plan these systems appropriately, information is needed on the technical, economic, and feasible [80] potential of renewable energies, which is determined by restrictions such as land availability, solar radiation, wind conditions, etc. Determining this potential is not straightforward, and there are many different approaches that have also led to scientific debates in the past [81,82]. The modules of the ETHOS suite described below are therefore continuously being developed to keep them up to date with the latest scientific findings [83,84].

3.2.1. Land Availability and Renewable Energy Simulation

ETHOS.GLAES [41] allows the processing of geographical information to identify areas suitable for a specific application. Typically, it is utilized to assess eligible areas for different renewable energy technologies but can be used for all land-use related questions as for instance already done to assess locations of salt caverns for underground hydrogen storage [85]. The spatial resolution can technically be as high as 1m x 1m, effectively the achievable accuracy depends on the selected input datasets. The exclusions based on multiple geographical entities selected by the user from different datasets can be blended within ETHOS.GLAES, and individual buffer distances to specified point or polygon features can be defined. Based on this information, ETHOS.GLAES iteratively calculates the remaining eligible area and returns it as a scalar percentage as well as a combined raster eligibility map. The geospatial operations within ETHOS.GLAES heavily rely on ETHOS.GeoKit [40], a versatile tool for geospatial analyses in Python which can also be used autonomously. Making use of calculation-efficient gdal [86] operations, it allows dealing with vector and raster data in a single package. ETHOS.GeoKit is often used to pre-process and harmonize vector network layers. In Caglayan et al. [87], for example, these layers were then clipped to the study area, aligned to coordinate reference systems and prepared for candidate grids. These layers were subsequently employed in the design of hydrogen transmission networks within a fully renewable European energy system.

Within a second step, ETHOS.GLAES places renewable energy technologies across the identified eligible areas. The distribution of polygons as well as point locations is possible, with an optional spatial orientation such as it is used e.g. to consider different distances between wind turbines in main or crosswind direction. The geospatial information obtained from ETHOS.GLAES can be directly utilized within ETHOS.RESKit [31]. Alternatively, continuous rasters indicating distances from each exclusion case can be generated, allowing for multi-criteria decision-making approaches.

ETHOS.RESKit [42] is a simulation tool, which calculates the output time-series of renewable and other energy technologies at a specific geolocation or area. For each energy technology, a separate module is implemented, currently covering wind turbines, photovoltaic systems, concentrated solar power and enhanced geothermal systems. Each module contains workflows to account for different weather data sources or methodological approaches. The workflows are usually based on a time-resolved weather data input, often combined with a static downscaling via the global wind atlas [88] respectively global solar atlas [89]. To ensure reliable and accurate results, validation is a crucial prerequisite. Wind workflows in ETHOS.RESKit currently exist both validated for MERRA-2 [90] on a European scale [20] and for ERA-5 [91] on a global scale [42]. The temporal resolution is usually determined by the main weather dataset, often hourly [90,91], whereas the spatial resolution is determined by the long-run average data used for the spatial resampling which typically is at 250m x 250m resolution [88,89]. The output of ETHOS.RESKit is, hence, a time-series, often in hourly resolution, of generated power of a specific renewable energy technology for a specific plant. This can be analyzed at high detail level for local assessments or be aggregated for use in energy system models like ETHOS.FINE [51] due to the vast amounts of data. Besides modules for power generation technologies, ETHOS.RESKit enables simulation of weather-dependent technologies in general. For instance, the specific energy demand of direct air capture (DAC) plants is severely affected by the prevailing air temperature and relative humidity [92] and can be simulated for specified locations using ETHOS.RESKit. While default DAC models from literature are already incorporated, the user can define further models as sought. Furthermore, other location specific time series data, such as the energy demand or water consumption of cooling systems, can be calculated by existing modules with ETHOS.RESKit.

Up until now, ETHOS.GLAES and ETHOS.RESKit have been utilized widely, spanning from national [93–96] over regional and continental [20,41,68,85,97,98] to global assessments [99,100]. ETHOS.GLAES and ETHOS.RESKit have also been used to generate the energetic potential at global scale for multiple IEA reports [25–30,101]. Their focus is on open-field PV and wind onshore, but further applications span other energy technologies like rooftop photovoltaics [95], geothermal systems [102], agri-, parking and floating photovoltaics [94] or salt caverns [85] as well. Typically, ETHOS.GLAES and ETHOS.RESKit are used together to generate input for energy system models [63,67].

An exception to this is the H_2 Atlas Africa [103], which provides openly available data via a web-based GUI. Here, ETHOS.GLAES and ETHOS.RESKit were used for renewable and hydrogen potential assessments. The application of ETHOS.GLAES is not limited to renewable energy technologies but can be applied to all land-use questions. In this regard, land-use change and impact of climate change on land-use are promising future applications of ETHOS.GLAES. The integration of weather products covering climate change in turn presents a promising future application for ETHOS.RESKit to assess the impact of climate change scenarios on renewable energy generation. The integration of workflows for further energy technologies is planned to create a framework which can provide all weather-dependent time series data needed for energy system models.

ETHOS.GLAES, ETHOS.RESKit, and ETHOS.GeoKit are open-source Python-based software packages, available via the conda-forge channel or for development use directly from their github repositories (https://github.com/FZJ-IEK3-VSA/glaes, https://github.com/FZJ-IEK3-VSA/reskit, https://github.com/FZJ-IEK3-VSA/geokit). The tools can be used either separately or in combination, allowing for a geolocation specific assessment of renewable energy potentials at local to global scales. Workflow managers within the packages provide the user with easy to apply workflows for different application cases.

3.2.2. Renewable Potential Assessment Workflows

As described above, most renewable resource assessments are not transparent and reproducible [72]. To counteract this, we have developed the ETHOS.PASSION and ETHOS.REFLOW workflows for our assessments.

ETHOS.PASSION [43] represented our first attempt to generate a conceptual workflow for rooftop photovoltaic potential assessment. PASSION comprises an open-source, scalable, and robust workflow based on three neural networks integrated into a two-look approach to identify roof areas using satellite images, place photovoltaic modules there, and determine their maximum techno-economic potential per roof half.

ETHOS.REFLOW [44] is a Python-based workflow management tool designed to ensure transparency and reproducibility in renewable energy potential assessments. It draws on our experience with the development of PASSION. REFLOW uses Spotify's Luigi as the core workflow manager and supports containerization through Docker for reproducible computing environments. The framework allows researchers to reproduce existing workflows through simple single-line commands using standardized JSON configuration files rather than modifying underlying code. This approach reduces technical barriers for users with varying programming experience while maintaining full reproducibility. The tool automatically manages Python package dependencies and can be easily integrated with any software that has a Python interface, including GLAES for land eligibility analysis and RESKit for power generation simulations.

REFLOW implements a structured computational workflow using a directed acyclic graph architecture that manages task dependencies and ordering. The framework addresses critical reproducibility challenges in renewable energy research, where studies often lack adequate documentation and code availability. REFLOW supports heterogeneous data types including meteorological time series (NetCDF), geospatial data (shapefiles, GeoTIFF), and tabular data (CSV, JSON). It allows full reproducibility through the full data science workflow of renewable potential analyses: from data acquisition and pre-processing through land eligibility assessments and power generation simulations, to report generation and visualization. Key features include comprehensive logging, checkpoint functionality for long-running analyses, parallel processing capabilities for HPC systems, and built-in validation routines for early error identification.

REFLOW has been successfully demonstrated through case studies including a technical offshore wind potential assessment of the North Sea [44] and a land use assessment of the worldwide solar and wind infrastructure [45]. The North Sea case study evaluated two methodologies across multiple scenarios for both fixed-foundation and floating turbine technologies, estimating an installable capacity ranging between 768-861 GW with annual electricity yields between 2,916-3,047 TWh. Ongoing applications include a techno-economic assessment of Europe's onshore wind energy under various social acceptance scenarios based on the proximity of wind infrastructure to scenic areas [104], and an assessment of Europe's offshore wind energy potential incorporating a novel physics-based model for estimating wake reductions from large-scale wind turbine deployment. The machine-readable outputs of RELFOW can be integrated directly with energy system optimization models, which allows for the future development of a fully reproducible comprehensive energy system analysis, from potential assessments through to full-scale energy system optimization.

3.3. Energy Systems Design

A unique feature of the ETHOS model suite is that the energy system analyses are possible on all spatial scales. In addition to the global and (inter-)national analyses already described, we are thus also able to conduct optimizations at municipal [60,61] and building level [56–59]. This supports us in evaluating the feasibility of the national transformation pathways at the local level and in providing policy advice on necessary regulations. An analysis of different spatial scales is made possible by our developed open-source Framework for Integrated Energy System Assessment (ETHOS.FINE) and a joint technology database. Through standardized features for technology and measure specification, the framework enables the accelerated implementation of energy system models and is the basis for all our optimization models.

