Helmholtz
Open-Source, Open-Model and Open-Data Software Suite for the Design, Scheduling and Control of Integrated Energy Systems

Kevin Förderer, Simon Waczowicz, Manuel Dahmen, Thiemo Pesch, André Xhonneux, Hüseyin Kemâl Çakmak, Haozhen Cheng, Alexander Kocher, Yifei Lu, Yiwen Pan, Junjie Zhang, Patrik Schönfeldt, Julian Bartels, Sunke Schlüters, Karsten von Maydell, Veit Hagenmeyer

Abstract

Research on energy systems is a multi-disciplinary undertaking requiring expert knowledge, data, models, algorithms and their implementation in the form of software. This document and milestone report presents Open-X solutions from the Helmholtz Energy System Design (ESD) Program – Topic 2 and outlines how they can be used by outlining four exemplary use cases.

Table of Contents

Introduction

Research on energy systems is a multi-disciplinary undertaking, requiring expert knowledge in different fields and the combination of diverse approaches, methods, and models. Simulations and analyses of large systems are time and resource consuming. Building on Open-X solutions can simplify and speed up research and the creation of solutions for smart energy systems. In the context of Helmholtz ESD – Topic 2, we published a series of results from first implementations of novel methods to maintained software. In this document we provide an overview of these solutions, followed by four exemplary use cases of the emerging software suite. Each example makes use of a combination of selected solutions from this suite and outlines how they may be integrated with each other, showcasing possibilities and hopefully inspiring further utilization.

The software in this suite is complementary to that of Helmholtz ESD – Topic 1.

Structure

Our software suite for design, scheduling and control of integrated energy systems includes various works that have been conducted with different goals and focuses. To allow for a structured overview, we cluster these works into four broad categories:

- Models — Models for a specific use case
- Methods — Methods to tackle a specific challenge
- Software — Software tools or development frameworks
- Data — Additional data well fitted for usage with the software suite

Many works fall into multiple of these categories. In the following catalog, we use tags to indicate the applicable categories. The following figure depicts the information presented for each work:

Name of the work	Tags: Model | Method | Software | Data
One sentence describing the utilization	
A brief description	
Links	
References	

In addition to the assigned tags, this catalog is divided into multiple sections. Works have been assigned to the sections according to their main character:

- Widely applicable solutions, frameworks, and platforms
- Solutions for specific use cases
- Supplementary Models
- Supplementary Data

These sections are closely related to the tag categories introduced above. Many solutions of the software category with their more versatile tools and frameworks for implementing own solutions are placed in *widely applicable solutions, frameworks and platforms*. Vice versa, methods accompanied with specific models are often found in the *solutions for specific use cases* section.

Overview

Here, we provide a high-level, graphical overview of the solutions found in this suite. It is designed to enable the identification of relevant works at a glance. In addition to assigning works to sections, we indicate main applications, e.g., design and operation of energy systems.

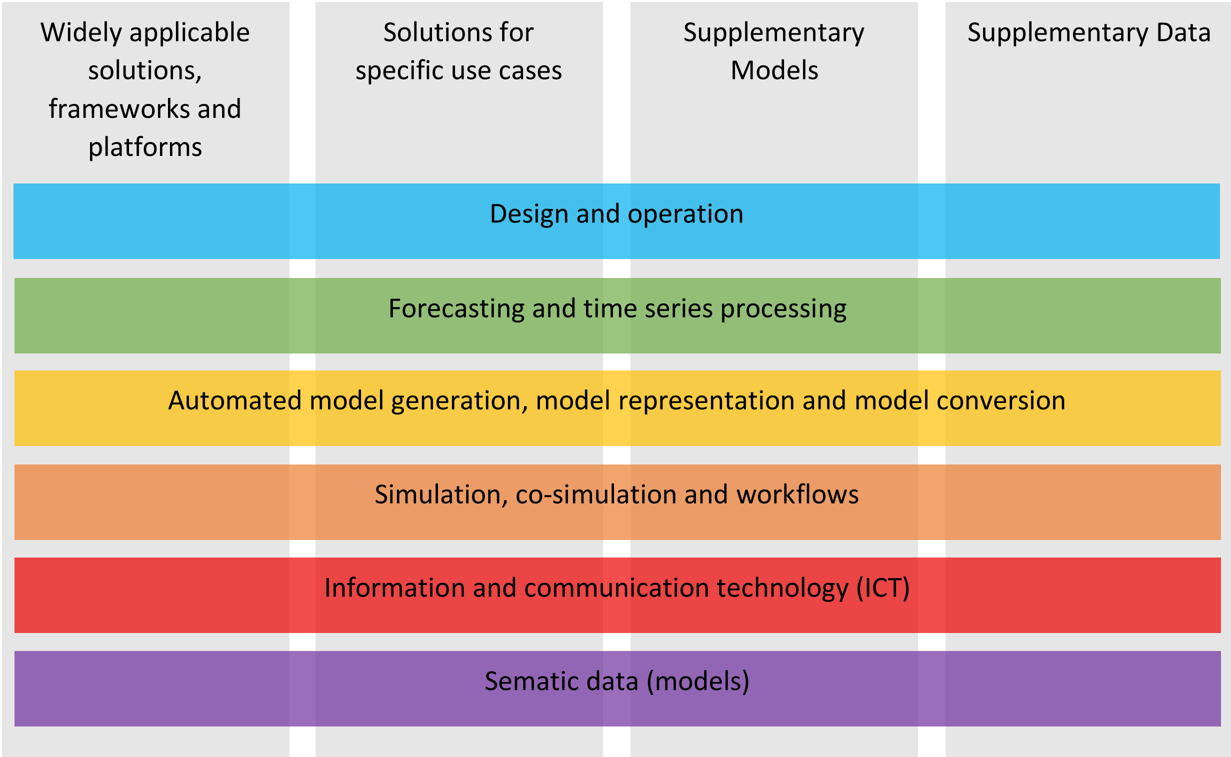

Figure 1: Overview on sections (vertical) and applications (horizontal) of the suite.

Figure 2: Widely applicable solutions, frameworks and platforms (left) and solutions for specific use cases (right).

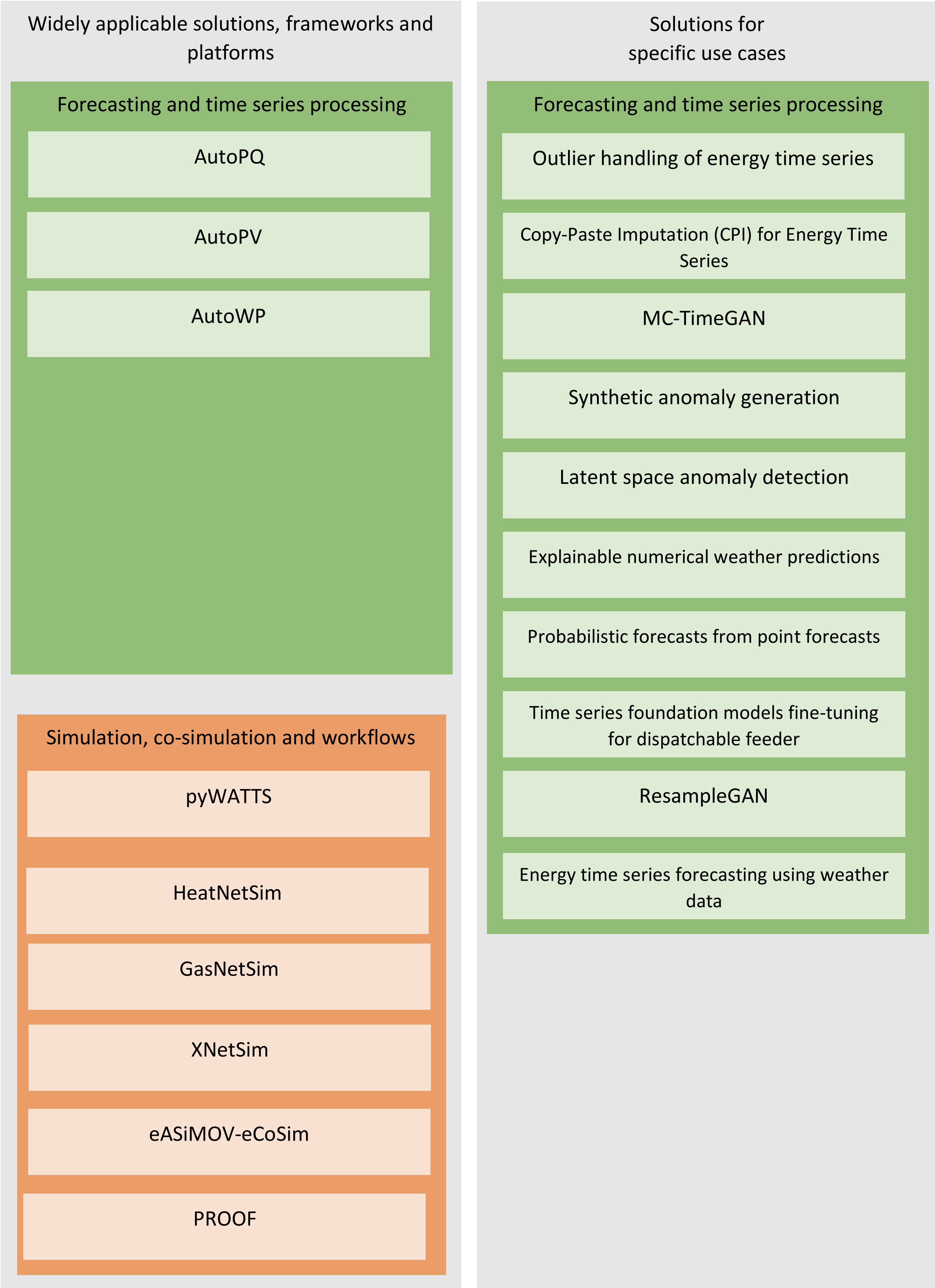

Figure 2 (continued): Widely applicable solutions, frameworks and platforms (left) and solutions for specific use cases (right).

