The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling✩

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Abstract

Energy system models have become indispensable tools for planning future energy systems by providing insights into different development trajectories. However, sustainable systems with high shares of renewable energy are characterized by growing cross-sectoral interdependencies and decentralized structures. To capture important properties of increasingly complex energy systems, sophisticated and flexible modelling tools are needed. At the same time, open science is becoming increasingly important in energy system modelling. This paper presents the Open Energy Modelling Framework (oemof) as a novel approach to energy system modelling, representation and analysis. The framework provides a toolbox to construct comprehensive energy system models and has been published open source under a free licence. Through collaborative development based on open processes, the framework supports a maximum level of participation, transparency and open science principles in energy system modelling. Based on a generic graph-based description of energy systems, it is well-suited to flexibly model complex cross-sectoral systems and incorporate various modelling approaches. This makes the framework a multi-purpose modelling environment for modelling and analyzing different systems at scales ranging from urban to transnational.

Keywords: decision support, energy system modelling, optimization, collaborative development, open science

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✩This document is a collaborative effort.
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1. Introduction

The global transition process towards more sustainable and low-carbon energy systems requires the development of alternative future trajectories for thorough scientific discussion. Using these, decision processes on different levels e.g. in transnational policy making or local energy planning can be supported. However, future energy systems imply a rising complexity in technical, economic and socioeconomic dimensions due to increasingly cross-sectoral and decentralized structures [1]. Insights into such complex systems can be gained by applying computer-based modelling approaches which create a quantitative basis for the above mentioned discussion and decision processes.

Depending on the specific investigation and research question, a variety of model types can be applied. Such model types include power flow models for electricity transmission network operation and planning, economic dispatch models for general capacity planning and unit commitment models for power plant utilization [2, 3, 4, 5]. Applications range from large-scale transnational investigations using purely economic top-down equilibrium models to detailed technical local infrastructure planning using bottom-up models based on technology-specific data. Moreover, many models can be adapted to integrate different sectors such as electricity, heat and mobility to investigate cross-sectoral interdependencies.

Energy system models and derived results have often been heavily discussed among different stakeholders and been criticized for not opening their internal logic and underlying assumptions [6, 7, 8]. As a result, in the last decade more scientists have opened their models and data [9, 10]. This process goes along with a general trend to open science in many other research fields. The rationale for open science includes improved efficiency, scrutiny and reproducibility of results, re-usability of scientific work and increased transparency of all scientific processes [11]. As the European Commission has recently started to push open science in its research programs [12], the subject of openness has finally moved into the public spotlight.

This paper presents the Open Energy Modelling Framework (oemof) as a novel approach to foster open science in the field of energy modelling and analysis. First, the idea of a single energy modelling framework is differentiated from other approaches to delineate the scientific contribution in Section 2. The underlying concept with its mathematical representation as well as the framework architecture and its implementation are outlined in Section 3. Building on this, the general process of application development is described in Section 4 along with a selection of existing applications. Finally, the general approach and its scientific contribution are summarized in Section 5.
2. Scientific contribution

To provide context, first a brief overview on relevant energy system modelling software is provided. Subsequently, the presented framework is compared to similar existing software and its unique features are outlined. For extensive reviews on this topic, please see Hall and Buckley [13], Connolly et al. [14] and Pfenninger et al. [1].

2.1. Overview of modelling landscape

In the following, we distinguish between the three terms model, model generator and framework. Models are concrete representations of real world systems (e.g. with a specific regional focus and temporal resolution). Such a representation may consist of multiple hard- or soft-linked sub-models to answer clearly-defined research questions. Models can be built using model generators that employ a certain analytical and mathematical approach (e.g. by the use of predefined set of equations, represented technologies). Finally, a framework can be understood as a structured toolbox including sub-frameworks and model generators as well as specific models (e.g. wind feed-in models). In addition this kind of a collection has other requirements for structures and processes that guide the development process.

With respect to open science principles, a rough division into a line of closed (1st generation) and open (2nd generation) models for energy system analysis can be derived.