3.3.1. Framework for Integrated Energy System Assessment (ETHOS.FINE)

ETHOS.FINE [51] provides a framework for modeling, optimizing and assessing energy systems. To set up an energy system model, modelers can assemble components from different object classes. These include sources and sinks representing imports and demands, conversion technologies that capture processes such as electricity generation, transmission elements that interconnect nodes or regions to facilitate the exchange of energy carriers, and storage units that enable temporal balancing of the system.

To manage model complexity, the framework provides built-in aggregation tools. Temporal resolution can be simplified using the integrated Python package tsam [12], which enables clustering of time steps into typical periods, segmentation of time series, or hybrid approaches, while spatial and technological detail can be reduced following established aggregation methods [49]. More detailed descriptions of these aggregation methods follow below. Transformation pathways can be examined by incorporating multiple investment periods under myopic, rolling horizon, or perfect foresight formulations [62]. Furthermore, the framework enables stochastic optimization for single-year planning problems with multiple parameter realizations, thereby facilitating the identification of more robust system configurations.

Recent applications include analyses of the influence of meteorological variability on optimal siting strategies for direct air capture technologies [92,105], investigations of the role of foresight horizons in shaping decarbonization trajectories [62], and participatory mapping of local cost potentials for green hydrogen in sub-Saharan Africa [98]. ETHOS.FINE is an open-source Python-based software package, available via the conda-forge channel or for development use directly from its GitHub repository [51].

3.3.2. Time Series Aggregation Module (ETHOS.tsam)

Incorporating large amounts of data is a particular challenge for energy system models, as they are generally based on optimization problems whose complexity increases disproportionately to the number of variables and constraints considered. This is a hurdle to the maximum level of detail that can be achieved with these models. For this reason, acceleration methods have been systematically developed, implemented, and validated that permit the incorporation of ever higher resolution datasets into ever larger models. These include the development of heuristics that reduce the resolution of models in those areas where high resolution does not provide added information value. Examples of these techniques include spatial [49] and temporal aggregation [12], i.e., grouping together regions and time steps considered by the models that do not significantly differ from each other.

In addition to comprehensive surveys [2,106] on energy system frameworks and the general handling of complexity in these systems, we achieved several further developments in the field of temporal aggregation. As part of our ETHOS model suite, our open-source tool ETHOS.tsam (Time Series Aggregation Module) for automated Pareto-optimal time series aggregation allows users to select different combinations of clustering approaches and representation methods for time series aggregation, thereby accelerating the solving of our optimization problems [12]. Our advanced but generally applicable clustering techniques allow for ad-hoc improvements of current approaches without requiring profound knowledge of the individual energy system model. These improvements comprise a method to find the optimal trade-off between the number of typical days and inner-daily temporal resolutions, and a representation method that can reproduce the value distribution of the original time series.

Our improvements in current methods dominate the status quo with respect to Pareto-optimality in terms of runtime and accuracy. While a speeding up factor of one magnitude could be achieved using traditional aggregation methods within a cost deviation range of two percent, our algorithms can achieve this accuracy with a runtime speedup by a factor of two orders of magnitude.

The ETHOS.tsam tool is published open-source on GitHub, and available via the PyPI (https://pypi.org/project/tsam/) and conda-forge channels. Beyond its core algorithms, it is designed to integrate seamlessly into existing modeling workflows with minimal adaptation effort as applied by modelers worldwide, for example, in prominent optimization frameworks such as PyPSA [9] and ETHOS.FINE [51,107]. Notably, ETHOS.tsam supports flexible temporal resolutions, including sub-hourly, which are becoming increasingly relevant as renewable energy penetration increases [108]. Additionally, it can handle multiple parallel time series, including load data, weather data, and market prices, thereby broadening its applicability. This flexibility renders it suitable for a variety of energy system analyses.

3.3.3. Spatial and Technological Aggregation (ETHOS.spagat)

As energy system models increase in spatial and technological resolution, their computational complexity grows substantially. This challenge becomes particularly pronounced in models that span large geographic areas and incorporate high shares of variable renewable energy sources, such as wind and solar power. In such cases, the models may become computationally infeasible to solve in a reasonable time.

To address this, the SPAGAT [49] tool is employed to reduce model complexity. It does so by identifying representative subsets of regions and variable components, thereby enabling aggregation without significant loss of critical information. This dimensionality reduction approach helps maintain the integrity of system dynamics while ensuring that the model remains computationally tractable.

The spatial and technological aggregation functions are integrated into the FINE framework. Therefore, the same installation as for FINE applies here. SPAGAT reduces:

(a) **The number of regions present in the energy system model.** The regions with similar attributes (operation rates, capacity, locational eligibility, etc.) of different components (renewable technologies, electricity demands, storages, etc.) can be grouped. The k-medoids clustering algorithm is used for grouping. In the next step, each component is aggregated, thus providing a reduced set of regions that represent the original region set.

(b) **The number of installation sites of variable renewable technologies such as wind turbines or photovoltaics.** A time series aggregation, using hierarchical clustering, is employed to reduce the number of individual installation sites of renewable technologies present in the energy system. In contrast to tsam, SPAGAT aggregates several time series into one representative series, whereas tsam aggregates the time steps of several single time series.

If the number of wind turbines are to be reduced, then in each region, the wind turbines' operation time series are first clustered using a hierarchical clustering algorithm. Next, a representative per group is obtained by taking the average of all the times series in the group and the sum of all their capacities.

3.3.4. Household Infrastructure and Building Simulator (ETHOS.HiSim)

ETHOS.HiSim [50] is a Python-based, open-source building simulation framework designed for bottom-up analyses of household scenarios and building energy systems. It generates detailed load profiles for electricity consumption and generation, heating demand, and smart control strategies. The framework is easy to install, user-friendly, and publicly available under a MIT license (https://github.com/FZJ-IEK3-VSA/HiSim).

ETHOS.HiSim is modular, highly scalable, and well-suited for automation and parallel computing. Users can select different temporal resolutions, ranging from 1 to 60 minutes, depending on the level of detail required. With ETHOS.HiSim all kinds of household infrastructures and building energy systems can be modelled and analyzed. Users can choose between different household scenarios like singles, families or seniors etc. providing different residents load profiles. Also, users can build their own energy system containing rooftop PV, solar thermal systems, boilers or heat pumps, fuel cells, batteries, energy management systems and many more. Different building types with diverse physical properties, including size, height, location, energy efficiency, u-values, rooftop orientation, can be simulated. Large building stock analyses can be conducted in an efficient and precise manner. Furthermore, different climate scenarios can be investigated, e.g., to evaluate the effects of climate change on building systems.

3.4. Socio-economics

As shown in Fig. 1, in addition to modules for techno-economic analysis, the ETHOS model suite also includes modules for the socio-economic assessment of energy systems, which are described below.

3.4.1. Dynamic macro-economic assessment (ETHOS.DEMARCO)

The macroeconomic environment in which energy system transformation occurs plays a crucial role in shaping key outcomes. Its influence extends well beyond the standard considerations of gross domestic product (GDP) growth and energy consumption. Additional important factors include openness to trade, the availability of essential industrial inputs, and the presence of production resources such as skilled labor, financial capital, and natural capital. These elements can either accelerate or slow progress toward achieving net-zero carbon emissions, making them critical to consider.

The central focus here is not only on how the transformation of the energy system affects the overall economy (as in Royston et al. [109]). Instead, we also investigate how broader macroeconomic conditions can influence both the success and pace of the transition to net-zero carbon emissions. At the same time, it remains important to assess the effects of the transition on key economic indicators such as GDP, wages, employment, and household consumption to provide context for a 'just transition.'

To support this analysis, we are developing a set of modules within ETHOS.DEMARCO that can be integrated with energy system optimization models or used as standalone tools. These tools are designed to evaluate the macroeconomic implications of various shocks and policy interventions. This approach expands the typical scope of energy system transformation assessments by also considering issues such as labor market policies, fiscal policies, and the resilience of the system to external shocks and how these factors might affect the energy system.

The development of these tools is informed by recent research [110–113] and draws on a wide range of economic models, including general equilibrium, disequilibrium, econometric approaches, and state-of-the-art agent-based modeling. Each method has its own strengths and limitations, but by applying these tools in parallel and selecting the most appropriate one for each use case, it is possible to provide a comprehensive assessment of key macroeconomic issues. Example applications include analyzing the implications of short-term economic constraints in a hybrid energy-economy setting [53], assessing system resilience [54], and examining the impacts of water scarcity [114].

Recent work [115] introduces a state-of-the-art macroeconomic modelling framework that is currently being incorporated into the DEMACRO module. By design, this framework supports cross-domain integration and anticipates closer connections with various aspects of the current ETHOS suite such as ETHOS.MO|DE (see section 3.4.2). Bi-directional linking is explicitly enabled, allowing for interactions between the modules. However, full incorporation into the DEMACRO toolbox is still a work in progress.