Catalog

The ordering of the elements within each section is of no particular meaning.

Widely Applicable Solutions, Frameworks and Platforms

pyWATTS | Method | Software

Python Workflow Automation Tool for Time Series

A non-sequential workflow automation tool for the analysis of time series data. pyWATTS includes modules with clearly defined interfaces to enable seamless integration of new or existing methods, subpipelining to easily reproduce repetitive tasks, load and save functionality to simply replicate results, and native support for key Python machine learning libraries such as scikit-learn, PyTorch, and Keras.

Links
https://www.sktime.net/en/latest/api_reference/auto_generated/sktime.pipeline.pipeline.Pipeline.html

References
https://doi.org/10.48550/arXiv.2106.10157

COMANDO | Model | Software

Framework for modeling and optimization of multi-energy systems

COMANDO is an open-source Python-based framework for flexible and component-oriented modeling of multi-energy systems developed at FZJ. Unlike typical energy systems modeling frameworks, COMANDO is not limited to mixed-integer linear programming (MILP) but supports nonlinear, dynamic and discrete modeling, making it particularly useful for technical system design and operation, where, e.g., part-load efficiencies or detailed thermodynamics have to be taken into account. User-specific component and system model descriptions give rise to two-stage optimization problems, with the first stage accounting for design decisions, e.g., technology choice, sizing, topology, and the second stage for operational decisions. From a single system model, COMANDO can generate different classes of optimization problems, e.g., the deterministic equivalent of stochastic problems or MILP problems through automatic linearization. It allows for easy integration of data-driven models such as artificial neural network component models and consideration of power grid constraints.

Users: Forschungszentrum Jülich, RWTH Aachen, DLR Institut für CO2-arme Industrieprozesse

Links
https://helmholtz.software/software/comando

References
https://doi.org/10.1016/j.compchemeng.2021.107366
https://doi.org/10.1016/j.compchemeng.2022.107745

https://doi.org/10.1109/OSMSES54027.2022.9769138

GasNetSim Model | Method

Gas Network Simulation with Complex Gas Mixture Compositions

GasNetSim is an open-source Python package (licensed under MPL-2.0) developed for steady-state and time-series gas network simulation. It focuses on modeling complex gas mixture properties and supports composition tracking across time-series simulations. It can be used to analyze the transformation of future gas grids, including hydrogen-enriched natural gas, pure hydrogen networks, and CO_2 transmission grids. GasNetSim is designed for co-simulation with other sectors, e.g., power and heating. Current development is on extending the framework with dynamic gas flow simulation capabilities.

Users: Forschungszentrum Jülich, Politecnico di Torino, Università degli Studi di Palermo

Links
https://jugit.fz-juelich.de/iek-10/public/simulation/gasnetsim
https://helmholtz.software/software/gasnetsim

References
https://doi.org/10.1109/OSMSES54027.2022.9769148
https://doi.org/10.1109/access.2025.3579340

HeatNetSim Model | Method

Simulation tool for heating and cooling networks suitable for future energy systems

HeatNetSim is an open-source Python package (licensed under MPL-2.0) developed for thermal network simulation. The tool can be used to simulate uni- and bidirectional flows (such as 5GDHC) and enables the integration of multiple waste heat sources. The simulation can be performed steady-state or with a dynamic temperature calculation to additionally consider time delays within the network. HeatNetSim is designed for co-simulation with other energy sectors such as the power and the gas sector.

Links
https://jugit.fz-juelich.de/iek-10/public/simulation/heatnetsim
https://helmholtz.software/software/heatnetsim

References
https://doi.org/10.1016/j.energy.2024.133588
https://doi.org/10.1109/osmses62085.2024.10668974

XNetSim Method | Software

A Scalable Hardware Accelerated Data-Centric Platform for Real-Time Dynamic Simulation of Multi-Energy Systems

XNetSim (licensed under MPL-2.0) is a scalable simulation tool for multi-energy systems. It focuses on performing faster-than-real-time transient or static simulation with coupled and individual energy systems. The tool utilizes parallel-in-space and parallel-in-time algorithms to accelerate the simulation processes and exploits natively hardware accelerators like GPUs, multi-core CPUs, and FPGAs to maximize performance. The tool can be used in the study of electro-magnetic transient level of dynamics in large-scale power grids, dynamics in gas grids considering gas mixture properties, as well as complex dynamics in coupled power and gas grids. Current focus is on the experimentation of new numerical methods, development of new components and the extension to the heating grid.

Links
https://jugit.fz-juelich.de/iek-10/public/simulation/xnetsim

References
A Scalable Data-Centric Approach for Real-Time Dynamic Simulation of Multi-Energy Systems Using Hardware Acceleration (under review)

MTRESS Model | Software

Model Template for Renewable Energy Supply Systems

MTRESS is a model template which enables users to create energy system models for individual residential and commercial buildings, as well as for neighborhoods and entire industrial properties. It is built upon oemof-solph and includes pre-built technologies from various sectors including Electricity, Heat and Gas (e.g., H2, Natural Gas, Biogas, etc.), which can be instantiated using data sheet values. Although being a linear model, the quality of energy flows (e.g. temperature and pressure) can be represented.
MTRESS is tailored for optimizing control strategies fulfilling fixed demand time series for electricity, heat, gas (including hydrogen), and domestic hot water using any selected combination of the implemented supply technologies. As part of an overarching toolchains, MTRESS can be used to optimize supply system configurations or for long-term planning by including assumptions (e.g., about the development of costs and the CO2 impact of the future energy mix).

Links
https://github.com/mtress/mtress/
https://helmholtz.software/software/mtress

References
https://doi.org/10.1109/osmses54027.2022.9768967
https://doi.org/10.48550/arxiv.2211.14080

oemof Model | Software

open energy modeling framework

The Open Energy Modelling Framework (oemof) is a Python toolbox for energy system modeling and optimization. The oemof project aims to be a loose organizational frame for tools in the wide field of (energy) system modeling. All project libraries are free software licensed under the MIT license.

Some of the ideas of MTRESS (e.g., support of hierarchical graphs) have been upstreamed to oemof to reach a wider audience. We also supported implementation of features that make oemof.solph interoperable with the HGF tool TSAM.

Links
https://github.com/oemof/
https://helmholtz.software/software/oemof-solph

References
https://doi.org/10.1016/j.simpa.2020.100028

KIT Model Viewer (Plugins) Software

Software for reading, exploring and editing semantic data models

The KIT Model Viewer is a freeware application used to visualize and analyze semantic data models from the fields of BIM (Building Information Modelling) and GIS (Geographic Information Systems). The focus is on open, standardized data formats.

For buildings, the IFC data model is supported in the SPF (STEP Physical File) and ifcXML file formats from version IFC2X onwards. For the building simulation, gbXML (Green Building XML) is supported, which serves as an exchange file format from BIM to energy simulation systems. For cities and districts, CityGML is supported from version 0.4.0 onwards including the ADE (Application Domain Extension) extension concept. Additionally, a whole range of other data formats are supported, either file-based or as a web service.

The tool offers a plugin SDK and there are various plugins, which are open source.

Links
https://github.com/KIT-IAI/SDM_KITModelViewer
https://github.com/KIT-IAI/SDM_Plugin_General

References
https://github.com/KIT-IAI/SDM_KITModelViewer

GMLToolbox Software

Tool for handling spatially related data

Tool for handling spatially related data in the standardized formats XPlanGML (all versions), CityGML (all versions and Application Domain Extensions(ADEs)), BoreholeML (version 3.0), ALKIS/NAS (version 5.1 and 6.0), or an INSPIRE format. For all formats, reading and writing of file-based data, geometrical and syntactical checking (schema validation), evaluation and change of attribute values, reference system transformations, as well as visualization with external viewers are supported. For this, two-dimensional geodata are transformed into the Structured Vector Graphics (SVG) format and displayed with a suited HTML browser. For three-dimensional geodata, the Keyhole Markup Language (KML) format is used as visualization format, and GoogleEarth as external viewer.

Links
https://github.com/KIT-IAI/GMLToolbox

References
-

AutoPQ Method | Software

Automated point forecast-based quantile forecasts

The underlying idea of AutoPQ is to generate a probabilistic forecast based on an arbitrary point forecast using a conditional Invertible Neural Network (cINN) and to make corresponding design decisions automatically, aiming to increase the probabilistic performance.

Links
https://helmholtz.software/software/autopq
https://github.com/SMEISEN/AutoPQ

References
https://doi.org/10.1016/j.apenergy.2025.125931

AutoPV Method | Software

Automated photovoltaic forecasts with limited information using an ensemble of pre-trained models

The underlying idea of AutoPV is to describe the arbitrary mounting configuration of a new PV plant as a convex linear combination of outputs from a sufficiently diverse ensemble pool of PV models of the same region. AutoPV incorporates three steps: i) create the ensemble model pool, ii) form the ensemble output by an optimally weighted sum of the scaled model outputs in the pool, and iii) rescale the ensemble output with the new PV plant's peak power rating.