The 1st generation models and model generators have a long tradition and are predominant in the academic energy system modelling field. Among the most widely used proprietary model generators is TIMES/MARKAL [15]. Models of this family have been used to answer research questions in the field of energy planning which is indicated by the high number of references in academic literature [13]. Similarly, MESSAGE is a prominent model generator that has been used for the IIASA global energy scenarios [16]. Besides this, the EnergyPLAN simulation model has been applied in various research projects to analyse sector integrated electricity, heat and transport systems [17].

The Balmorel model [18] can be seen as one of the first 2nd generation energy system models. It has been designed for power and heat dispatch modelling with optional investment within the Baltic region and is written in GAMS. Another early project is the model generator OSeMOSYS [19] which is mainly used for long-term integrated assessment and energy planning. This project aims to facilitate modelling and education through a free software philosophy and a simple, easy-to-learn interface. Since then, various other projects with different purposes have been developed (e.g. urbs [20], PyPSA [21], calliope [22]). Their focus covers the full range from power flow simulation to long-term investment models. A list of open source models can be found on the website of the Openmod-Initiative [9]. While some of these projects are models for a specific region, others can be classified as model generators.
2.2. Comparison to other software

Since the list of available modelling software is extensive, the framework is compared to similar existing tools. For this, major categories with single characteristics are introduced. These encompass the general suitability for open science, the technical concept and overall modelling functionality.

A requirement of open science is the free availability of the software itself. Freely available software is software that is available without additional cost. The usage of fee-based software creates barriers to reproducibility, since the experiment can only be repeated if the respective licence is procured. Moreover, an open licence enables users to distribute, understand and change the source code and thus enhances transparency since model assumptions and internal logic can be understood, changed and evaluated to determine their influence on the results. The issue of re-usability can also be addressed when software is published under an open licence since other developers can re-use any part of the software. Finally, collaborative software development allows for continuous improvements, enables an easier detection of bugs and makes it possible to discuss new features in a transparent manner. Collaborative development in this context refers to joint work on the software’s code without mandatory institutional ties. This includes a common road map, discussion of new features and changes and in general a high level of communication among the developers. A central characteristic of this definition is the transparency of all associated processes.

The concept is defined by technical and structural characteristics. Implementing the software in a high-level language lowers barriers to usage and contribution. High-level programming languages are characterized by a strong abstraction from computer’s hardware, are easier to use and understand, may include elements of natural language and make software development simpler. The more external libraries available for a language, the easier the implementation of various tasks in the modelling tool-chain. Further, interfaces to other languages can be used to extend capability. A generic data model enables a separation between the mere topological description and subsequent calculation (within an optimization, for example). Generic data models are data structures designed specifically to suit the representation of data of a particular problem rather than to store data of multiple different problems. Graph-based representation of energy systems, for instance, can be used to represent electricity systems as well as heating systems. Providing the option to define the level of accuracy flexibly is an added value of energy system modelling toolboxes. For example, it allows for user-defined precision in representation of time in modelling an energy system components by extending the libraries scope through user-defined components. Another aspect of the concept is designing it for multiple purposes. This extends the core functionality by other useful tools. An example would be an energy system modelling toolbox that includes tools for generating feed-in profiles of renewable energy sources.

Functionality, in this case, is defined by concrete modelling capabilities for model types such as economic dispatch, investment planning (also across multiple periods, called multi-period investment planning), power flow calculation
and unit commitment. Furthermore, the general capability to model sector coupling problems is a prerequisite for modelling multi-sectoral energy systems such as electricity, heat and transport.

To compare the framework to other tools, Table 1 lists a selection of popular 1st and 2nd generation of modelling frameworks and model generators. Though oemof shares certain characteristics with existing software, the collaborative development, the generic data model and multi-model toolbox (framework) differentiates oemof.

| Open science | Concept | Functionality |
|--------------|---------|--------------|
| Free of charge | Open licence | Collaborative development |
| WASP IV | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | [23] |
| EnergyPlan v12 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | [17] |
| MARKAL/TIMES | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | [15] |
| MESSAGE-III | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | [16] |
| oemof v0.2 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | [24] |
| urbs v0.7 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | [20] |
| calliope v0.5.3 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | [25] |
| PyPSA v0.12 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | [21] |
| OSeMOSYS | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | [19] |

Table 1: A comparison of features of selected software tools that are similar to oemof. Note that for OSeMOSYS multiple implementations in different languages exist.