3.4.2. Mobility behavior

ETHOS.MO|DE.behave [55] is a Python-based software package used for estimating and simulating discrete choice models. ETHOS.MO|DE.behave uses advanced discrete choice methods to quantitatively analyze survey data on consumer choice behavior. To this end, ETHOS.MO|DE.behave contains routines for estimating conventional multinomial logit models. Notably, it is the first software tool to provide functions for estimating mixed logit models with non-parametric distributions. In addition, post-processing tools are available that help to analyze and apply the previously estimated choice models quickly. Furthermore, simulation methods are included which can be used in particular in transportation research [102,103], among other areas. One example of this is simulating long-term mobility-related decisions, such as whether to buy a car, and short-term decisions about how to travel on an upcoming trip. This information can then be used to calculate transport demand and the energy required for both public and private transport.

ETHOS.MO|DE.behave has been developed as a broadly applicable framework for the rapid quantitative analysis of choice behavior based on discrete choice theory. A typical use case can be seen in the analysis of survey data. The following four steps must be followed. First, the survey data must be prepared according to the input format specified in the repository's documentation. Then, in the second step, the relevant model attributes must be selected and the further model parameters specified. Next, a multinomial or mixed logit model is estimated. Finally, the estimated model parameters and simulation results are analyzed and visualized.

A recent application of ETHOS|MODE in the ETHOS modelling suite involves providing input parameters to ETHOS.NESTOR (Section 4) relating to passenger transport demand by transport mode, as well as powertrain mixes. Both data sets are relevant for estimating transport energy demands, including the type and quantity of fuels, which depend on the powertrain type and efficiency. The software package ETHOS.MO|DE.behave and its associated workflows are currently being further developed, with the aim of making them also available as open source.

4. Model Instances and Interfaces

In this section, we describe the model instances of the ETHOS.FINE energy system optimization framework (see Fig. 3). The framework is used to define possible technologies and measures, as well as all inputs to be used for a specific energy system within a spatial boundary. Although other modules such as RESKit were also used for case studies (see details above), these are not optimization model instances in this sense, which are used for various questions and sensitivity calculations as in the case of energy systems. The model instances described below can be recreated using the open-source modules of the ETHOS model suite. However, they are not yet available as open source – work is currently underway on their publication.

ETHOS.FineEurope. The ETHOS.FineEurope model is a spatially and temporally highly resolved energy system optimization model depicting the European energy system by covering the EU-27 as well as the United Kingdom, Norway, and Switzerland. The model focuses on electricity, natural gas and hydrogen infrastructures, representing the import, generation, storage, and transmission of these energy carriers. Reassignment of existing natural gas underground storage and pipeline infrastructure is explicitly considered (see Fig. 3). Other sectors are represented by their exogenously defined demand for electricity, hydrogen, and natural gas (see details in Supplementary Material). Ongoing developments include modeling the value chains of hydrogen derivatives and synthetic fuels, including their transport via ships and trucks. Besides ETHOS.FINE, the model utilizes various other packages from the ETHOS model suite and databases to generate the model input [67]. The model can be applied in a myopic, rolling horizon, or perfect foresight setting with a variable investment period length to analyze the different transformation pathways toward greenhouse gas neutrality.

In a first study [67], the model is used to investigate the optimal balance between the domestic production of hydrogen and its import from the world market. Thereby, the model results show that neither a fully self-sufficient system nor a complete reliance on imports is cost-optimal by 2050. Additionally, the results show also that varying weather conditions can change the optimal import share by up to 60%, thereby highlighting the importance of a flexible and diversified hydrogen supply strategy. Recently, the model was also expanded to include endogenous technological learning [116], which led to a significant increase in complexity. In this case, this computational efficiency challenge had to be addressed through appropriate temporal (section 3.3.2), spatial, and technological aggregation (section 3.3.3).

ETHOS.NESTOR. The ETHOS.NESTOR (**N**ational **E**nergy **S**ystem model with sec**TOR** coupling) model is a sector integrated, single-node energy system optimization model with hourly resolution (see Fig. 3). It represents national energy systems with high technological detail through a bottom-up modelling of process chains in the sectors energy supply, industry, residential and non-residential buildings, and mobility. Thus, energy demand from these sectors is endogenously optimized with respect to exogenous demands for industrial goods, transport demands for people and freight, and heated areas. The model calculates cost-optimal transformation pathways from existing national energy systems towards future energy systems by minimizing total systems costs while ensuring that emission reduction targets are met. To achieve this, ETHOS.NESTOR uses the modelling capabilities of ETHOS.FINE and several other packages from the ETHOS model suite to generate model input data (see Fig. 4).

The model is currently being developed for a few other countries, but in the past ETHOS.NESTOR was used solely for the German energy system. For example, one study [62] analyzes the impact of different foresight horizons on the transformation of the German energy system towards greenhouse gas neutrality. Another article [63] shows that moderate consideration of visual impacts by wind turbines and open-field photovoltaics in their siting processes does not have a significant impact on Germany's future energy system design and costs. Furthermore, the model has been used to investigate different recycling options for industrial processes and their effects on the German energy system [64], or the role of hydrogen as an important energy carrier in a greenhouse gas neutral system [65,126].

Along with ETHOS.FineEurope, ETHOS.NESTOR is the most complex model in the ETHOS suite, resulting in computation times ranging from several hours to two weeks. For this reason, aggregated versions of the model were recently developed to enable the calculation of thousands of scenario variations [127].

ETHOS.Infrastructure. The ETHOS.Infrastructure model depicts Germany with higher spatial resolution to integrate transmission infrastructure considerations into the energy transformation pathway optimization (see Fig. 3). The spatial resolution is based on the current high-voltage electricity grid. Voronoi regions around the grid buses are used as basis and aggregated to 80 regions to reduce model complexity, supplemented by two offshore regions to model offshore electricity generation. The model covers the exchange of electricity, natural gas, hydrogen and heat between the modeled regions along existing, planned and newly built transmission lines. Furthermore, reassignment of existing infrastructure, e.g. converting natural gas pipelines to hydrogen pipelines or natural gas underground storages to hydrogen storages, is included in the model. Demand of residential, industrial and commercial

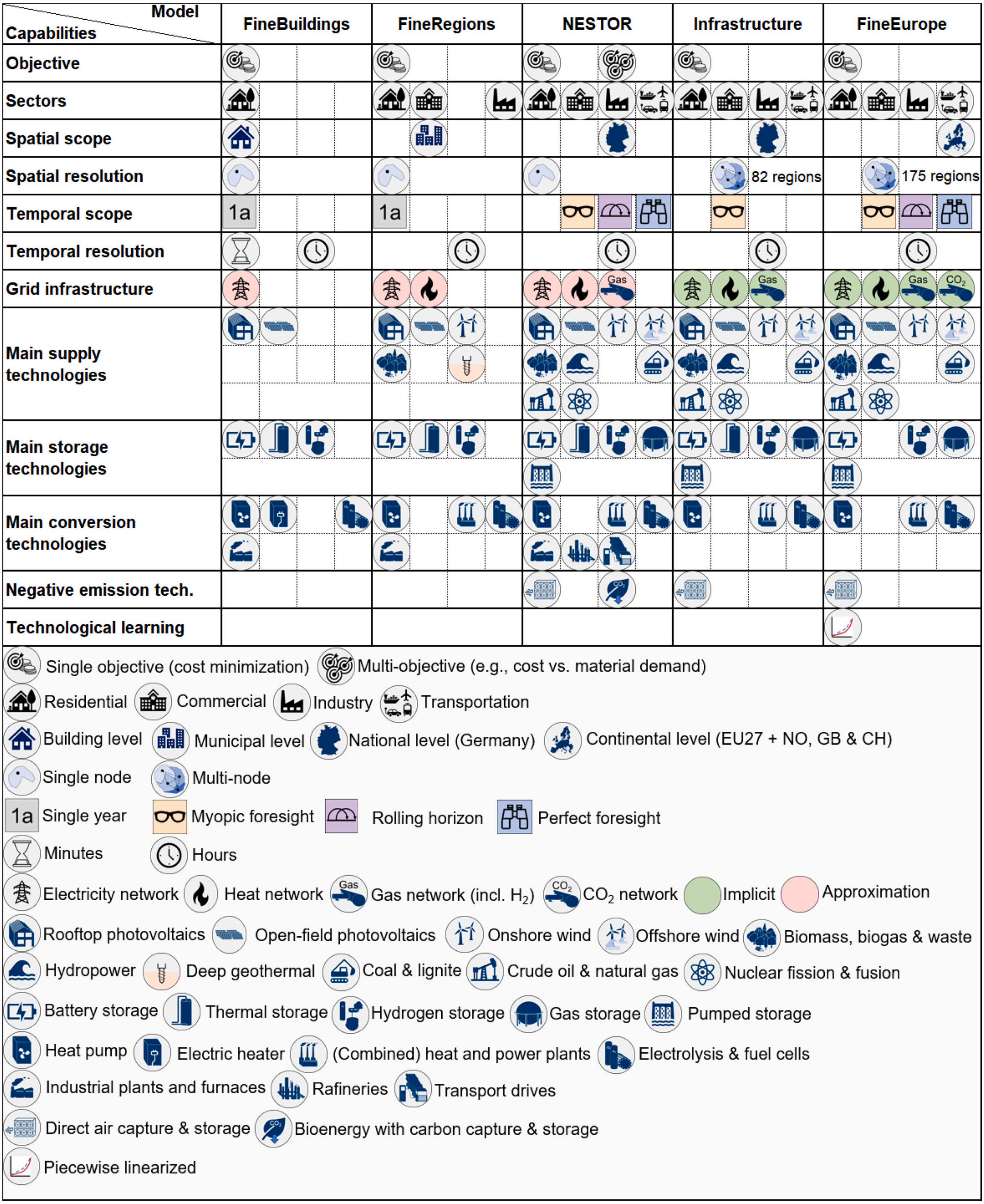

Fig. 3. Specifications of the five major FINE model instances. With the FINE framework, any degree of freedom would be possible in each model – therefore, only the details of previous use case studies are listed in the table.