Links
https://helmholtz.software/software/autopv
https://github.com/SMEISEN/AutoPV

References
https://doi.org/10.1145/3575813.3597348

AutoWP Method | Software

Automated wind power forecasts with limited computing resources using an ensemble of diverse wind power curves (together with TU Ilmenau und FhG AST Ilmenau)

The underlying idea of AutoWP is to represent a new WP turbine as a convex linear combination of WP curves from a sufficiently diverse ensemble. The method consists of three steps: i) create the ensemble of normalized WP curves, ii) form the normalized ensemble WP curve by the optimally weighted sum of the WP curves in the ensemble, and iii) re-scale the ensemble WP curve with the new WP turbine's peak power rating.

Links
https://helmholtz.software/software/autowp

References
https://doi.org/10.58895/ksp/1000174544-1

Open energy services Method | Software

Framework and community for the development and operation of services for energy management applications

Approach and framework (developed at FZI Karlsruhe, supported by KIT IAI) to split the complex optimization algorithms employed by energy management systems into standardized components, which can be provided as a service with marginal costs at scale.

Links
https://open-energy-services.org/open-source/
https://github.com/fzi-forschungszentrum-informatik/energy-service-generics/

References
https://doi.org/10.1017/dce.2025.14

PROOF Method | Software

Process Orchestration Framework

Tool and framework for the generic coupling of software modules and simulators to create workflows and co-simulations. It is not limited to specific use cases or domains.

PROOF provides, among other features, a coupling mechanism, orchestrator and GUI, and is based on containerization technologies.

Links
Scheduled to be published in the near future.

References
https://doi.org/10.1109/OSMSES58477.2023.10089680

eASiMOV-eCoSim Method | Software

Co-Simulation-Framework for the Analysis of sector-coupled energy system analysis using co-simulation

The eASiMOV framework (energy system Analysis, Simulation, Modeling, Optimization, and Visualization) with its software module eCoSim enables sector-coupled energy system analysis via co-simulation [1]. The framework enables model and simulator coupling using a server/client architecture with support for FMI/FMU and code-based simulators with interfaces to common programming languages (Python, Java, Matlab). Co-simulations can be performed using parallelized co-simulation execution on high-performance computers, e.g., for variation analysis, or via a geographically distributed approach that supports model and data privacy [2]. The distributed architecture also enables use in specialized areas, such as distributed optimal power flow computation between distribution network operators (DSO) and transmission network operators (TSO), while maintaining their model and data sovereignty [3].

Links
https://github.com/KIT-IAI/eCoSim
Scheduled for open-source publication in early 2026

References
[1] https://doi.org/10.1515/auto-2019-0081
[2] https://dl.acm.org/doi/10.1145/3632775.3661990
[3] https://doi.org/10.1016/j.epsr.2024.110710

eASiMOV-eCoSimWeb Method | Software

A platform for collaborative modelling and co-simulation for sector-coupled Multi-Energy System Analysis

The eASiMOV-eCoSimWeb platform facilitates collaborative, cross-institutional development of multi-energy models through seamless interoperability with domain-specific tools such as Python, MATLAB®, and Modelica. The primary innovation of this system is high-resolution district- and urban-scale simulation, in which individual buildings are represented as multi-physical units with embedded thermodynamics, electrical and thermal devices with controls, and energy-conversion systems. These granular building models are dynamically coupled with heat and electricity distribution networks [1].
A cloud-native architecture [2] ensures computational scalability by leveraging advanced technologies (cluster computing, containerization) and supports the simultaneous co-simulation of a large number of coupled multi-physics models, with deterministic synchronization across distributed engineering teams. The system's modular design, across components and associated controllers, facilitates collaboration among energy system researchers and provides a solid foundation for developing innovative models and controllers. eASiMOV-eCoSim and eCoSimWeb are designed for researchers, urban planners, and energy suppliers to provide a platform for learning, experimentation, and collaborative development of new models and methods for sector-integrated multi-energy system analysis.
The eCoSimWeb collaboration platform will be primarily used for collaboration within Helmholtz and third-party funded projects.

Links
Video: https://publikationen.bibliothek.kit.edu/1000159679

References
[1] https://doi.org/10.1109/APPEEC61255.2024.10922291
[2] https://doi.org/10.5445/IR/1000182805

ePowCoRe Method | Software

A Novel Generic Representation of Power Grids Enabling Open-Source Model Conversion Modules

ePowCoRe is designed as an interoperability framework to enable cross-tool analysis in contemporary power system studies. It addresses the longstanding challenge posed by heterogeneous and proprietary data formats across simulation platforms, which hinder model exchange and comparative assessments. The proposed solution is a graph-based, tool-agnostic representation of power system models that serves as a universal intermediate format. Automated conversion methods built on this representation enable reliable translation of models across different simulation environments.
The framework supports various open-source and commercial software model formats, such as DIgSILENT PowerFactory, MATPOWER, Simscape Electrical, and RSCAD FX. Comparative power-flow, RMS, and EMT analyses demonstrate that the converted models retain high fidelity to the original. To promote transparency, reproducibility, and community engagement, the complete modeling schema and conversion tools have been released under an open-source license.

Links
https://helmholtz.software/software/epowcore
https://github.com/KIT-IAI/ePowCoRe

References
https://doi.org/10.1109/OSMSES62085.2024.10668981

PyAPI-RTS Method | Software

A Python library to read and manipulate RSCAD® draft files, used for power system modeling and simulation on RTDS simulators.

Real-time simulation of modern power systems is becoming more important as renewable and inverter-based generation grows. Hardware such as RTDS NovaCor relies on RSCAD, a GUI-driven modeling environment that lacks automation capabilities. PyAPI-RTS addresses this gap by providing a Python-based programming interface (pyapi_rts) that enables programmatic creation, modification, and analysis of RSCAD models. It supports adding, removing, and editing components, building models from scratch, and representing models as graphs to facilitate advanced manipulation and analysis.

Links
https://helmholtz.software/software/pyapi-rts
https://github.com/KIT-IAI/PyAPI-RTS

References
https://ieeexplore.ieee.org/document/10089671

ALICE Model | Method | Software | Data

Modeling language and software tool for the structured definition and processing of building information

ALICE is a modeling framework for the structured description of buildings and their energy-relevant properties. It provides a concise, human-readable mini-language to describe rooms, zones, and their semantic attributes. ALICE focuses on capturing the main architectural, thermal, and usage-related information at a high level of abstraction. The framework enables consistent and scalable building model generation without requiring detailed manual modeling.

Links
https://jugit.fz-juelich.de/iek-10/public/tools/alice2modelica

References
https://doi.org/10.1016/j.applthermaleng.2025.125598

ALICE2Modelica Model | Method | Software | Data

Automatic generation of modelica models based on room descriptions in ALICE language and floor plans

ALICE2Modelica is a software tool that supports the automated generation of detailed, physics-based (white-box) Modelica building models, ranging from single rooms to multi-zone buildings. It converts inputs written in the ALICE mini-language and SVG floor plans into fully parameterized Modelica models, enabling fast and scalable simulation as well as Model Predictive Control (MPC) for building energy management. The generated models include key physical components such as walls, windows, thermal zones, shading devices, and control inputs, while also defining thermal and control coupling between adjacent rooms. This enables the consistent and efficient creation of both small- and large-scale building models, making ALICE2Modelica particularly valuable for smart-building research and advanced control applications.

Links
https://jugit.fz-juelich.de/iek-10/public/tools/alice2modelica

References
https://doi.org/10.1109/OSMSES62085.2024.10668986

MASSIVE Model | Method | Software | Data

Agent-based framework for market-based scheduling of decentral energy systems

Agent-based framework designed to enable market-based scheduling of decentral energy systems. For the agents, both pure simulations as well as agents which make use of mode-based optimization can be used. The framework supports both hierarchical and distributed control architectures, allowing flexible coordination across multiple system levels. MASSIVE is suitable for both theoretical research and real-time operation, enabling the study, deployment, and validation of advanced control strategies in practical energy systems.

Links
https://jugit.fz-juelich.de/iek-10/public/optimization/massive

References
https://doi.org/10.1007/978-3-032-03101-3_23

Solutions for Specific Use Cases

Outlier handling of energy time series Model | Method

Managing Anomalies in Energy Time Series for Automated Forecasting

Provides three different general strategies for managing anomalies in energy time series forecasting, namely the raw, the detection, and the compensation strategy. The study shows that applying the compensation strategy is generally beneficial for managing anomalies despite requiring additional computational costs because it mostly outperforms the detection and the raw strategy when the input data contains anomalies.

Links
https://github.com/KIT-IAI/EnhancingAnomalyDetectionMethods

References
https://doi.org/10.1007/978-3-031-48649-4_1

Copy-Paste Imputation (CPI) for Energy Time Series Method

Data-Driven Copy-Paste Imputation for Energy Time Series

This CPI method copies data blocks with similar characteristics and pastes them into gaps of the time series while preserving the total energy of each gap. It outperforms the benchmark imputation methods selected for comparison in the linked study. The comparison furthermore shows that the CPI method uses matching patterns and preserves the total energy of each gap while requiring only a moderate run-time.

Links
https://helmholtz.software/software/copy-paste-imputation

References
https://doi.org/10.1109/TSG.2021.3101831

MC-TimeGAN Model | Method | Data

Multivariate Conditional Time-series Generative Adversarial Networks

The Multivariate Conditional Time-series Generative Adversarial Networks (MC-TimeGAN) is a generative model designed to synthesize multivariate conditional time series. It extends the TimeGAN framework to generate synthetic time-series data in a conditional manner, focusing on grid congestion multivariate time series for a power distribution grid by modifying labels.