2.3. Unique framework features

A core feature of the framework is its collaborative development with the goal of community building. Many existing tools are not developed by a single institution. For example, researchers are encouraged to develop and improve the source code of MARKAL and other tools of the Energy Technology Systems Analysis Program (ETSAP)[26]. However, the review processes and decisions are not transparent and valuable information may be lost in case of rejection of input. In contrast, oemof strives for an open process to encourage future improvements. To align with open science principles the idea is to enable full transparency of the development process and not only the final source code. For
that reason, the project follows a strict free software philosophy. In addition, processes are designed for community building, collaborative and transparent source code development.

Another unique feature is the *generic data model* which has emerged from the collaboration of various researchers with different research interests and backgrounds. This has led to the development of a framework with a common basis (Section 3.1) consisting of a layer-structured set of tools and sub-frameworks. A generic graph-based basis allows to differentiate between the topology of an energy system and its calculation based on a specific mathematical approach. The oemof framework may be seen as a domain specific language [27] that represents arbitrary energy systems as a graph. As a consequence, oemof can represent energy systems at a high abstraction level as well as a detailed single power plant.

Generally, the framework serves as a *multi-purpose toolbox* for energy system modelling and has been designed to integrate a growing set of toolboxes in future. Open source model generators like *calliope* Pfenninger and Keirstead [22] and the toolbox *OseMOSYS* Howells et al. [19] are designed to build specific models of one model family or type by the use of predefined sets of equations (e.g. bottom-up linear optimization based models). Furthermore, some of the existing projects, such as *PyPSA* [21], include several model generators for different purposes that may be combined. In contrast to other tools, oemof encompasses model generator methods to generate specific economic dispatch, investment and unit commitment models. Beyond this, it provides a structured set of tools to facilitate the modelling process. In its current state, this set includes an optimization library (model generator) as well as tools to simulate feed-in from renewable energy sources or local heat demand for a specific region.

In summary, the underlying concept, the software architecture, the free software philosophy and in particular the framing processes (e.g. open meetings, open code review, open web-conferences, open platforms and open pull-requests) enable collaborative development and participation. These combined features distinguish oemof from existing projects and constitute a basis for open science in the field of energy system modelling. Its academic value lies exactly in this difference in terms of open science.

### 3. Concept, architecture and implementation

To help in understanding the framework, its underlying concept, architecture and specific implementation are outlined here. First, a general mathematical representation of energy systems is proposed which serves as a base for higher level software architecture presented subsequently. Finally, the specific implementation is described and justified.

#### 3.1. Underlying concept

The main feature of the framework is the separation of an energy system’s topological description from its computation. The representation may serve as
a foundation to run graph-based algorithms (to determine whether the graph is connected, for example) or to perform exploratory analyses. Subsequently parameters of the system (or sub-systems) can be computed based on concrete modelling methods. Due to this property, oemof can incorporate other models and model generators with varying modelling approaches and different programming languages.

To achieve this, a generic concept which constitutes the foundation of all the oemof libraries has been developed. In this concept, an energy system is represented as a network consisting of nodes and edges connecting these. Nodes \( N \) are subdivided into buses \( B \) and components \( C \). When representing an energy system, an additional constraint that buses are solely connected to components and vice versa is imposed. Components are meant to represent actual producers, consumers or processes of the energy system while buses are meant to represent how these components are tied together. Edges are used to represent the inputs and outputs of a component.