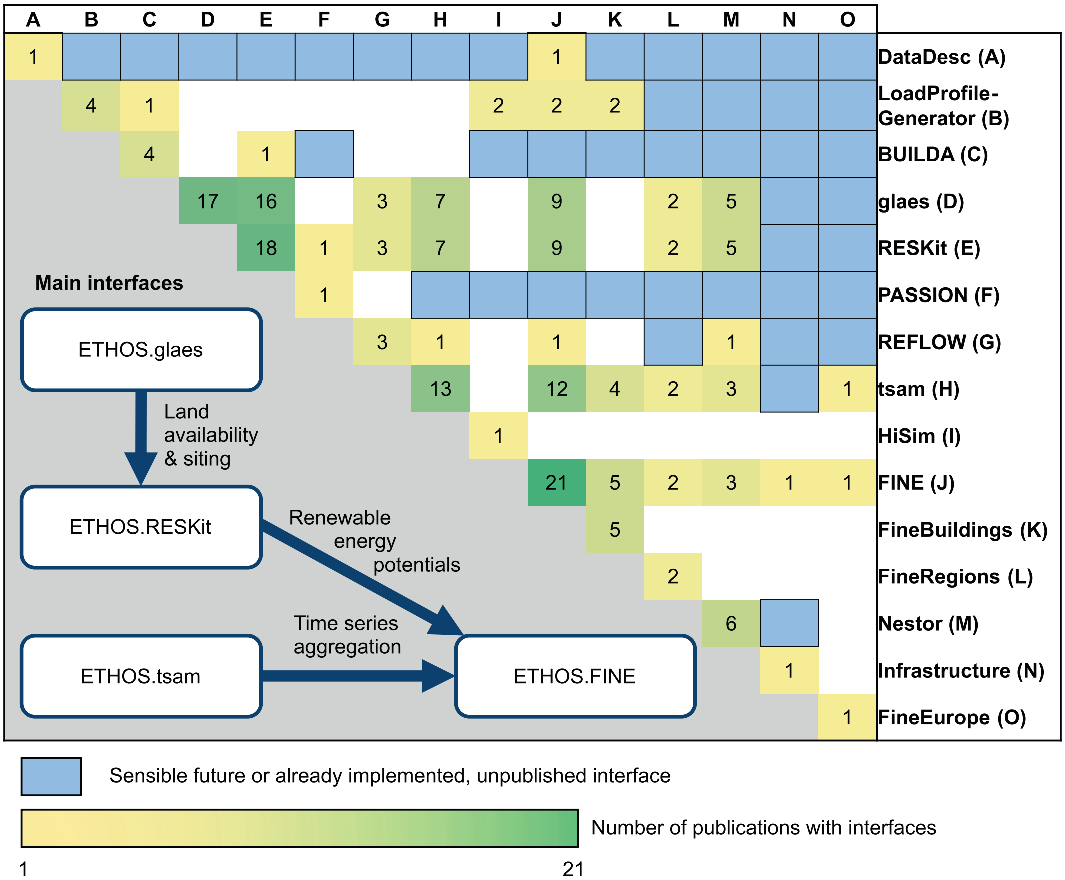

Fig. 4. Overview of ETHOS interfaces established in 35 articles published between 2022 and 2025. The correlation matrix shows which modules have been used in combination in the articles [12,31,36,38,39,43–45,49,50,57–63,65,66,68,92,94–96,98,100,117–125]. The interfaces shown in the grey bottom part of the figure are the ones that appeared most frequently in the articles.

sectors is given as exogenous input. The model can be applied in a myopic setting with a variable period length.

To increase sectoral coverage, ETHOS.Infrastructure can be coupled with ETHOS.NESTOR using optimized capacities and demand profiles and distribute them on a regional level. The distribution of capacities and their operation are done within the optimization in a cost-optimal manner considering grid bottlenecks. This approach has been used to investigate the role of liquid hydrogen and its transportation means via railway, truck and ship transport in an energy system optimized for the year 2045 [66]. Model results show that liquid hydrogen is only transported if hydrogen is requested as liquid, which might occur for the aviation sector or if high purity levels of hydrogen are required. Railway transport is shown to be a cost-efficient transportation option for liquid hydrogen but bottlenecks in the rail network limit its potential.

ETHOS.FineRegions. The ETHOS.FineRegions model is a municipal energy systems model that represents municipalities as a single node (see Fig. 3), similar to ETHOS.NESTOR. Therefore only simplified estimates of all infrastructures, such as heating networks, are provided based on established approaches from the literature [128,129]. Through the efficient design of the highly detailed model, together with complexity reductions based on time series aggregations, we were able to design the robust and cost-optimized energy systems of all 11,000 German municipalities for the first time [60]. For the parallel computation of more than one million optimizations, we used high-performance computing cluster infrastructure. This makes the ETHOS suite one of the few tools worldwide capable of conducting both detailed national and municipal energy system optimization of a whole country. One further example is the EXPANSE energy system model, which has already been applied to over two thousand Swiss municipalities [130,131], and to Switzerland as part of Europe [132,133].

Another ETHOS.FineRegions study [61] for 330 municipalities in the Upper Rhine Graben area in South Germany demonstrated that the novel technology of direct lithium extraction from thermal water can make deep geothermal plants cost-competitive with other renewable energy technologies. The modeled simultaneous supply of electricity in Organic Rankine processes and the provision of heat via district heating networks would primarily displace photovoltaic plants, wind turbines and heat pumps from cost-optimized systems. Our analysis further indicates that deep geothermal plants in 10% of the 330 municipalities could provide enough lithium to produce about 1.2 million electric vehicle battery packs per year, equivalent to 70% of the current (2022) annual electric vehicle registrations in the EU.

ETHOS.FineBuildings. The ETHOS.FineBuildings model identifies cost-optimal technology portfolios for building energy systems across different building types (see Fig. 3). Analyses [56] show that autonomous buildings can be realized through sector-coupled systems combining rooftop photovoltaics with conversion technologies, e.g., heat pumps, electrolysis, fuel cells, and electric boilers, and storage options including batteries, thermal storage, and hydrogen. Integrating a reversible solid oxide cell with liquid organic hydrogen carriers can achieve full electrical and thermal self-sufficiency with a cost premium of about 50%. High shares of on-site renewable generation can reliably meet electricity and heat demand depending on building type and load structure, although hydrogen costs must fall below 0.20 €/kWhH_2 to be economically viable by 2050. [57]

The model has also been used to evaluate the effect of temporal resolution on system design and reliability [48,58,117,134]. Results show that high temporal resolution can be crucial for accurately capturing storage dynamics and component sizing; for example, hourly models can underestimate inverter capacity by up to 50% compared with minute-level optimizations. Time-series aggregation can significantly reduce computational effort while maintaining accuracy, and sensitivity to high-resolution modeling decreases as the number of buildings increases.

Further instances. The ETHOS.FINE framework is very flexible and has been used for many other cases. One example is optimal siting of direct air capture (DAC) plants, aimed at removing CO_2 from the atmosphere. DAC plants depend heavily on prevailing weather conditions, which impact the productivity of CO_2 sequestration and the energy demand of the DAC system. A recent study [92] applies ETHOS.FINE to identify optimal locations for DAC plants across 11,000 German municipalities, while considering local renewable energy potentials including onshore wind, tracking PV, battery storage and a heat-pump for high and low temperature DAC processes. The model endogenously sizes all components and dispatches them to minimize total annual system cost, and reports municipality-specific Levelized Costs of DAC (LCOD) as total annualized system cost divided by the captured CO_2 across all hours. Further studies extend this model and apply it globally to analyze the cost differences between high and low temperature DAC processes. Using the ETHOS.FINE framework, we model a LCOD merit order showing the optimal locations for removing CO_2 until 2050 with both processes [135].