Links
https://github.com/KIT-IAI/MC-TimeGAN

References
https://doi.org/10.1109/iSPEC59716.2024.10892479

Synthetic anomaly generation Model | Method | Data

Modeling and Generating Synthetic Anomalies for Energy and Power Time Series

A method that generates synthetic anomalies based on real-world anomalies that can be inserted into energy and power time series. It models and uses four types of commonly occurring anomalies to insert synthetic anomalies of each type into arbitrary energy or power time series. The method is not only capable of generating synthetic anomalies with real-world properties, but also beneficial for training supervised anomaly detection methods.

Links
https://github.com/KIT-IAI/GeneratingSyntheticEnergyPowerAnomalies

References
https://dl.acm.org/doi/10.1145/3538637.3539760

Latent space anomaly detection Method

Enhancing Anomaly Detection Methods for Energy Time Series Using Latent Space Data Representations

An approach to generally enhance anomaly detection methods for energy time series by taking advantage of their latent space representation. It creates latent space data representations using a conditional Invertible Neural Network (cINN) and a conditional Variational Autoencoder (cVAE) and directly applies existing supervised and unsupervised detection methods to this representation.

Links
https://github.com/KIT-IAI/EnhancingAnomalyDetectionMethods

References
https://dl.acm.org/doi/10.1145/3538637.3538851

Explainable numerical weather predictions Model | Method | Data

Intrinsic Explainable Artificial Intelligence Using Trainable Spatial Weights on Numerical Weather Predictions

An approach to forecast energy that scales and adds intrinsic explainability by design using trainable spatial weights to make accurate forecasts on large spatial areas. The trained weights can be interpreted spatially to enhance explainability and increase trust.

Links
https://github.com/KIT-IAI/Intrinsic-Explainable-AI-Using-Trainable-Spatial-Weights

References
https://doi.org/10.1145/3632775.3662161

Energy time series forecasting using weather data Model | Method | Data

Using weather data in energy time series forecasting: the benefit of input data transformations

Provides weather data input transformations of station-based and grid-based weather data for forecasting renewable energy time series. In the accompanying study, these improve the forecast accuracy compared to using the raw weather data between 3.7 and 5.2%, depending on the target energy time series, where statistical and dimensionality reduction data transformations are among the best.

Links
https://github.com/KIT-IAI/Weather-Data-Transformations-for-Energy-Time-Series-Forecasting

References
https://doi.org/10.1186/s42162-023-00299-8

Probabilistic forecasts from point forecasts Model | Method | Data

Generating probabilistic forecasts from arbitrary point forecasts using a conditional invertible neural network

An approach for generating probabilistic forecasts from arbitrary point forecasts applying a conditional Invertible Neural Network (cINN) to learn the underlying distribution of the data and then combine the uncertainty from this distribution with an arbitrary point forecast to generate probabilistic forecasts.

Links
https://github.com/KIT-IAI/ProbabilisticForecastsFromArbitraryPointForecasts

References
https://doi.org/10.1007/s10489-024-05346-9

Probabilistic day-ahead battery scheduling Model | Method

Probabilistic day-ahead battery scheduling based on mixed random variables for enhanced grid operation

An analytical approach enabling the asymmetric allocation of quantified power uncertainties between a residential battery system and the power grid, introducing a new degree of freedom into the scheduling problem. This is accomplished by employing mixed random variables—characterized by both continuous and discrete events—to model battery and grid power uncertainties. These variables are embedded into a continuous stochastic optimization framework, which computes probabilistic schedules for battery operation and power exchange with the grid. Test cases demonstrate that the proposed framework can be used effectively to quantify and reduce grid uncertainties while maximizing residential self-sufficiency.

Links
https://github.com/JaMoPinter/Day-Ahead-Battery-Scheduling

References
https://doi.org/10.1016/j.segan.2025.101813

Time series foundation models fine-tuning for dispatchable feeder Model | Method

Decision-focused fine-tuning of time series foundation models for dispatchable feeder optimization

Based on Moirai as a state-of-the-art foundation model, which offers robust and generalized results with few-shot parameter-efficient fine-tuning, this solution provides decision-focused fine-tuning within time series foundation models to offer a scalable and efficient solution for decision-focused learning applied to the dispatchable feeder optimization problem. Comparing the decision-focused fine-tuned Moirai with a state-of-the-art classical prediction-focused fine-tuning Moirai, we observe an improvement of 9.45% in Average Daily Total Costs.

Links
https://github.com/KIT-IAI/Decision-Focused-Fine-Tuning-of-Time-Series-Foundation-Models-for-Dispatchable-Feeder-Optimization

References
https://doi.org/10.1016/j.egyai.2025.100533

Augmented Pre-trained Graph Neural Networks for Grid-Supportive Flexibility Control Model | Method

GNN-based inference of power requirements for congestion mitigation

The software provides an extension of a graph neural network (GNN) application for power flow approximation. It can infer minimum load or generation requirements for congestion mitigation. The utilization of the pre-trained power flow inferring GNN provides a head start in training compared to end-to-end training of the GNN. The pre-trained model demonstrates robust generalization capabilities, effectively inferring optimal power values for congestion mitigation across grid topologies outside of the training distribution. Furthermore, the approach can easily be adapted to other use cases.

Links
https://github.com/KIT-IAI/PretrainedPowerflowGNN

References
https://doi.org/10.1145/3679240.3734663

PIDE Model | Method

Photovoltaic integration dynamics and efficiency for autonomous control on power distribution grids

Tool for simulating the integration of distributed energy resources (DER)s and evaluating their impact on autonomous reactive power control in the distribution grid.

The provided case studies include a one-year sensitivity analysis based on Monte Carlo simulations, compare distributed and decentralized DER control strategies, and demonstrate the role of autonomous inverters in providing ancillary services.

Links
https://github.com/KIT-IAI/PIDE

References
https://doi.org/10.1186/s42162-025-00489-6

GBOML DER Model | Method

Grid Aware Portfolio Optimization of a Multi-Energy DER

Model and tool for designing the portfolio of a complex multi-energy DER (e.g., an Energy Hub) in a cost-optimal way for a specific location in the grid, while simultaneously considering the provision of grid-supporting services.
It uses an algorithm that minimizes the total cost of the DER, i.e., investment and operation, while relieving the surrounding electrical grid.

Links
https://github.com/KIT-IAI/GBOML_DER

References
https://doi.org/10.1109/ispec59716.2024.10892444

PowerMarketSim Model | Method

Fundamental European Day-Ahead Market Model

PowerMarketSim is a fundamental market model for the European day-ahead market in which decentralized bidding and market clearing are linked via Lagrangian relaxation, allowing both bidding and dispatch to be determined endogenously. By representing cross-zonal network constraints through congestion rents, the model produces structural price signals that reflect the underlying economic and physical limits.

Compared with existing fundamental models, the proposed approach reproduces DA price patterns more accurately and provides unit-level schedules that can be used for other simulation tools in other sectors. In this way, the market model provides the economically feasible operating points that grid-simulation tools lack, effectively guiding the units in the grid layer and enabling consistent cross-sector analyses.

Links
https://jugit.fz-juelich.de/iek-10/public/simulation/PowerMarketSim

References
https://dx.doi.org/10.2139/ssrn.5946752

ResampleGAN Model | Method

Temporal Transformation in Data Resolution with Generative Adversarial Transformers

Provides a method to bridge the temporal granularity gap utilizing Generative Adversarial Transformers (GATs) for upsampling, which can be trained without access to any ground-truth high-resolution data.

Compared with conventional interpolation methods, the introduced method can reduce the root mean square error (RMSE) of upsampling tasks by 9%, and the accuracy of a model predictive control (MPC) application scenario is improved by 13%

Links
https://github.com/KIT-IAI/ResampleGAN

References
https://arxiv.org/abs/2508.10587

Supplementary Models

AixLib Model library

Modelica modeling library for building energy systems

AixLib is an open-source Modelica library that supports realistic and flexible modeling and simulation of building energy systems. It provides a wide range of validated, physics-based components for buildings, HVAC systems, and renewable energy technologies, enabling detailed thermal and energy analyses. The modular structure allows models to be composed from individual components up to complete building and energy systems. AixLib is well suited for advanced control methods such as Model Predictive Control, enabling transparent, control-oriented studies based on white-box models rather than black-box approaches. Key components of the model library have been systematically adapted by Forschungszentrum Jülich to support their use in hierarchical and distributed Model Predictive Control (MPC) architectures.

Links
https://github.com/RWTH-EBC/AixLib

Supplementary Data

Grid-oriented control of heat pumps — Data

Dataset that characterizes the grid-oriented control of heat pumps via SG-Ready

The related published article under the title "Characterization of grid-oriented control of heat pumps via SG-Ready" can be found at: https://doi.org/10.1049/icp.2025.1999

Links
https://doi.org/10.5281/zenodo.14678762

References
https://publikationen.bibliothek.kit.edu/1000178527

LLEC Experimental Buildings – Control strategies — Data

Experimental data of three identical residential buildings controlled with different controllers for heating demand response

The datasets are created by running five experiments on three buildings located in the Living Lab Energy Campus (LLEC) Experimental Buildings of the Energy Lab at the Karlsruhe Institute of Technology (KIT). All three buildings have identical building envelopes and are supplied with district heating energy. The purpose of these experiments is to evaluate the performance of three control strategies for heating demand response in nearly identical conditions.

Links
https://doi.org/10.5281/zenodo.17455075

References
https://doi.org/10.1016/j.apenergy.2025.126666

LLEC Experimental Buildings – Smart Readiness Indicator validation — Data

Experimental data of two residential buildings supplied by heat pump and district heating under multiple heating scenarios during winter 2023-2024

The datasets are created by running multiple experiments on two buildings located in the Living Lab Energy Campus (LLEC) Experimental Buildings of the Energy Lab of Karlsruhe Institute of Technology. The datasets monitor the energy performance of the buildings equipped with different energy systems and experimented under different scenarios during winter 2023-2024.