An energy system that is represented in such a way can be mathematically described using concepts from graph theory by looking at it as a bipartite graph \( G \). The mathematical formulation of this graph in its general form is given in equation 1. A more detailed description of this concept with its theoretical foundation has been published by Wingenbach Wingenbach et al. [28].

\[
G := (N, E) \tag{1}
\]
\[
N := \{B, C\}
\]
\[
E \subseteq B \times C \cup C \times B
\]
\[
C^+ \subseteq C
\]
\[
C^- \subseteq C
\]
\[
T \subseteq C
\]

Components can be subdivided further into sources \( C^+ \), sinks \( C^- \) and transformers \( T \):

1. **Transformers** have inflows and outflows. For example, a gas turbine consumes gas from a gas bus and feeds electrical energy into an electricity bus. The relation between inflow and outflow can be specified in the form of parameters, for example by specifying the transfer function or an efficiency factor.
2. **Sinks** only have inflows but no outflows. Sinks can represent consumers of which households would be an example.
3. **Sources** have outflows but no inflows. For example, wind energy or photovoltaic plants but also commodities can be modelled as sources.

A similar, purely mathematical formulation of multi-commodity network flow optimization models for dynamic energy management has been illustrated by Zeng Zeng and Manfren [29]. Furthermore, related structures of energy systems can also be found in different energy models [19, 30, 15, 31]. These
publications demonstrate that using a graph is an intuitive way of representing an energy system. The main difference of our approach when compared to existing ones is the identification (and its object-oriented implementation) of a specific graph structure that may be used as a representation for all types of energy systems. Every calculation based on a specific model will be derived from this representation. A graphical representation of how to describe an arbitrary energy system using this network structure is shown schematically in Figure 1.

![Figure 1: Schematic illustration of an energy system represented as an oemof network.](image)

Based on the described concept, oemof provides basic components which can be used directly while also facilitating the development of more specific components built upon the basic ones.

3.2. Mathematical description: The solph-library

Currently, the solph-library can be used to create mixed-integer linear optimization problems from a pre-defined set of components. In order to model different elements of an energy system, several classes that may represent real-world objects such as power plants or consumers based on the described graph logic are provided. Every class has associated objective expression terms, optimization variables and constraints. Depending on the object attributes set by the user these associated terms will be added to the model.

The objective function for a specific model consists of different expressions depending on chosen components and their attributes. Hence, only a general description for main categories of distinct expression types is given in this section. Generally, total costs for the simulated time horizon $T$ are minimized, whereas the expression term includes time-dependent terms for all variables $w$ associated with an edge $(s, e)$ (i.e. connecting a start node $s$ and an end node $e$) and for all variables $v$ associated with a node $n$. In addition, time-independent terms for node and edge weights may be added.
The parameter $c$ may be interpreted as a specific cost and the time-increment $\tau$ is determined by the temporal resolution. Sets $I_1$ to $I_4$ stand for the possibility of multiple costs and weights for one edge or node. Domains $D$ of variables $w$ and $v$ can either be positive reals, positive integers or binary, as a special subtype of integer.

$$D = \{ \mathbb{R}^+, \mathbb{Z}^+, \{0,1\} \}$$ (3)

Generally, all variables are bounded by lower and upper bounds which are set based on the class attributes of the modelled components.

$$0 \leq w_{(s,e)}^i(t) \leq \bar{w}_{(s,e)}^i(t) \quad \forall i \in I_1, \forall (s,e) \in E, \forall t \in T \quad (4)$$

$$0 \leq w_{(s,e)}^i \leq \bar{w}_{(s,e)}^i \quad \forall i \in I_2, \forall (s,e) \in E \quad (5)$$

$$0 \leq v_{n}^i(t) \leq \bar{v}_{n}^i(t), \quad \forall i \in I_3, \forall n \in N, \forall t \in T \quad (6)$$

$$0 \leq v_n^i \leq \bar{v}_n^i, \quad \forall i \in I_4, \forall n \in N \quad (7)$$

The library consists of a large set of constraints that are documented extensively in the latest online documentation of the software. In addition, the library is being continuously improved. Therefore, possible constraints are subject to changes and depend on the version of the library. For these two reasons the constraints are not outlined in detail. Instead, a general form of constraint which all specific component constraints must follow is given in equation 8.

$$\sum_{k \in P_n} \sum_{j \in J_1} u_{(k,n)}^j \cdot w_{(k,n)}^j + \sum_{k \in S_n} \sum_{j \in J_2} u_{(n,k)}^j \cdot w_{(n,k)}^j + \sum_{j \in J_3} v_n^j \cdot v_n^j + M \leq 0 \quad \forall n \in N \quad (8)$$
The important characteristic of this constraint is the reduced possibility space of related variables inside one specific constraint. Defined from the perspective of a node \( n \), only variables \( w \) and \( v \) associated with an edge from one of its predecessors \( P_n \) to node \( n \), an edge from node \( n \) to one of its successors \( S_n \), or the node itself may appear. In this context, the parameter \( a \) may be interpreted as an efficiency, for example. The sets \( J_1 \) to \( J_3 \) stand for the possibility of multiple parameters and weights for one edge or node.