Model Interfaces. The ETHOS model suite is currently under construction and undergoing continuous development. Therefore, as described above, a small portion of the models is not yet open source, and interfaces such as those to ETHOS.Quinex will only be introduced in future publications. The already established model interfaces can be seen in Fig. 3. The figure shows that the modules for determining renewable energy potential (ETHOS.glaes & ETHOS.RESKit) and for complexity reduction are most often combined with the energy system optimization models based on the ETHOS.FINE framework.

5. Discussion and conclusion

The ETHOS model suite presented here provides a comprehensive framework for energy system analysis based on a uniform database. It enables model-based investigation of a wide range of research questions in the field. Although most modules are already available as open source and have been successfully linked in previous applications, further development remains necessary. Ongoing work aims to make all models openly accessible and to advance their development within an open and collaborative environment.

In addition, standardized workflows are being established for all stages of the modeling process. This approach has already been successfully demonstrated with ETHOS.REFLOW for renewable energy potential assessment [44]. To further enhance integration, uniform and efficient interfaces are required to ensure optimal model coupling. Community ontologies, such as the Open Energy Ontology, will be used to process data and metadata in a machine-actionable manner. This will also mean that all output data have to be provided in standardized formats, such as the IAMC format [136], in the future.

The model suite can also be readily connected to other open external tools. For example, results from energy scenarios could be used in prospective Life Cycle Assessment [137] with tools such as Brightway [138] to assess system-level environmental impacts (more information in Supplementary Material). Appropriate interfaces will need to be developed for this purpose, and inventory management could benefit from existing data-handling tools such as ETHOS.DataDesc [31,32] and ETHOS.Quinex [34] to support data harmonization. In this context, our research team is developing an ETHOS.FINE model instance that endogenously accounts for material requirements in system optimization [139]. Extensions similar to those implemented in REMIND-PyPSA-Eur [140] are also conceivable to link integrated assessment models (IAMs) with coarser temporal resolution to energy system models. While we have not yet encountered any major convergence issues when coupling existing modules (e.g., iterative coupling of ETHOS.NESTOR and ETHOS.Infrastructure), such issues could very well arise in the future. The article [140] on REMIND-PyPSA-Eur has clearly shown that 100% convergence may not be achievable due to structural differences between models.

Furthermore, although analyses with a temporal resolution of one minute have already been conducted using the model suite [141], interactions between the detailed equipment operation level, the system operation level, and the wide-area system planning level have not yet been investigated. However, such linkages and corresponding models could, in principle, be implemented within ETHOS.FINE.

In addition, while individual modules of the suite are unique (e.g., ETHOS.Quinex), many modules are comparable to similar models found in the literature. For example, the functionalities of ETHOS.FineEurope are comparable to those of PyPSA-Eur [140]. The strength of the suite lies rather in the interaction of its many modules to address a variety of research questions. It is also unlikely that all modules in the suite will ever be combined to address a single specific question; instead, individual selected modules will be used flexibly in combination for different questions.

In the long term, the model suite aims to provide a unified platform for comprehensive analyses of energy systems ranging from net-zero to beyond-net-zero [142] configurations. The approach with the suite will ensure consistent data use and harmonized model assumptions. It will also facilitate the automated integration of models from adjacent fields – such as renewable energy potential assessment or natural language processing-based data collection – into system optimization applications. Ultimately, the goal is to foster a large, open research community that collaboratively advances the suite and contributes to informed, evidence-based decisions in support of the energy transition.

CRediT authorship contribution statement

Jann Michael Weinand: Conceptualization, Methodology, Software, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Johannes Behrens:** Writing – original draft, Software. **Julian Belina:** Writing – original draft, Software. **Alicia Benitez:** Writing – original draft. **Arne Burdack:** Writing – review & editing, Software. **Shuying Chen:** Writing – review & editing, Software. **Kristina Dabrock:** Writing – original draft, Software. **Mak Đukan:** Writing – original draft, Supervision. **Philipp Dunkel:** Writing – original draft, Software. **Jan Göpfert:** Writing – original draft, Software. **Maxime Gorres:** Writing – original draft, Software. **Thomas Grube:** Writing – original draft, Supervision, Software. **Noor Titan Putri Hartono:** Writing – review & editing, Supervision. **Heidi Heinrichs:** Writing – review & editing, Writing – original draft, Supervision, Software, Funding acquisition. **Shitab Ishmam:** Writing – review & editing, Software. **Theresa Klütz:** Writing – original draft, Supervision, Software. **Patrick Kuckertz:** Writing – original draft, Supervision, Software. **David Neuroth:** Writing – original draft, Software. **Olalekan Omoyele:** Writing – original draft, Software. **Shruthi Patil:** Writing – original draft, Software. **Tristan Pelser:** Writing – original draft, Software. **Noah Pflugradt:** Writing – original draft, Supervision, Software. **Katharina Rieck:** Writing – original draft, Software. **Andrew Ross:** Writing – original draft, Supervision. **Thomas Schöb:** Writing – original draft, Supervision. **Kai Schulze:** Writing – original draft. **Hawal Shamon:** Writing – review & editing, Supervision. **Maximilian Stargardt:** Writing – review & editing, Software. **Sandra Venghaus:** Writing – review & editing, Supervision. **Stefan Vögele:** Writing – review & editing, Supervision. **Henrik Wenzel:** Writing – original draft, Software. **Christoph Winkler:** Writing – review & editing, Writing – original draft, Supervision, Software. **Christina Wulf:** Writing – review & editing, Supervision. **Petra Zapp:** Writing – review & editing, Supervision. **Jochen Linßen:** Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used the tools "ChatGPT" and "DeepL" in order to check grammar and spelling, and to make improvements to readability and style. After using these tools, the authors reviewed and edited the content as needed, and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Resource availability

Please refer to Table 1.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2026.102305.

Data availability

No data was used for the research described in the article.

References

[1] Chang M, et al. Trends in tools and approaches for modelling the energy transition. Appl Energy 2021;290(116731). https://doi.org/10.1016/j.apenergy.2021.116731.

[2] Hoffmann M, et al. A review of mixed-integer linear formulations for framework-based energy system models. Adv Appl Energy 2024;16:100190. https://doi.org/10.1016/j.adapen.2024.100190.

[3] Morrison R. Energy system modeling: Public transparency, scientific reproducibility, and open development. Energ Strat Rev 2018;20:49–63. https://doi.org/10.1016/j.esr.2017.12.010.

[4] Lombardi F, Pfenninger S. Human-in-the-loop MGA to generate energy system design options matching stakeholder needs. PLOS Clim 2025;4:e0000560. https://doi.org/10.1371/journal.pclm.0000560.

[5] Schulze K, Kullmann F, Weinand JM, Stolten D. Overcoming the challenges of assessing the global raw material demand of future energy systems. Joule 2024;8:1936–57. https://doi.org/10.1016/j.joule.2024.05.016.

[6] Hofmann, F., Hampp, J., Neumann, F., Brown, T. & Hörsch, J. atlite: A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series. *JOSS* **6**, 3294, 10.21105/joss.03294 (2021).

[7] Hatton L, et al. The global and national energy systems techno-economic (GNESTE) database: Cost and performance data for electricity generation and storage technologies. Data Brief 2024;55:110669. https://doi.org/10.1016/j.dib.2024.110669.

[8] Wilkinson MD, et al. The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 2016;3:160018. https://doi.org/10.1038/sdata.2016.18.

[9] Brown T, Hörsch J, Schlachtberger D. PyPSA: Python for Power System Analysis. JORS 2018;6:4. https://doi.org/10.5334/jors.188.

[10] Hilpert S, et al. The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling. Energ Strat Rev 2018;22:16–25. https://doi.org/10.1016/j.esr.2018.07.001.

[11] Pfenninger S, Pickering B. Calliope: a multi-scale energy systems modelling framework. JOSS 2018;3, 825:10.21105/joss.00825.

[12] Hoffmann M, Kotzur L, Stolten D. The Pareto-optimal temporal aggregation of energy system models. Appl Energy 2022;315:119029. https://doi.org/10.1016/j.apenergy.2022.119029.

[13] Dardor D, et al. ROSMOSE: A web-based decision support tool for the design and optimization of industrial and urban energy systems. Energy 2024;304:132182. https://doi.org/10.1016/j.energy.2024.132182.

[14] Nikas A, et al. Where is the EU headed given its current climate policy? A stakeholder-driven model inter-comparison. Sci Total Environ 2021;793:148549. https://doi.org/10.1016/j.scitotenv.2021.148549.

[15] McPherson M, et al. Modeling the transition to a zero emission energy system: A cross-sectoral review of building, transportation, and electricity system models in Canada. Energy Rep 2023;9:4380–400. https://doi.org/10.1016/j.egyr.2023.02.090.

[16] Huppmann, D. *et al.* pyam: Analysis and visualisation of integrated assessment and macro-energy scenarios. *Open Res Europe* **1**, 74, 10.12688/openreseurope.13633.1 (2021).