Links
https://doi.org/10.5281/zenodo.14810475

References
https://doi.org/10.1016/j.enbuild.2025.116128

sci2grid Model | Software | Data

Data models focusing on electricity transmission and gas transport infrastructure.

The sci2grid data models are designed to primarily process georeferenced information for objects such as supply lines, substations or compressor stations. This information is automatically extracted from open data sources and may include geo-coordinates, line lengths and diameters, or installed capacities. In addition, complementary information is manually collected from individual online sources, such as press articles, verified, and integrated into the models. Missing data is estimated using heuristic methods to provide consistent and comprehensive data models for subsequent analyses. At present, it provides gas transport and electricity transmission grid models for Europe that can be used to investigate grid-related challenges.

Such openly available and transparent grid models have a wide range of applications. They can be used for the assessment of energy system scenarios, the simulation of grid operation, the identification of bottlenecks in energy supply, the evaluation of grid development plans, and the determination of future grid expansion needs.

Links
https://www.dlr.de/de/ve/forschung-und-transfer/infrastruktur/modelle/sci2grid
https://helmholtz.software/software/sci2grid
https://www.energieforschung.de/de/aktuelles/projekteinblicke/2022/scigrid-gas

References
https://doi.org/10.1109/OSMSES54027.2022.9769122

Exemplary Use Cases

Our suite contains fundamental building blocks and solutions for various applications. By combining them as needed, a wide variety of use cases can be handled and adapted in a modular fashion. In this section, we outline selected use cases to highlight how different solutions from the suite can be integrated to tackle complex tasks and research questions.

Impact of the Market-Oriented Operation of Power-Grid-Supporting Electrolyzers on Germany's Electricity and Gas Transmission Networks

GasNetSim	PowerMarketSim	sci2grid

This exemplary use case analyzes the impact of large-scale electrolysis on Germany's electricity and gas transmission networks using a modeling chain that combines our new simulation tools with our open-source infrastructure datasets. The analysis is based on two consecutive weeks from 2022, selected because they represent diverse operating conditions: one week with very high wind feed-in followed by a week dominated by conventional and PV generation.

The study begins with a market simulation in **PowerMarketSim** without any electrolyzers, reflecting only the dispatch of conventional and renewable generators (Figure 3a). The resulting spatially resolved generation and consumption patterns are mapped onto the German transmission network using the **sci2grid** power grid dataset to calculate power flows (Figure 3b-d). These simulations reveal pronounced North–South congestion during the wind-rich week due to the need to transport large wind surpluses toward southern and eastern load centers (Figure 3b), while such bottlenecks largely disappear in the subsequent low-wind week (Figure 3c-d).

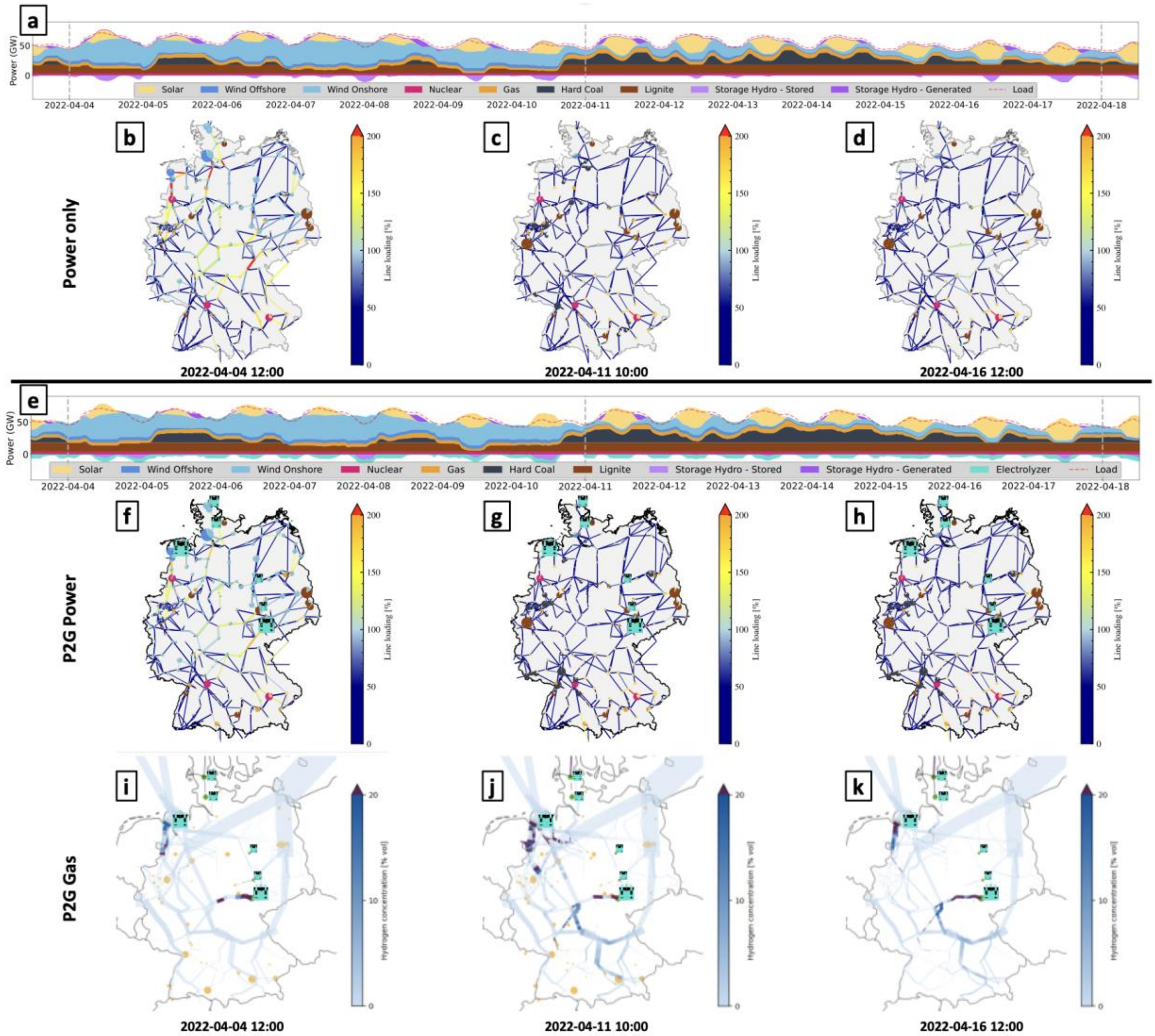

Figure 3: Market dispatch, power flows, and gas network hydrogen concentrations for two consecutive weeks in 2022. Panels (a–d) show the baseline system without electrolyzers, illustrating strong North–South power flow congestion during

the wind-rich week. Panels (e–h) present the power system with 6 GW of electrolysis located at six strategic nodes, where market-driven operation absorbs surplus wind energy and reduces transmission loading. Panel (i-k) show the resulting hydrogen distribution in the gas grid, where local exceedances of the 20 vol% blending limit occur near injection points.

In the next step, 6 GW of electrolysis capacity are introduced at six strategically selected nodes that feature both electricity and gas grid connections and are located directly upstream of typical power grid congestion corridors. In **PowerMarketSim**, these electrolyzers are modeled as flexible, price-responsive demand units that predominantly operate during low-price hours, while fulfilling a 50%-65% minimum utilization requirement during a day (Figure 3e). For this study, the entire amount of hydrogen produced is injected into the natural gas grid. This market-based dispatch is again mapped onto the **sci2grid** power grid model. The resulting power flow simulations show that the additional local demand from electrolysis substantially reduces long-distance transmission requirements, so that the North–South congestion observed in the baseline case is significantly alleviated, particularly during the wind-rich week (Figure 3f). This proves especially beneficial because low electricity prices generally coincide with these wind-rich periods, meaning that market-driven electrolyzer operation naturally occurs exactly when it most effectively mitigates transmission congestion.

Finally, the implications of this electrolyzer operation for the gas infrastructure are assessed using **GasNetSim** together with the **sci2grid** gas grid dataset. The simulations show that hydrogen injections from the six large electrolyzers can lead to local exceedances of the 20 vol% blending limit in nearby pipelines. Since such exceedances would not be permissible in real operation, this indicates that although electrolysis reduces loading in the electricity grid, gas network limits would become binding and require operational management (Figure 3i-k).

Taken together, the results show that while strategically placed, market-driven electrolysis can alleviate electricity grid congestion, its operation also makes evident that hydrogen blending limits in the gas network could be exceeded, meaning that electrolyzer operators would need to restrict their electricity market participation accordingly and that an integrated market framework is required for such interactions to be captured adequately in system simulations.

RESUR – Platform for Analysis of Disruptive Events

PROOF	*eASiMOV-eCoSim*	*eASiMOV-eCoSimWeb*

Architecture and Description

The RESUR platform was designed to integrate data, models, simulators, and frameworks to address short-term energy supply issues during incidents, also referred to as disruptive events, such as cyberattacks, heat waves, and network and system failures. RESUR, as a project, is structured into six work packages (WPs), each undertaken by colleagues from the Helmholtz Centers Forschungszentrum Jülich (FZJ) and Karlsruhe Institute of Technology (KIT), with the German Aerospace Center (DLR) as an associated partner. The RESUR multi-layer concept includes an initiator, expert, scenario, and model-coupling layer. These layers encapsulate the expert knowledge required to build a scientific workflow. At the initiator layer, an initial research question is formulated, and a workflow is developed. In the expert layer, the initial question is translated into a textual description, and the research question's boundary conditions are defined. Experts preselect the simulation models to be coupled. At the scenario layer, a scenario, including the required data and relevant parameterizations for the simulation models, is created from the textual description. This step aligns with the needs of the coupled models. In the model coupling layer, as shown exemplary in Figure 4, technical and semantic couplings between the models are established, and the workflow is implemented within a suitable co-simulation platform.