### 3.3. Project architecture

The project tries to accommodate energy system modellers with a large set of functionalities they typically need. To achieve this, the project and its development process follow an architecture that groups the content of the framework into functional and organizational units. This architecture consists of the four layers depicted in Figure 2. These four layers are used to categorize the libraries associated with the oemof project according to their dependencies and commonalities.

The framework itself and its underlying concept are implemented using an object-oriented approach in the high-level programming language Python and they are published under the GNU GPL3 licence. Python libraries are called packages; the main component of the framework is the oemof package. This package covers the first layer completely and the second layer partially. The layers beyond the first differentiate how closely libraries are associated with the oemof package and its developers in terms of organizational ties as well as technical dependencies.

**Figure 2: Layer structure of the oemof project architecture.**

1. At the core layer a generic graph structure is implemented via core classes. These classes are used to instantiate the objects comprising an energy system graph and define how an energy system is described. In addition, the basic application programming interface (API) is defined, through which the
core objects and their properties representing the graph are accessed. The entire core layer is kept free from energy system-specific logic in order to accommodate a broad spectrum of modelling approaches. Additionally, it allows decoupling of the energy system’s representation from how it is modelled. The intended use of the core objects in layers above the core layer is communicated via carefully chosen naming and explicit documentation.

2. The namespace layer contains associated libraries that share the same basic system formulations, i.e. libraries modelling energy systems as graphs described in terms of objects from the core layer. They depend on the basic API by either directly using core classes or adding functionality on top of them via inheritance. That way, different modelling approaches can be used on energy systems described in a uniform way, namely as energy system graphs consisting of instances of core classes or of classes inherited from them. Possible modelling methods can model energy systems with respect to cost, power-flow or any other kind of simulation or optimization goal. Currently the oemof.solph can be used to generate linear (mixed-integer) optimization problems from an energy system representation based on core objects. However, the graph structure is capable of accommodating other concepts such as evolutionary optimization or agent-based modelling.

3. The oemof cosmos layer contains libraries from the field of energy system modelling that are associated with oemof in an organisational way without sharing the basic API. These libraries, while still part of the oemof project, are not developed as part of the same package and may thus be used, reviewed and developed by third-party modellers and experts as well. However, as they are developed as part of the framework, they follow the common development rules (Section 3.5). As most modellers are not primarily programmers, sharing the same development, structure and documentation rules can help in learning how to use the libraries. One example of such a library is the windpowerlib [32], a library generating feed-in time series of wind energy turbines from meteorological data.

4. Open source does not necessarily lead to cooperation [10]. To facilitate cooperation, the oemof linked layer contains existing community libraries. These libraries are written in Python but do not necessarily share the same rules. However, in order to be considered associated, they should meet general standards for quality, code development, longevity, maintenance and community structure. One example of such a library is the pvlib [33], which is a library developed independently from oemof and which will be integrated into the framework via interfaces in the feedinlib. The process of developing these interfaces has already lead to code contributions towards pvlib, instead of the creation of a parallel, competing solution.

3.4. Implementation

The graph concept has been implemented at the core layer in the form of a class hierarchy which is sketched in Figure 3. The root elements of this class hierarchy are Node, Edge and EnergySystem. Node is the abstract base class
for *Bus* and *Component*, which are used to represent nodes in the bipartite graph representing the energy system. Further, components are subdivided into *Source*, *Sink* and *Transformer* classes depending on how they are connected to *Bus* objects. Objects of the class *Edge* represent the directed edge between two nodes, i.e. the connection between a *Bus* and a *Component* object. The class *EnergySystem* serves as a container for nodes and may hold additional information about the energy system.