[17] Siala K, Odersky L. pyGRETA, pyCLARA, pyPRIMA: A pre-processing suite to generate flexible model regions for energy system models. SoftwareX 2021;16:100860. https://doi.org/10.1016/j.softx.2021.100860.

[18] Syranidou C. *Integration erneuerbarer Energiequellen in das zukünftige europäische Stromnetz unter Verwendung eines verifizierten übertragungsnetzmodells mit hoher räumzeitlicher Auflösung* (RWTH. Aachen University; 2020.

[19] Groß, T. M. *Multiregionales Energiesystemmodell mit Fokus auf Infrastrukturen*.

[20] Ryberg DS, et al. The future of European onshore wind energy potential: Detailed distribution and simulation of advanced turbine designs. Energy 2019;182:1222–38. https://doi.org/10.1016/j.energy.2019.06.052.

[21] Heuser P-M. *Worldwide hydrogen supply infrastructure based on renewable energy* (RWTH. Aachen University; 2021.

[22] Lopion PM. *Model-based analysis of cost-efficient CO$_{2}$ reduction strategies* (RWTH. Aachen University; 2020.

[23] Juelich Systems Analysis. Pathways to a net-zero energy system: a regional magnifying glass on infrastructure, economy and society. Available at https://www.fz-juelich.de/en/ice/ice-2/news/meldungen/regional-magnifying-glass-on-infrastructure-economy-and-society (2024).

[24] Juelich Systems Analysis. European Energy Transition: Germany in the Heart of Europe. Available at https://www.fz-juelich.de/en/ice/ice-2/news/meldungen/european-energy-transition-germany-in-the-heart-of-europe (2024).

[25] IEA. Global Hydrogen Review 2023. Available at https://www.iea.org/reports/global-hydrogen-review-2023 (2023).

[26] IEA. Global Hydrogen Review 2024. Available at https://www.iea.org/reports/global-hydrogen-review-2024 (2024).

[27] IEA. Global Hydrogen Review 2025. Available at https://www.iea.org/reports/global-hydrogen-review-2025 (2025).

[28] IEA. Latin America Energy Outlook 2023. Available at https://www.iea.org/reports/latin-america-energy-outlook-2023 (2023).

[29] IEA. Empowering Ukraine Through a Decentralised Electricity System. Available at https://www.iea.org/reports/empowering-ukraine-through-a-decentralised-electricity-system (2024).

[30] IEA. Unlocking Ukraine's Hydrogen Opportunity: A Roadmap. Available at https://www.iea.org/reports/unlocking-ukraines-hydrogen-opportunity-a-roadmap (2025).

[31] Kuckertz P, et al. DataDesc: A framework for creating and sharing technical metadata for research software interfaces. Patterns (New York N.Y.) 2024;5:101064. https://doi.org/10.1016/j.patter.2024.101064.

[32] Kuckertz P, et al. A framework for reproducibly managing coupled research software and data assets based on shared transformation functions. Patterns (New York, N.Y.) 2026;5. https://doi.org/10.1016/j.patter.2026.101493.

[33] Göpfert J, Kuckertz P, Weinand JM, Stolten D. Wiki-Quantities and Wiki-Measurements: Datasets of Quantities and their Measurement Context from Wikipedia. Scientific Data 2025;12:1277. https://doi.org/10.1038/s41597-025-05499-3.