At the model-coupling level, models are connected in the framework PROOF (KIT) through its graphical user interface using predefined interfaces. A valid conversion between the simulation models' data formats is ensured by selecting the appropriate data transformation scripts. A typical scenario involves coupling the gas and electricity sectors at the transmission level. The primary focus is on providing power-consumption data for the electricity grid at the 110kV level. It also links gas-fired power plant demand from the 110kV electricity network model, along with additional gas demand from industry and the residential sector in the German Gas Transport & Distribution network model (see top-right in Figure 4). For this, ETHOS.NESTOR (FZJ) supplies electrical energy demand data at a coarse resolution using a top-down approach. To communicate with the 110kV electrical network model, which employs a bottom-up approach, data-provisioning blocks are introduced. As described in detail in the next section, the electrical energy demand data are spatially disaggregated down to the municipality level. Open data are used to determine the load type (commercial, residential, or industrial) in different areas. A mathematical optimization problem is formulated to map municipal load data to 110kV substations. This multi-objective optimization aims to minimize costs, measured by distances from municipalities to substations—either as straight-line distances or along power lines—and to ensure uniform transformer utilization at the substations. As a result, the power load at the 110kV station is provided through static year-round timetables. In a hybrid simulation approach that combines static and dynamic simulations, static time-series data for municipalities are replaced with highly detailed bottom-up sector-coupling models, including grid models and coupled parameterized building models with electrical and thermal devices and controllers (see the bottom-left panel in Figure 4). These building models generate various residual loads, which are then coupled with the respective grid. The grids are created automatically using generic energy network models for power, gas, and heat, based on workflows that employ soft-coupled tools and open data sources, such as OpenStreetMap (OSM), and open-source software. The sector-coupled multi-energy system co-simulation is implemented using the eCoSim co-simulation module of the eASiMOV framework (KIT), which communicates with the workflow manager and exchanges relevant simulation data.

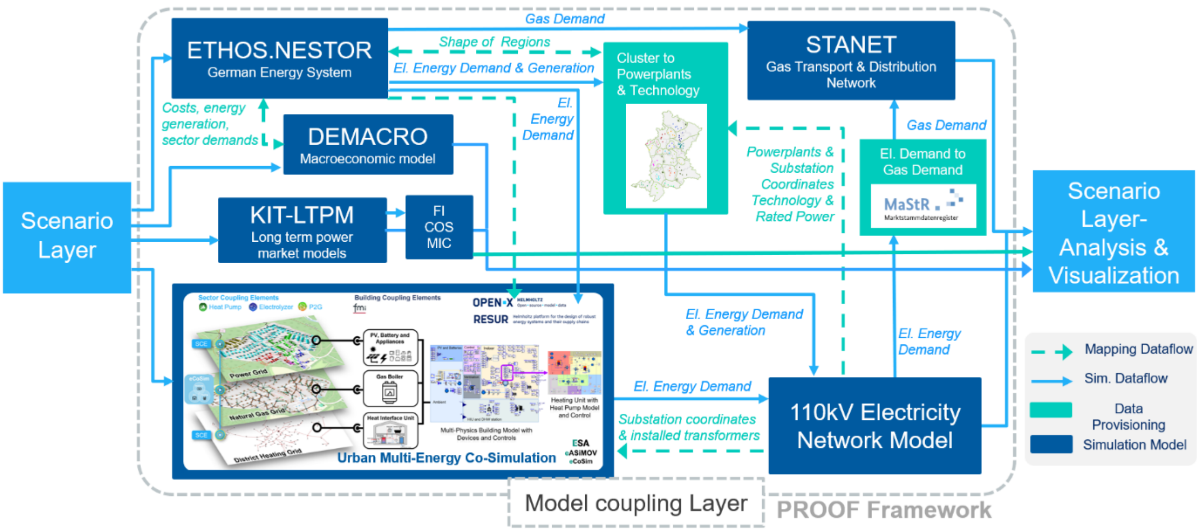

Figure 4: Illustration of a multi-domain energy system workflow linking a national energy system model (ETHOS.NESTOR) with a detailed 110kV electricity grid and a gas transportation grid model, as well as the eASiMOV-eCoSim co-simulation, an integrated co-simulation of a sector-coupled district heating, gas, and electricity grid that integrates white-box building models with electrical and heating appliances (bottom-left). The automated creation of generic energy networks during the model-creation phase employs workflows that integrate soft-coupled tools, all based on open data, particularly OpenStreetMap. The turquoise arrows represent the required links between the models for harmonizing the different data

formats of the simulation models. Further modules as DEMACRO, KIT-LTPM, and FICOSMIC can be activated to account for economic and market factors.

Analyzing the Open Data and Model Granularity Gap

In the context of the RESUR project, a new methodology was analyzed to integrate simulations of low-voltage, medium-voltage, and high-voltage grids into a single co-simulation, employing both top-down and bottom-up approaches for data acquisition and model generation. The coupling of the developed model, data, and software is shown in Figure 5.

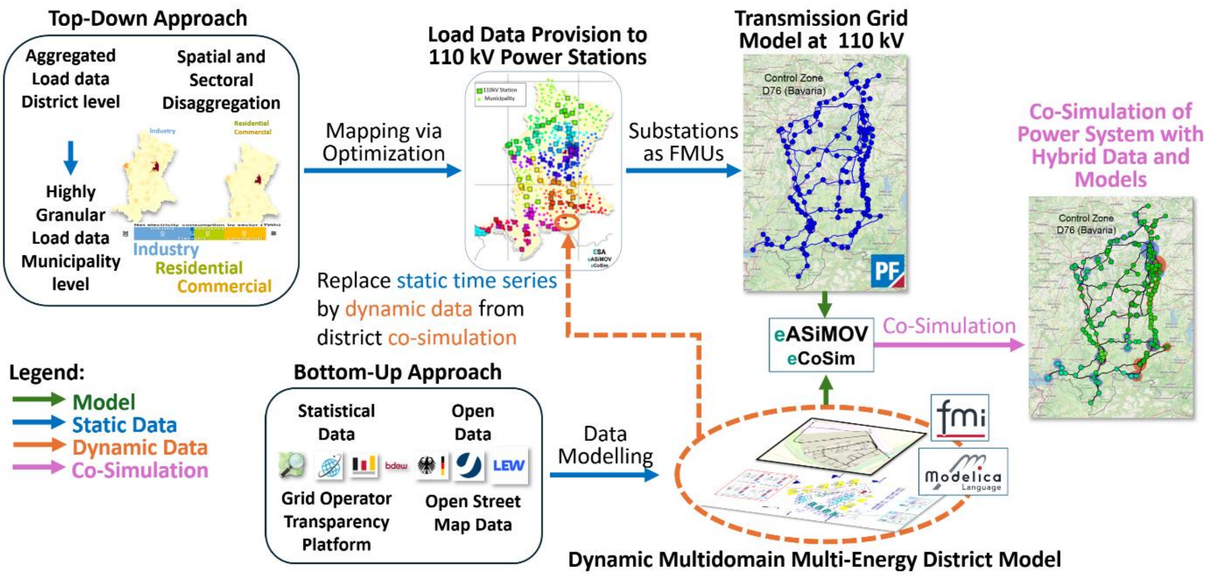

Figure 5: Top-Down and Bottom-Up Approaches for coupling energy system and power grid models and associated data within the RESUR platform.

In the top-down approach, the D76 region in Germany, as the target area for this study, is analyzed in detail for statistical data such as population numbers, industrial structure, and electrical energy consumption. Shares of the different electrical consumption sectors (residential, commercial, industrial) are considered. This data is then transformed to the required spatial and temporal resolution. For the D76 region, the spatial resolution is at the municipality level.

Using this information and the locations of the 110kV power stations provided by the 110kV grid model, a multi-objective optimization problem is formulated to assign municipalities' load centers to 110kV substations. The most important factors are the distances between municipalities and substations, and the substations' even load utilization across the grid.

Continuing the top-down approach, FMUs are built for the final load time series for each municipality as simple time tables. These are connected to the PowerFactory 110kV transmission grid model via eASiMOV-eCoSim, enabling distributed co-simulation on two workstations. With this modular approach, detailed simulation models of selected municipalities can be replaced by simple FMUs via a coupled co-simulation in which each chosen municipality runs its own co-simulation and forwards the results to the “main” co-simulation.

For this, a bottom-up approach is needed, after solving the problem of assigning municipalities to substations. Using combinations of different open and statistical data at the municipality level, a low-voltage grid model in PowerFactory is generated (doi:10.1109/TSG.2024.3406765). For each residential building in the area, a multi-physics building model is created and coupled to the low-voltage grid using eASiMOV-eCoSim, thereby forming the municipal component of the previously mentioned coupled co-simulation. Because this is computationally more expensive than the pure top-down approach, a total of five workstations are required for the coupled co-simulation, which comprises approximately 350 simulation modules.

When comparing both the top-down and bottom-up approaches, the exemplary municipality of Rögling in Bavaria shows that the final energy consumption for the bottom-up approach is 1001 MWh/a, which is more accurate than the official data from the Bavarian government of 1196 MWh/a, compared to the top-down approach with 1763 MWh/a. This indicates that using a combination of both approaches is important for more accurate estimates of electrical energy consumption.