All basic energy system components such as energy demands, (renewable) energy sources and transformers between different energy buses can be modelled by means of these basic classes. Additional components that introduce new features can be added via inheritance. If sub-classing is not suitable, new classes can be created and used together with the core classes. As an example, the *solph* library introduces a storage class with different individual parameters.

A demonstration of separation of the description of the energy system from its computation can be seen through the introduction of the *Edge* class, which is separate from the *Node* class hierarchy. Objects of this class hold information about the flow between two nodes, such as maximum available transfer capacities of power line flows or whether the amount of a certain flow is fixed and if so, its value. As evidence of the generic flexibility, objects of this class are used in the *solph* library to build inter-temporal constraints for different kinds of energy system optimization problems such as combined heat and power modelling or unit commitment.

The *EnergySystem* class serves as a container for the aforementioned elements and provides the possibility of adding extra information such as grouping structures or optimization parameters. Additionally, it provides interfaces to save and restore the energy systems instance and to process results. This allows
for an intuitive handling of energy systems by treating them as their own entity. An implementation using the high level programming language Python has the advantage of a rich set of external libraries usable for scientific computing. Oemof itself makes heavy use of external modules for optimization problems (pyomo \cite{34}) and data handling (pandas \cite{35}).

3.5. Documentation, collaboration and testing

‘A critical part of any piece of software is the documentation’ has already been stated by Greenhall and Christie \cite{36}. This is of particular importance for open source projects with many users and a changing developer base. With the objective of thorough documentation in all stages and formulation of general nomenclature, a documentation strategy on four different levels similar to that of Howells et al. \cite{19} is followed:

1. **Comments inside the code** are used to explain non-intuitive lines of source code to new developers and interested users at the lowest level.
2. **Docstrings** located inside the source code describe the API, i.e. how to use the various classes, methods, and functions.
3. **Higher level descriptions** provide the user with additional information about the possible interactions between different libraries or application-specific usage information. These manuals are located inside the repository and are therefore shipped with the source code.
4. **Examples** provide an additional source of documentation that is particularly useful to new users and developers.

Keeping such detailed documentation consistent and up-to-date across continuous releases comes at the expense of a high maintenance effort. Nevertheless, it is of special importance; the oemof documentation is the place to find information on the formulas used within an oemof-based model. Up-to-date, consistent documentation that tracks changes in a timely fashion is essential if external users want to understand the internal logic of a model, especially in scientific applications. The upside is that documentation adhering to these principles acts as a citable source of information, reducing the amount of redundant information that must be sourced and digested in order to understand a model. This in turn increases transparency and comparability.

As oemof is an open-source community project, a common platform for collaboration is needed. Similar to Greenhall and Christie \cite{36} as well as other open-source energy modelling projects, oemof uses GitHub for collaboration, code hosting and bug tracking, which allows for easy copying and forking of the project. To lower entry barriers for new developers, hierarchies for all processes are kept as flat as possible. We have found that this can create a sense of belonging for collaborating developers which increases participation. GitHub is based on the version control system git and code can be developed in parallel on different branches. In order to ensure an effective branching strategy and release management, a well-established git workflow model \cite{37} is set as the standard for all developers. Contributions to the code base are managed through pull
requests, which allow for an open review of potential changes. Further, code changes are checked for conflicts before being merged back into the development branch by the developer in charge of the affected library.

In order to test oemof’s functionality in case of changes to multiple parts of the code base, unit tests are employed. During the testing process, all integrated application examples are run and the created results are checked against stored historical results. Only if all examples run without errors is a pull request merged back into the development branch. This procedure ensures the functionality even if major changes to the code base are applied from one release version to another.

4. Usage: Applications

The framework is not designed to be a standalone executable. Instead, the oemof libraries are meant to be used in combination to build energy system models. In the following we will refer to such models as oemof-applications.

4.1. Application development

Applications can be developed by the use of one or more framework libraries depending on the scope and purpose. Figure 4 illustrates an example process of building an application. Modelling can thus range from a few plain steps in a standalone Python executable to complex procedures bundled in a new Python library based on oemof. Due to the modular concept, specific functionalities of oemof libraries can be substituted easily depending on the modelling task. This provides a high degree of freedom for developers, which is particularly relevant in scientific working environments with spatially distributed contributors and fast evolving research questions.