[34] Göpfert J, Quinex, et al. Quantitative Information Extraction from Text using Open and Lightweight LLMs. The Innovation 2026;9. https://doi.org/10.1016/j.xinn.2026.101391.
[35] Pflugradt, N., Stenzel, P., Kotzur, L. & Stolten, D. LoadProfileGenerator: An Agent-Based Behavior Simulation for Generating Residential Load Profiles. *JOSS* **7,** 3574, 10.21105/joss.03574 (2022).
[36] Neuroth D, Pflugradt N, Weinand JM, Büsing C, Stolten DETHOS. ActivityAssure—An open-source validation framework for synthetic European activity profiles. Energ Buildings 2025;326:115036. https://doi.org/10.1016/j.enbuild.2024.115036.
[37] Belina, J., Pflugradt, N. & Stolten, D. ETHOS.PeNALPS: A Tool for the Load Profile Simulation of Industrial Processes Based on a Material Flow Simulation. *JOSS* **9,** 6358, 10.21105/joss.06358 (2024).
[38] Dabrock K, Pflugradt N, Weinand JM, Stolten D. Leveraging machine learning to generate a unified and complete building height dataset for Germany. Energy AI 2024;17:100408. https://doi.org/10.1016/j.egyai.2024.100408.
[39] Dabrock K, Ulken J, Pflugradt N, Weinand JM, Stolten D. Generating a nationwide residential building types dataset using machine learning. Build Environ 2025;274:112782. https://doi.org/10.1016/j.buildenv.2025.112782.
[40] Ishmam S, et al. ETHOS.GeoKit: A Python Toolkit for Analyzing and Altering Geospatial Data for Energy Systems Modeling and Beyond. SoftwareX 2026;35:102870. https://doi.org/10.1016/j.softx.2026.102870.
[41] Ryberg D, Robinius M, Stolten D. Evaluating Land Eligibility Constraints of Renewable Energy Sources in Europe. Energies 2018;11:1246. https://doi.org/10.3390/en11051246.
[42] Peña-Sánchez EU, et al. Towards high resolution, validated and open global wind power assessments. Nat Commun 2026;17:539. https://doi.org/10.1038/s41467-026-68337-z.
[43] Pueblas R, Kuckertz P, Weinand JM, Kotzur L, Stolten D. ETHOS.Passion: An open-source workflow for rooftop photovoltaic potential assessments from satellite imagery. Sol Energy 2023;265:112094. https://doi.org/10.1016/j.solener.2023.112094.
[44] Pelser T, Weinand JM, Kuckertz P, Stolten D. ETHOS.REFLOW: An open-source workflow for reproducible renewable energy potential assessments. Patterns (New York N.Y.) 2025;6:101172. https://doi.org/10.1016/j.patter.2025.101172.
[45] Weinand JM, Pelser T, Kleinebrahm M, Stolten D. Countries across the world use more land for golf courses than wind or solar energy. Environ Res Commun 2025;7:21012. https://doi.org/10.1088/2515-7620/adb7bd.
[46] Kotzur L, Markewitz P, Robinius M, Stolten D. Impact of different time series aggregation methods on optimal energy system design. Renew Energy 2018;117:474–87. https://doi.org/10.1016/j.renene.2017.10.017.
[47] Kotzur L, Markewitz P, Robinius M, Stolten D. Time series aggregation for energy system design: Modeling seasonal storage. Appl Energy 2018;213:123–35. https://doi.org/10.1016/j.apenergy.2018.01.023.
[48] Hoffmann M, et al. Typical periods or typical time steps? A multi-model analysis to determine the optimal temporal aggregation for energy system models. Appl Energy 2021;304:117825. https://doi.org/10.1016/j.apenergy.2021.117825.
[49] Patil S, Kotzur L, Stolten D. Advanced spatial and technological aggregation scheme for energy system models. Energies 2022;15:9517. https://doi.org/10.3390/en15249517.
[50] Rieck K, Dabrock K, Pflugradt N, Weinand JM, Stolten D. Large-scale quantification of the future self-covered heat demand using a nationwide residential building database. Energy 2025;317:134622. https://doi.org/10.1016/j.energy.2025.134622.
[51] Klütz T, et al. ETHOS.FINE: A Framework for Integrated Energy System Assessment. JOSS 2025;10, 6274:10.21105/joss.06274.
[52] Raseta, M., Kleefeld, A., Grajewski, M. & Ross, A. Green-Kubo Relations for Networked Economic Systems: An Exact Solution for Quantifying Economic Resilience from Input-Output Susceptibility, 10.2139/ssrn.4936915 (2024).
[53] Raseta M, Ross AG, Vögele S. Macro-level implications of the energy system transition to net-zero carbon emissions: Identifying quick wins amid short-term constraints. Economic Analysis and Policy 2025;85:1065–78. https://doi.org/10.1016/j.eap.2025.01.011.
[54] Ross AG, Raseta M, Grajewski M, Kleefeld A. Resilience and recovery in networked economic systems: An ex-ante analysis of susceptibility to aspects of a potential China–Taiwan conflict. Pap Reg Sci 2025;104:100094. https://doi.org/10.1016/j.pirs.2025.100094.
[55] Reul JP, Grube T, Linßen J, Stolten D. MODE.behave: a python package for discrete choice modeling. JOSS 2023;8, 5265:10.21105/joss.05265.
[56] Knosala K, et al. Hybrid hydrogen home storage for decentralized energy autonomy. Int J Hydrogen Energy 2021;46:21748–63. https://doi.org/10.1016/j.ijhydene.2021.04.036.
[57] Knosala K, et al. The role of hydrogen in German residential buildings. Energ Buildings 2022;276:112480. https://doi.org/10.1016/j.enbuild.2022.112480.
[58] Omoyele O, et al. Impact of temporal resolution on the design and reliability of residential energy systems. Energ Buildings 2024;319:114411. https://doi.org/10.1016/j.enbuild.2024.114411.
[59] Mantuano C, et al. Data imputation methods for intermittent renewable energy sources: implications for energy system modeling. Energ Conver Manage 2025;339:119857. https://doi.org/10.1016/j.enconman.2025.119857.
[60] Risch S, et al. Scaling energy system optimizations: techno-economic assessment of energy autonomy in 11 000 German municipalities. Energ Conver Manage 2024;309:118422. https://doi.org/10.1016/j.enconman.2024.118422.
[61] Weinand JM, et al. Low-carbon lithium extraction makes deep geothermal plants cost-competitive in future energy systems. Adv Appl Energy 2023;11:100148. https://doi.org/10.1016/j.adapen.2023.100148.
[62] Maier R, et al. Impact of foresight horizons on energy system decarbonization pathways. Adv Appl Energy 2025;18:100217. https://doi.org/10.1016/j.adapen.2025.100217.
[63] Tsani T, et al. Quantifying the trade-offs between renewable energy visibility and system costs. Nat Commun 2025;16:3853. https://doi.org/10.1038/s41467-025-59029-1.
[64] Kullmann F, Markewitz P, Kotzur L, Stolten D. The value of recycling for low-carbon energy systems - A case study of Germany's energy transition. Energy 2022;256:124660. https://doi.org/10.1016/j.energy.2022.124660.
[65] Schöb T, Kullmann F, Linßen J, Stolten D. The role of hydrogen for a greenhouse gas-neutral Germany by 2045. Int J Hydrogen Energy 2023;48:39124–37. https://doi.org/10.1016/j.ijhydene.2023.05.007.
[66] Busch T, Groß T, Linßen J, Stolten D. The role of liquid hydrogen in integrated energy systems–A case study for Germany. Int J Hydrogen Energy 2023;48:39408–24. https://doi.org/10.1016/j.ijhydene.2023.05.308.
[67] Dunkel P, Klütz T, Linßen J, Stolten D. Interannual weather variability reshapes Europés cost-optimal hydrogen supply strategy, Cell Reports Sustainability (2026), https://doi.org/10.1016/j.crsus.2026.100836 (in press).
[68] Ishmam S, et al. Mapping local green hydrogen cost-potentials by a multidisciplinary approach. Int J Hydrogen Energy 2024;87:1155–70. https://doi.org/10.1016/j.ijhydene.2024.08.501.
[69] Kuckertz, P. *et al.* Software and Data Integration. Available at https://zenodo.org/records/8117988 (2023).
[70] IRENA. Statistics Data. Available at https://www.irena.org/Data (2025).
[71] The Danish Energy Agency. Analyses and statistics. Available at https://ens.dk/en/analyses-and-statistics (2025).
[72] Pelser T, et al. Reviewing accuracy & reproducibility of large-scale wind resource assessments. Adv Appl Energy 2024;13:100158. https://doi.org/10.1016/j.adapen.2023.100158.
[73] Schönau, J., Kuckertz, P., Weinand, J. M., Kotzur, L. & Stolten, D. Currency Conversion for Python (CuCoPy). Available at https://github.com/FZJ-IEK3-VSA/CuCoPy (2024).
[74] Göpfert, J., Kuckertz, P., Weinand, J., Kotzur, L. & Stolten, D. Measurement Extraction with Natural Language Processing: A Review, 2191–2215, 10.18653/v1/2022.findings-emnlp.161.
[75] Booshehri M, et al. Introducing the open energy ontology: enhancing data interpretation and interfacing in energy systems analysis. Energy AI 2021;5:100074. https://doi.org/10.1016/j.egyai.2021.100074.
[76] Kleinebrahm M, Torriti J, McKenna R, Ardone A, Fichtner W. Using neural networks to model long-term dependencies in occupancy behavior. Energ Buildings 2021;240:110879. https://doi.org/10.1016/j.enbuild.2021.110879.
[77] Haider S, Schegner P. Data for heuristic optimization of electric vehicles' charging configuration based on loading parameters. Data 2020;5:102. https://doi.org/10.3390/data5040102.
[78] Boeckl B, Kienberger T. Sizing of PV storage systems for different household types. J Storage Mater 2019;24:100763. https://doi.org/10.1016/j.est.2019.100763.
[79] Lovati M, et al. Design of a residential photovoltaic system: the impact of the demand profile and the normative framework. Renew Energy 2020;160:1458–67. https://doi.org/10.1016/j.renene.2020.07.153.
[80] Tsani T, Weinand JM, Linßen J, Stolten D. Quantifying social factors for onshore wind planning – A systematic review. Renew Sustain Energy Rev 2024;203:114762. https://doi.org/10.1016/j.rser.2024.114762.
[81] McKenna, R. *et al.* On the socio-technical potential for onshore wind in Europe: A response to Enevoldsen et al. (2019), Energy Policy, 132, 1092-1100. *Energy Policy* **145,** 111693, 10.1016/j.enpol.2020.111693 (2020).
[82] Enevoldsen P, et al. On the socio-technical potential for onshore wind in Europe: A response to critics. Energy Policy 2021;151:112147. https://doi.org/10.1016/j.enpol.2021.112147.
[83] Heinrichs HU, et al. Large-scale resource assessments for solar photovoltaics: A review of potential definitions, methodologies and future research needs. Renew Energy 2026;261:125080. https://doi.org/10.1016/j.renene.2025.125080.
[84] McKenna R, et al. High-resolution large-scale onshore wind energy assessments: A review of potential definitions, methodologies and future research needs. Renew Energy 2022;182:659–84. https://doi.org/10.1016/j.renene.2021.10.027.
[85] Caglayan DG, et al. Technical potential of salt caverns for hydrogen storage in Europe. Int J Hydrogen Energy 2020;45:6793–805. https://doi.org/10.1016/j.ijhydene.2019.12.161.
[86] Rouault, E. *et al.* GDAL. Available at https://zenodo.org/records/14046734 (2026).
[87] Caglayan DG, Heinrichs HU, Robinius M, Stolten D. Robust design of a future 100% renewable european energy supply system with hydrogen infrastructure. Int J Hydrogen Energy 2021;46:29376–90. https://doi.org/10.1016/j.ijhydene.2020.12.197.
[88] Davis NN, et al. The global wind atlas: A high-resolution dataset of climatologies and associated web-based application. Bull Am Meteorol Soc 2023;104:E1507–25. https://doi.org/10.1175/BAMS-D-21-0075.1.
[89] The World Bank, ESMAP & SOLARGIS. Global Solar Atlas. Available at https://globalsolaratlas.info/map (2026).
[90] Gelaro R, et al. The modern-era retrospective analysis for research and applications, Version 2 (MERRA-2). J Clim 2017;30:5419–54. https://doi.org/10.1175/JCLI-D-16-0758.1.
[91] C3S. ERA5 hourly data on single levels from 1940 to present (2023).
[92] Wenzel H, et al. Weather conditions severely impact optimal direct air capture siting. Adv Appl Energy 2025;19:100229. https://doi.org/10.1016/j.adapen.2025.100229.