Sector-Coupled Multi-Energy Systems Analysis (MES)

eASiMOV-eCoSim *eASiMOV-eCoSimWeb*

Collaborative Modelling of MES

The target area for the presented multi-energy system (MES) analysis is the Gredler community, a newly developed residential district. To ensure the model accurately reflects the community's future energy operation characteristics, we engaged in multiple rounds of technical communication with municipal utility companies, real estate developers, and investors. Using the contractor-provided architectural construction blueprints, heating network design schemes, and new building plans, we systematically modeled the area's multi-energy system to create a community-level digital twin for future planning evaluation and operational strategy research.

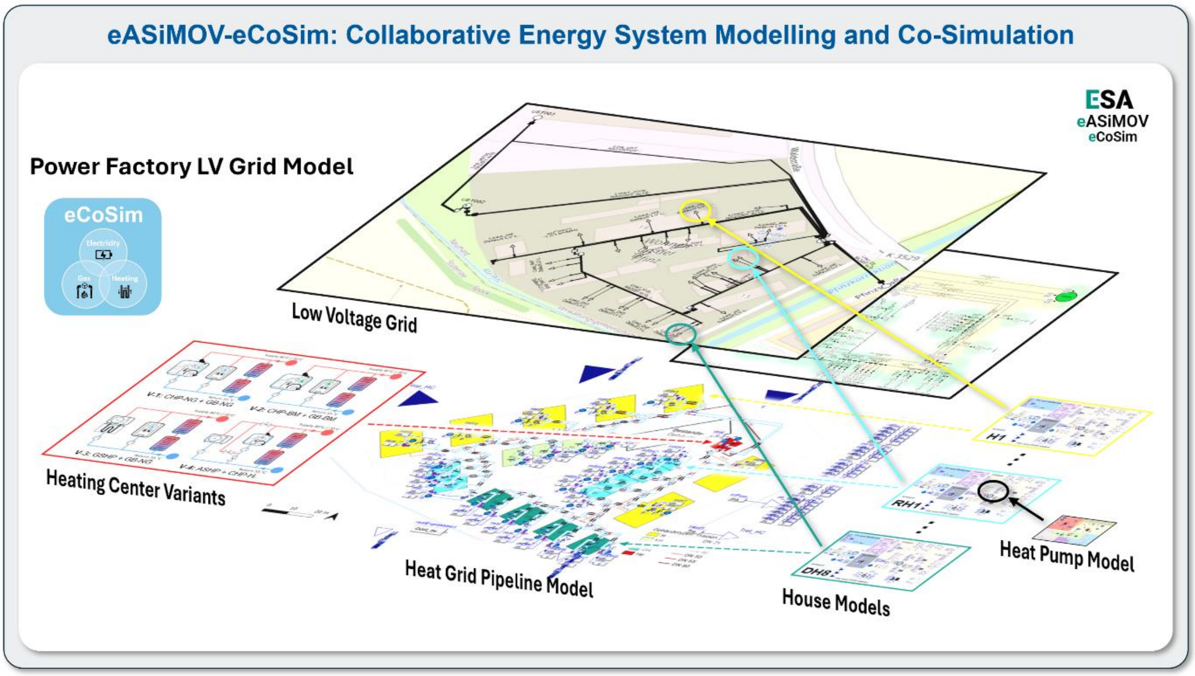

Figure 6: Modelling of a multi-energy system for a real-world laboratory "Gredler Areal" comprising an electrical low-voltage grid, a heat grid, white-box models of buildings, and variants for the heating center

The area plan comprises 29 buildings of diverse types: 7 apartment buildings, 4 chain buildings, 10 terraced buildings, and 8 semi-detached buildings. Since buildings themselves are the primary energy consumption terminals, we considered "buildings" as key interfaces connecting various energy networks (heating, electricity, etc.) in the overall architectural design. Taking into full account residents' living behaviors, comfort needs, and dynamic changes in the indoor environment, we aim to develop a high-fidelity model that closely represents the actual operating state, thereby enabling in-depth analysis of community energy consumption, building dynamic behavior, and energy network synergy characteristics.

Regarding modeling tools, the building model is based on the modular, configurable, and bottom-up Modelica white-box model proposed in (doi:10.1109/SoutheastCon56624.2025.10971478). The heating network model is also built using Modelica, and includes:

- building heat exchanger interfaces (HIU),
- pipeline network,
- and a multi-energy center model containing four types of energy supply variants, which are
    - natural gas-driven CHP (combined heat and power) + gas-fired boiler solution
    - biomethane-driven CHP + biomethane boiler solution
    - ground source heat pump + natural gas boiler solution
    - air source heat pump + hydrogen-based CHP solution.

By combining these energy sources, we can systematically compare the performance of community energy systems under traditional fossil-fuel, renewable, and future hydrogen pathways.

For the power system, PowerFactory was used to model the distribution network, with voltage levels set at 20/0.4 kV, and the power grid was coupled to buildings and heating network centers.

Finally, using the eCoSim co-simulation platform, we exported the building and heating network models in FMU format and integrated them with the PowerFactory power grid model via the API, thereby enabling joint modeling and co-simulation of multimodal and multi-energy networks. This digital twin system provides a solid technical foundation for subsequent research on energy-efficiency improvement strategies, operational optimization control, and multi-energy coupling-effect analysis.

Collaboration Platform eCoSimWeb for MES Analysis

The collaborative web-based platform eASiMOV-eCoSimWeb enables multi-physics co-simulations across institutions (see Figure 7). The entire web-based process is exemplarily described for the Gredler community, as described in the previous section for MES analysis. The simulation consists mainly of four types of simulators that represent the area. There is a heating center with various configurations, a heat grid model, an electrical grid consisting of a low-voltage network, and, lastly, 29 buildings ranging from multifamily houses to single-family houses.

In the concrete simulation, the heat grid pipeline model receives inputs from the heating center and from each house model and provides outputs to them. The heating center supplies electrical energy for generation to the low-voltage grid, while the houses supply their electrical load to the grid.

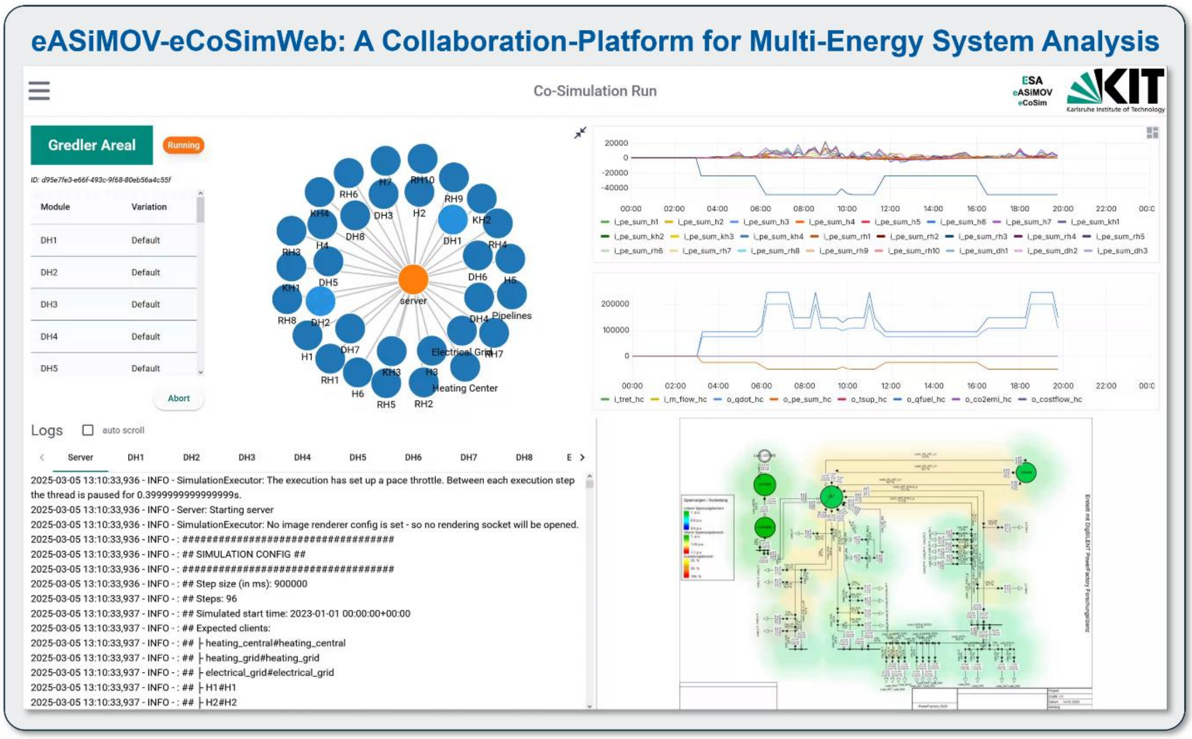

Figure 7: Collaborative web-based platform eASiMOV-eCoSimWeb enabling multi-physics-based co-simulations and variants analysis.

When the simulation, in this case Gredler, is selected, an overview of the participating simulation models and a description of the simulation are displayed. A project simulation manager previously provided the project description and models, which can be uploaded by participating users. In this step, the variants to be run during co-simulation can be selected for each module, if provided. An example of this is the different heating network variants possible in the area.

At this step, the simulation can be created, and the run parameters, like step size resolution for a simulation step, the number of simulation steps, and optional parameters for logging during the simulation, can be configured. At the start of the simulation, a visual overview of all participating modules is provided. After the simulation initialization is complete, two Grafana dashboards present results for the low-voltage grid and the heating center.

After the simulation completes, the results are saved to a database. The results data for this or previous simulation runs can be viewed and exported, each identified by a unique simulation run ID.