![Diagram](Figure 4: Building an application based on libraries of the oemof cosmos and external libraries (dark grey).

Depending on the problem, input data can be created by means of libraries such as the feedinlib or demandlib library. A standardized result processing
library (*outputlib*) provides all optimization results in convenient data structures that are ready for exports to different formats, detailed analyses and plotting. Although this feature might appear trivial, it is one major advantage over other heterogeneous optimization tool-chains that require switching between tools e.g. GAMS for the modelling and a spreadsheet-based solution for result processing.

However, in considering the modelling workflow for the oemof namespace layer, all applications have some major steps in common and include all required data pre- and post-processing. First, an empty energy system object is created. This object acts as a container for the nodes and carries information such as the time resolution. The energy system object may also hold different variants of the system representing different scenarios. Additionally, methods to handle nodes are provided. The next step is the instantiation of nodes and flows of the modelled energy system which are added to the existing energy system instance (population of energy system). Subsequently, the results of the energy system can be computed by simulating or optimizing the system. Finally, results can be processed with the output library of oemof. The *oemof-outputlib* makes it easy to get different views of the results and plots based on a uniform output data format.

### 4.2. Example application workflow: System optimization

One common use case for a modelling process that utilizes different toolboxes is the optimization of energy systems. In this process the *solph* library can be used in combination with existing input and output data libraries. First, feed-in data for renewable power plants and electricity demand profiles can be generated within the *feedinlib* and *demandlib* libraries. Subsequently, the data are used as exogenous parameters within the *solph* library before the optimization results are processed within the *outputlib*.

The *solph* library allows the creation of mixed-integer linear models. As a common requirement, an energy system graph has to be created with classes from the *core* layer, respective *solph* subclasses from the *namespace* layer or a mix of both. The energy system serves as a container that holds all nodes and general information such as the temporal resolution of the optimization problem. Since an oemof optimization model inherits from a model of the *pyomo* package, the full functionality of this package can be leveraged. Depending on the experience and modelling task, three different ways exist to create an optimization problem based on an oemof energy system instance.

1. In the most common and easiest use case, the energy system describes a graph with flows on its edges by combining basic components and buses. The optimization model for this use case is automatically created by a logic that transfers the graph (connections between buses and components and their attributes) into respective constraints, e.g. commodity balance equations or inequalities for lower and upper flow bounds. When using this way of modelling, all models are derived by the object parametrisation and no mathematical definitions like sets, variables or parameters have to be implemented.
2. In the second use case, basic energy systems can be adapted by defining additional constraints on top of the aforementioned graph logic. Since this logic is consistent throughout, entry barriers for new users are lowered. As one example, an annual limit on a commodity flow can be implemented easily by a definition of (in)equations applied to a set of flows.

3. In the third use case, custom components can be added to a model. This is possible by subclassing from core components or by creating one’s own components from scratch. As mentioned before, the full functionality of the `pyomo` package can be utilized to model complex internal relations of components with numerous constraints, specific sets and different variable domains. Such a component needs to provide input/output slots that may be connected with flows of graph.

All use cases can be applied separately or combined within one model. The model type itself, e.g. an economic dispatch, investment or unit commitment model, is determined by its parametrisation. This allows for maximum flexibility, as one can quickly change the model, from economic dispatch to investment, for example, by exchanging single components, say a storage with fixed capacity (parameter) by one with variable cost-determined capacity (decision variable), for example. In a similar way, complete sub-graphs can be exchanged quickly by connecting or disconnecting them from a main problem.

4.3. Existing applications

The framework has already been used to build comprehensive applications for different research projects (see [38, 39, 40, 41, 42, 43]). In addition, oemof is also used actively in teaching by some institutions in order to gain insight into complex energy systems. An example for such a system modelled as an oemof application is illustrated in Figure 5. In the following, selected oemof applications are described to illustrate the broad range of applications. These distinguish themselves by technologies considered, demand sectors modelled, regional representation, the time horizon of the analysis, the modelling methodology to represent technological characteristics and perhaps a market representation.