[93] Pawar ND, et al. Potential of green ammonia production in India. Int J Hydrogen Energy 2021;46:27247–67. https://doi.org/10.1016/j.ijhydene.2021.05.203.
[94] Maier R, et al. Potential of floating, parking, and agri photovoltaics in Germany. Renew Sustain Energy Rev 2024;200:114500. https://doi.org/10.1016/j.rser.2024.114500.
[95] Winkler C, et al. High-Resolution rooftop photovoltaic potential assessment for a resilient energy system in Ukraine. Energy Convers Manage: X 2025;28:101242. https://doi.org/10.1016/j.ecmx.2025.101242.
[96] Risch S, et al. Potentials of renewable energy sources in germany and the influence of land use datasets. Energies 2022;15:5536. https://doi.org/10.3390/en15155536.
[97] Ryberg DS, Tulemat Z, Stolten D, Robinius M. Uniformly constrained land eligibility for onshore European wind power. Renew Energy 2020;146:921–31. https://doi.org/10.1016/j.renene.2019.06.127.
[98] Winkler C, et al. Participatory mapping of local green hydrogen cost-potentials in Sub-Saharan Africa. Int J Hydrogen Energy 2025;112:289–321. https://doi.org/10.1016/j.ijhydene.2025.02.015.
[99] Heuser P-M, Ryberg DS, Grube T, Robinius M, Stolten D. Techno-economic analysis of a potential energy trading link between Patagonia and Japan based on CO2 free hydrogen. Int J Hydrogen Energy 2019;44:12733–47. https://doi.org/10.1016/j.ijhydene.2018.12.156.
[100] Franzmann D, Heinrichs H, Stolten D. Global geothermal electricity potentials: A technical, economic, and thermal renewability assessment. Renew Energy 2025;250:123199. https://doi.org/10.1016/j.renene.2025.123199.
[101] IEA. Renewable Energy Opportunities for Mauritania. Available at https://www.iea.org/reports/renewable-energy-opportunities-for-mauritania (2023).
[102] Franzmann, D. *et al.* Impact of Spatial Aggregation on Global Renewable Energy System with ETHOS.modelBuilder, 10.2139/ssrn.5252316 (2025).
[103] Forschungszentrum Jülich. H2 Atlas Africa. Available at https://africa.h2atlas.de/africa (2026).
[104] Chen, et al. Data-driven landscape scenicness mapping for continental-scale onshore wind resource assessment. Energy AI 2026;24:100752. https://doi.org/10.1016/j.egyai.2026.100752.
[105] Wenzel H, et al. Direct air capture enables sustainable methanol production in water-scarce regions. Nat Commun 2026;17:8495. https://doi.org/10.1038/s41467-026-76865-x.
[106] Kotzur L, et al. A modeler's guide to handle complexity in energy systems optimization. Adv Appl Energy 2021;4:100063. https://doi.org/10.1016/j.adapen.2021.100063.
[107] Welder L, et al. Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany. Energy 2018;158:1130–49. https://doi.org/10.1016/j.energy.2018.05.059.
[108] Omoyele O, et al. Increasing the resolution of solar and wind time series for energy system modeling: A review. Renew Sustain Energy Rev 2024;189:113792. https://doi.org/10.1016/j.rser.2023.113792.
[109] Royston S, Selby J, Shove E. Invisible energy policies: A new agenda for energy demand reduction. Energy Policy 2018;123:127–35. https://doi.org/10.1016/j.enpol.2018.08.052.
[110] Pisciella P, van Beesten ER, Tomasgard A. Efficient coordination of top-down and bottom-up models for energy system design: An algorithmic approach. Energy 2023;284:129320. https://doi.org/10.1016/j.energy.2023.129320.
[111] Klimek P, Poledna S, Thurner S. Quantifying economic resilience from input-output susceptibility to improve predictions of economic growth and recovery. Nat Commun 2019;10:1677. https://doi.org/10.1038/s41467-019-09357-w.
[112] Ross AG, McGregor PG, Swales JK. Labour market dynamics in the era of technological advancements: The system-wide impacts of labour augmenting technological change. Technol Soc 2024;77:102539. https://doi.org/10.1016/j.techsoc.2024.102539.
[113] Ross AG, McGregor PG, Swales JK, Roy G. Examining the interplay of labour productivity policies and industrial-energy-environmental policy goals. Int J Energy Res 2023;1–12:2023. https://doi.org/10.1155/2023/6622968.
[114] Ross AG, Connolly K, Vögele S, Kuckshinrichs W. A macro-level analysis of the socio-economic impacts of climate change driven water scarcity: incorporating behavioural and resilience aspects. Water Res X 2024;23:100223. https://doi.org/10.1016/j.wroa.2024.100223.
[115] Ross, A. Exploring Macroeconomic Effects of Climate and Energy Transitions: An Agent-Based Modelling Perspective. Available at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=6236958 (2026).
[116] Behrens J, Zeyen E, Hoffmann M, Stolten D, Weinand JM. Reviewing the complexity of endogenous technological learning for energy system modeling. Adv Appl Energy 2024;16:100192. https://doi.org/10.1016/j.adapen.2024.100192.
[117] Omoyele O, et al. A high-resolution downscaling approach for solar irradiance using statistical parameter matching. Renew Energy 2026;256:124551. https://doi.org/10.1016/j.renene.2025.124551.
[118] Marmullaku, D., Klütz, T., Linßen, J. & Stolten, D. Opportunities of European Hydrogen Supply Potentials for Germany's Hydrogen Market. Available at https://ieeexplore.ieee.org/document/11050316 (2025).
[119] Chen S, et al. Higher onshore wind energy potentials revealed by kilometer-scale atmospheric modeling. Geophys Res Lett 2024;51. https://doi.org/10.1029/2024GL110122.
[120] Kullmann F, Linßen J, Stolten D. The role of hydrogen for the defossilization of the German chemical industry. Int J Hydrogen Energy 2023;48:38936–52. https://doi.org/10.1016/j.ijhydene.2023.04.191.
[121] Franzmann D, et al. Green hydrogen cost-potentials for global trade. Int J Hydrogen Energy 2023;48:33062–76. https://doi.org/10.1016/j.ijhydene.2023.05.012.
[122] Jacob R, et al. The future role of thermal energy storage in 100% renewable electricity systems. Renewable Sustainable Energy Transition 2023;4:100059. https://doi.org/10.1016/j.rset.2023.100059.
[123] Zier M, Pflugradt N, Stenzel P, Kotzur L, Stolten D. Industrial decarbonization pathways: The example of the German glass industry. Energy Convers Manage: X 2023;17:100336. https://doi.org/10.1016/j.ecmx.2022.100336.
[124] Zier M, Pflugradt N, Kotzur L, Stolten D. Decarbonising energy-related CO2 emissions in the glass industry. Glass International 2022;45:44–46+49.
[125] Li J, et al. Co-planning of regional wind resources-based ammonia industry and the electric network: A case study of Inner Mongolia. IEEE Trans Power Syst 2022;37:65–80. https://doi.org/10.1109/TPWRS.2021.3089365.
[126] Marmullaku D, et al. Quantifying hydrogen's role in multi-sector decarbonization using price-elastic demand curves. Adv Appl Energy 2026;21:100265. https://doi.org/10.1016/j.adapen.2026.100265.
[127] Müller, G., Schöb, T., Weinand, J. M. & Staffell, I. Probabilistic Identification of Technology Tipping Points in Deeply Decarbonised Energy Systems. Available at https://arxiv.org/abs/2606.16469 (2026).
[128] Persson U, Wiechers E, Möller B, Werner S. Heat Roadmap Europe: Heat distribution costs. Energy 2019;176:604–22. https://doi.org/10.1016/j.energy.2019.03.189.
[129] Weinand JM, McKenna R, Karner K, Braun L, Herbes C. Assessing the potential contribution of excess heat from biogas plants towards decarbonising residential heating. J Clean Prod 2019;238:117756. https://doi.org/10.1016/j.jclepro.2019.117756.
[130] Sasse J-P, Trutnevyte E. Distributional trade-offs between regionally equitable and cost-efficient allocation of renewable electricity generation. Appl Energy 2019;254:113724. https://doi.org/10.1016/j.apenergy.2019.113724.
[131] Wang Z, Trutnevyte E. Demand-side flexibility of electric vehicles and heat pumps in the Swiss electricity system with high shares of renewable generation. Energy 2025;338:138903. https://doi.org/10.1016/j.energy.2025.138903.
[132] Sasse J-P, Trutnevyte E. A low-carbon electricity sector in Europe risks sustaining regional inequalities in benefits and vulnerabilities. Nat Commun 2023;14:2205. https://doi.org/10.1038/s41467-023-37946-3.
[133] Sasse J-P, Trutnevyte E. Regional impacts of electricity system transition in Central Europe until 2035. Nat Commun 2020;11:4972. https://doi.org/10.1038/s41467-020-18812-y.
[134] Omoyele O, Hoffmann M, Weinand JM, Stolten D. Subhourly temporal resolution in PV energy system modeling: effects on design, reliability, and computational efficiency. Energy Convers Manag: X 2026;31:102186. https://doi.org/10.1016/j.ecmx.2026.102186.
[135] Okosun K, et al. Global strategic deployment of Direct Air Capture technologies. Int J Greenh Gas Control 2026;155:104743. https://doi.org/10.1016/j.ijggc.2026.104743.
[136] Huppmann D, et al. pyam: Analysis and visualisation of integrated assessment and macro-energy scenarios. Open Res Europe 2021;1, 74. https://doi.org/10.12688/openreseurope.13633.2.
[137] Sacchi R, et al. PRospective EnvironMental Impact asSEment (premise): A streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renew Sustain Energy Rev 2022;160:112311. https://doi.org/10.1016/j.rser.2022.112311.
[138] Mutel, C. Brightway: An open source framework for Life Cycle Assessment. *JOSS* **2**, 236, 10.21105/joss.00236 (2017).
[139] Söltzer L, Wortmann B, Stolten D, Linßen J, Heinrichs H. Material bottlenecks of batteries within the energy transition. Resour Conserv Recycl 2026;227:108745. https://doi.org/10.1016/j.resconrec.2025.108745.
[140] Odenweller A, et al. REMIND-PyPSA-Eur: Integrating power system flexibility into sector-coupled energy transition pathways. Prog Energy 2026. https://doi.org/10.1088/2516-1083/ae3ffe.
[141] Omoyele O, et al. ETHOS.TISED: A python package for temporal downscaling of solar irradiance. SoftwareX 2026;34:102688. https://doi.org/10.1016/j.softx.2026.102688.
[142] Weinand JM. Energy system science must look beyond net zero. Nat. Rev. Clean Technol. 2026. https://doi.org/10.1038/s44359-026-00170-5.