Sustainability Analysis with MES-Model Variants

This study conducted a comprehensive year-round assessment of the energy, economic, and sustainability performance of four heating center schemes and performed co-simulations with digital twin models of 29 buildings in the region (https://doi.org/10.1109/APPEEC61255.2024.10922291). The results show significant differences among the schemes in carbon emissions, operating costs, energy mix, and future adaptability, providing clear technical recommendations for community energy infrastructure planning.

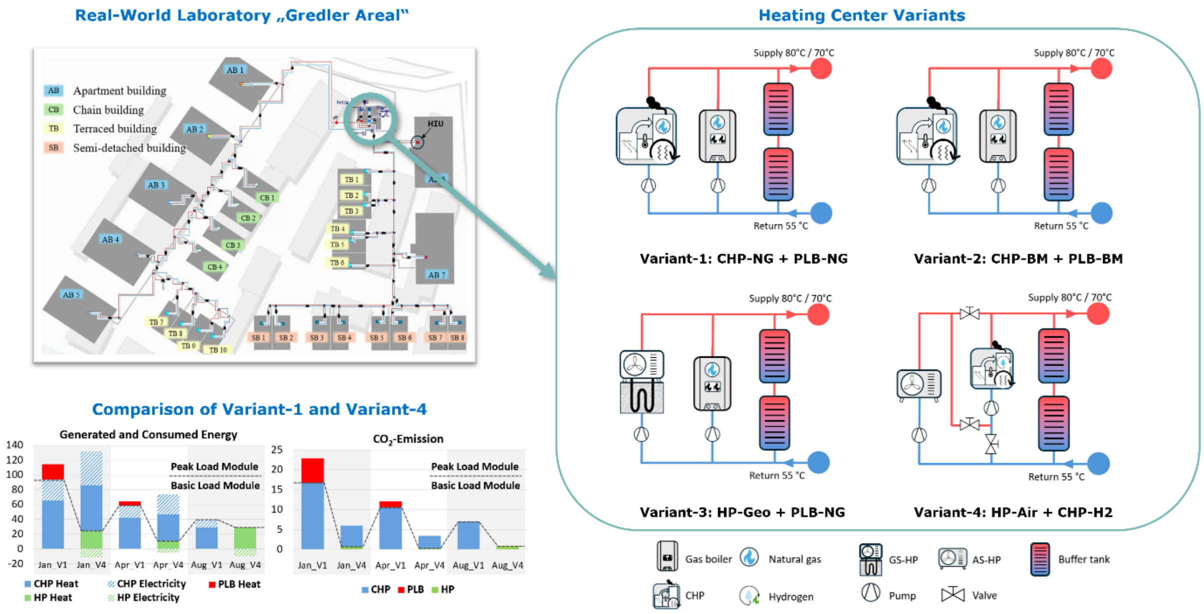

Figure 8: MES model variants of the Gredler with a year-round assessment of the energy, economic, and sustainability performance of four heating center schemes, and performed co-simulations with digital twin models of 29 buildings

Variant-1, serving as the baseline (natural gas CHP + natural gas peak boiler), can stably meet the regional heat load demand, exhibiting high technological maturity and low implementation risk, but it has the highest carbon emission level, approximately 136 tons of CO_2 annually. Although selling surplus CHP electricity to the grid can reduce heating costs to some extent, it still falls short of future emission reduction requirements. Variant-2, while maintaining the original system structure, replaces the energy medium from natural gas with biomethane, reducing overall carbon emissions by nearly 70% compared to the baseline. It represents the technical path with the greatest potential for emission reduction among the four schemes, without changing the equipment configuration. However, due to the high cost of biomethane, heating costs increase significantly, making it less economical than other options. However, this variant offers the advantages of low retrofitting difficulty and rapid deployment, making it well-suited to scenarios that aim to achieve emission reductions quickly in urban renewal projects.

In contrast, Variant-3 uses a ground-source heat pump instead of a CHP as the baseload unit, while retaining a natural gas boiler to meet peak demand. Due to the high efficiency of the ground-source heat pump, this solution significantly reduces natural gas consumption, requiring only 264 MWh annually to meet all building heat loads, making it the option with the lowest primary energy consumption among the four options. Without considering electricity sales revenue, it becomes the option with the lowest heating cost and best economic performance. Simultaneously, its carbon emissions are lower than those of the baseline and the biomethane option, but it is constrained by the available space for ground-source deployment, making it more suitable for communities with geothermal resources.

Variant-4, combining an air-source heat pump and a hydrogen-powered CHP, is considered the most promising configuration for future energy systems. Owing to the near-zero carbon footprint of green hydrogen and the high efficiency of heat pumps, this scheme achieves the lowest carbon emissions among the four variants, with an annual reduction of 77.2%. Although its equipment investment cost is higher and the price of hydrogen fuel is significantly higher than that of traditional energy sources, making its heating cost uncompetitive in the short term, its flexibility, scalability, and adaptability to future energy structures are the best, making it particularly suitable for long-term development scenarios aiming to create zero-carbon or demonstrative communities.

In summary, the four schemes correspond to different strategic positioning: Variant-1 is suitable as a baseline for current status assessment; Variant-2 can achieve significant emission reductions without changing the system structure; Variant-3 performs best in terms of economics and is the best choice for cost-sensitive projects; while Variant-4 offers the highest sustainability and future compatibility, making it the preferred scheme for moving towards a carbon neutral vision. The overall analysis emphasizes the importance of early planning for energy systems and shows that differences among energy pathways will directly affect operating costs, carbon emissions, and energy security for future communities, thereby providing clear direction for regional energy decision-making.

Market-based Scheduling of Decentral Energy Systems

The operation of decentralized energy systems requires novel approaches. One such approach is the MASSIVE framework. In this use case, MASSIVE is combined with the optimization framework COMANDO to derive market bids using mathematical optimization. In addition, a real-world demonstration of the framework is presented, leveraging the Smart Areas at FZJ and KIT within the ESD program. The implementation uses the Helmholtz ICT platform as a dedicated middleware to enable data exchange and operational integration.

At first, this section presents the core building blocks of the MASSIVE framework, which enables decentralized coordination within local energy communities. It is based on an agent architecture with autonomous decision-making entities, a market-based coordination mechanism, and an ICT infrastructure for real-time communication. These elements are described below before the experimental setup is introduced.

Agent modeling and roles

Agents first generate forecasts of their individual energy profiles. In the MASSIVE framework, these models are configured via plain-text files, allowing agents to be instantiated as digital twins using real-time data. Forecasts are either component-specific (e.g., photovoltaic systems) or based on aggregated simulation results, as in the case of campus agents.

Two types of agents are distinguished: model-based agents, which use environmental data from the German Weather Service (DWD) to derive forecasts for energy generation or building demand, and optimizing agents, which additionally exploit the flexibility of their systems and optimize operation based on local price signals to minimize costs. Agents are further classified by market role into consumers, producers, and prosumers, who both consume and generate energy and can use storage systems for arbitrage.

Market design and clearing mechanism

Coordination is achieved through a local market operating in 15-minute intervals, inspired by real intraday markets. Market clearing follows the merit-order principle and is based on a linear optimization model that evaluates bids, allocates energy, and determines market prices. The objective is to minimize total costs within the local energy community.

Within the simulation, agents use fixed prices for supply and demand, while complex bidding strategies are not considered. Nevertheless, dynamic clearing outcomes emerge due to varying load and generation conditions, demonstrating that effective coordination is possible even with fixed bids.

Agent communication

Communication between agents and the market is implemented via MQTT using a publish/subscribe architecture. Agents publish their bids to predefined topics, while a central marketplace module acts as the sole subscriber and distributes the clearing results. Direct communication between agents is excluded to ensure data privacy.

The exclusive use of MQTT reduces complexity and latency and enables fast reactions. To integrate real hardware, a FIWARE-based ICT platform is used to transmit sensor data from technical systems to the agents. A handshake mechanism allows agents to dynamically register and deregister with the marketplace during runtime.

Agents are containerized and deployed on OpenStack-based virtual machines. This architecture supports parallel execution, scalability, and a clear separation between agents and the marketplace, ensuring a realistic and event-driven communication environment.

Experimental setup in Smart Areas

The framework was applied in a hybrid experimental setup combining purely simulated components with real-world energy demonstrators. Network constraints were neglected for simplicity. Initially, a fully simulated market environment was established, including agents for photovoltaic generation, electric vehicles, a building with a heat pump, a battery storage system, and a campus agent aggregating multiple LLEC components. A grid agent representing backup capacity was added to ensure feasible market clearing.

Bid generation was handled either locally within individual agents or, in the case of the campus agent, through a hierarchical controller that aggregated results from multiple simulations via MQTT-based communication. In a second validation step, selected market-cleared load profiles were applied to physical energy demonstrators. These agents relied on physics-based models that accurately represented the deployed hardware, but no live coupling between market and hardware was implemented.

A PEM electrolysis and a lithium-ion battery system were used to validate the feasibility of executing market-based schedules under real operating conditions. Bid generation for physical assets was based on digital twins configured within the MASSIVE framework, with the optimization extended to incorporate real-time feedback and battery aging effects. After market clearing, setpoints were transmitted to the hardware via an MQTT–Modbus interface. All agents and adapters were containerized and deployed using Kubernetes, while operational data were fed back through a FIWARE-based ICT platform and stored in an InfluxDB to keep simulation models synchronized with the physical systems.

Supplement: ESD ICT-Platform Deployment

FIWARE is at the core of the ICT platform and used alongside MQTT to interconnect different services, tools and hardware. A detailed description of the implementation at FZJ is given in: https://doi.org/10.1109/osmses62085.2024.10668993

The deployment kit can be found at: https://helmholtz.software/software/fiware-deployment-kit