The renewable energy pathways simulation system (`renpassG/S`) [44] is a bottom-up fundamental Western European electricity market model. Future scenarios of the power plant dispatch and price formation in Germany and its interconnected neighbouring countries can be modelled based on operational and marginal costs and the assumption of an inelastic electricity demand. Based on `renpassG/S`, a spin-off model that is adapted to the requirements of the Middle East and North Africa (MENA) region was created. In this application the `solph` library was used with a restriction to purely linear equations. Both applications use a standardized interface to csv-files for the `solph` library that was created to simplify the usability for users with no programming experience.

The `openMod.sh` application is a flexible software tool that is strongly based on oemof’s underlying concept [41]. This model has been applied in participative workshops for the development of regional climate protection scenarios. The combination of a graphical browser-based user interface combined with...
an open-source modelling approach enhances the modeller-decision-maker interface. The extension of the underlying concept to a database concept shows that this concept may not only be used for the computation of systems but also for their representation in a relational database. Due to the open licence and the high-level language, oemof applications can be set up on public servers with little effort and without legal barriers.

An example for the flexible extension of oemof at the application level is the Heating System Optimization Tool (HESYSOPT) [45]. In this application, detailed heating system components are modelled with mixed integer linear programming techniques that are based on oemof.solph functionalities. Using the underlying pyomo library solph provides an interface to add new components within the application. After a review, such components can be integrated into solph to be available for the entire community.

As a fourth example, reegis [46] models heat and power systems on a local scale. The objective is to evaluate district heating and combined heat and power technologies in energy systems with a high share of renewable resources from an environmental and economical perspective. The local system is connected in terms of electricity to a national model based on the idea of the model renpassG!S [44] which is extended to include the heating sector. This application uses oemof’s windpowerlib, feedinlib and demandlib to provide the input data for the model. Further, the solph library is used to create a large-scale linear
model and a detailed mixed integer linear problem. This example demonstrates how models of different scale may be combined in one application.

These applications illustrate the flexibility of oemof and the extent of the potential user group, not only with regard to the content, but also concerning the level of involvement. It is possible to build a full-scale energy system model adapted to the user’s needs by just employing existing functionalities. Moreover, different models can be combined and adapted with little effort to create tools for specific purposes. This enables users to answer challenging research questions within a single framework.

5. Conclusion

The paper presents the Open Energy Modelling Framework (oemof) as a contribution to the scientific modelling community. With a collaborative and open development process, it is designed for transparency and participation. Complementary to its technical features, the project constitutes a novelty in energy system modelling and aims to facilitate open science in this research field.

One central feature of oemof is the generic graph-based foundation which has been implemented using an object-oriented programming methods in the high-level language Python. The cross-institutional collaborative development of the framework has started a process towards this common and generic structure. This concept highlights the distinction between the description of an energy system with its components and subsequent computations based on combining an intuitive description with a specific mathematical approach. It lays the foundation for a universal representation of multi-sectoral energy systems at different scales. Another important feature is its strict open-source and non-proprietary philosophy. This philosophy, the underlying concept and the extensive documentation allow new developers to adapt or extend the framework easily and leverage features of other scientific Python libraries. With these properties, the project is suitable for new developers and users and thereby supports a continuous development process.

The framework has been successfully applied in different research projects at several institutions. Existing oemof applications include electricity market models, detailed technical unit commitment models for district heating systems and sector coupled regional energy system models. Energy systems ranging from distributed or urban ones up to a national scale may be modelled, making the framework a multi-purpose modelling environment for strategic energy analysis and planning.

Although it takes effort for new users to learn to build an oemof-based application, we think there are good reasons to choose oemof. Firstly, the flexibility in application development allows adjustments along with changing research objectives and may thus avoid lock-in effects. This seems to be particularly relevant for project-based research. Secondly, the community character of the oemof-project is another important factor. The possibility for active participation in development and decision processes allows users to be part of a community. We
argue that this can create a sense of belonging, a value that goes beyond the technical features of the software.

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