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Code exposed: Review of five open-source frameworks for modeling renewable energy systems

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ABSTRACT

Energy system modeling is a commonly used method to provide policy recommendations and insight to transformation pathways of energy systems. However, the low open-source availability of the frameworks in practice often leads to low interpretability and transparency of energy modeling system configurations. The configuration of an energy model entails how its system components, such as power plants, storage systems and grids operate, and which parameters are used to define them. In order to understand the impact of different model configurations and working principles on the model output, a thorough comparison between various modeling frameworks is necessary. This work thereby consists of a comparison of five open-source energy system modeling frameworks (OS-ESMFs) *oemof*, *GENeSYS-MOD*, *Balmorel*, *urbs* and *GENESYS-2* on the mathematical level and spotlights selected methodological differences in renewable energy system modeling. The comparison shows diversity in the complexity of selected system components and helps to define the best use-cases and scales of application for each framework. Impacts of modeled features on the results were demonstrated by implementing two harmonized scenarios depicting the German electricity system using each framework. While similar model results were obtained for both scenarios, some differences were present, especially in the long-term expansion planning model. Some of those differences could be traced back to the identified modeling differences.

1. Introduction

With increasing time pressure to act on the transition towards renewable and sustainable energy systems [1], policymakers are in demand of robust research to inform their energy and climate policies. Energy system modeling, as a well-established method, supports the examination of complex questions in such a transition [2]. However, the repertoire of energy system models at present is vastly diverse, and a variety of energy system modeling framework (ESMF)s exist to address similar research and policy questions [3]. Given the wide choice, it is important for decision-makers to know that the planning instruments they depend on are reliable and fit the purpose.

The movement of open-source energy system modeling frameworks (OS-ESMFs) enables open insight into their functioning and thus enables their comprehensive assessment. Through their transparency, they enable an evaluation of their methods and allow to ensure the quality and suitability of models to future challenges, also for third-parties [4–6]. This supports the development of adequate instruments and their use and promotes plausible and cost-efficient pathways towards sustainable energy systems.

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List of abbreviations

ESMF	energy system modeling framework
OS-ESMF	open-source energy system modeling framework
GENESYS-2	Genetic Optimization of a European Energy Supply System
GENeSYS-MOD	Global Energy System Model
Balmorel	The Baltic Model of Regional Electricity Liberalization
oemof	Open Energy Modeling Framework
MIMO	multiple-input and multiple-output
E2P	energy-to-power ratio
CHP	combined heat and power plant

Achieving a sustainable and cost-efficient energy system in the future is one of the world's most pressing challenges that motivates ESMFs to develop and new ones to arise. Some of the most commonly used ESMFs include The Baltic Model of Regional Electricity Liberalisation (Balmorel) [7], MARKAL [8], UREM [9], EMOF [10], among others. The growing number of ESMFs and continuous enhancements increase the relevance of comparing ESMFs among each other. Such comparisons can potentially increase the scientific exchange between energy system modelers and thus improve the quality of future developments, avoid duplications, and support usability as well as transparency [11]. However, the ESMF model framework documentations focus mainly on giving a general overview rather than showing the full capabilities of the tools and only rarely do they present actual model limitations.

For some ESMFs, comprehensive documentation can be found, e.g. for *Balmorel* [12], for *urbs*,[2] or for *Open Energy Modelling Framework (oemof)*,[3] but due to the fast pace of further developments, these documentations may not be kept up to date [13,14]. To overcome this, the authors of [13] suggest performing a version update analysis for modeling tools to inform users about functionality updates. They compare model versions, including both mathematical model constraints as well as selected modeling results. The methodology is exemplified using the MARKAL model applied to a 6-year period. However, even with such version analysis, it would be challenging for tool users to keep up with the documentation, which led to several assessment papers for modeling frameworks.

Other works such as [3,15,16] provide reviews with the primary goal to create decision support for choosing energy models appropriately. A review of 75 energy system modeling tools is provided in [3], exclusively considering tools published after 2012. The review provides an extensive overview of currently available modeling tools and their capabilities. Due to its vast scope, the review cannot consider the tools in great detail, although it would be necessary to assess whether a tool fits its purpose. In [15], 37 ESMFs are reviewed to identify suitable energy tools for analyzing the integration of renewable energy into various energy systems. The analysis is survey-based by interviewing the ESMF maintainers. The study presents the results as individual text descriptions for each tool, with only limited analysis concerning the actual differences of the tools. In [17] 54 energy system modeling tools are reviewed in a similar survey-based approach. In contrast to previous works, the authors emphasize the application aspects of modeling tools but without going into detail for individual frameworks.

The authors of [18] identify the need for a standard way of presenting tools to perform comparisons more easily. Therefore, they propose categorizing the energy system models into three classes. They apply the proposed classification of energy systems models on 22 energy system models in the UK to shed light on the diversity of the applied energy system models. Additional literature focusing on a common way to compare ESMFs includes [19], in which they classify energy models according to nine dimensions.

Other papers build upon these dimensions, such as [20] comparing 18 tools based on the geographic focus, number of regions, time horizon and model type. Authors of [14] propose a model matrix methodology for comparisons and illustrate this by comparing 47 tools based on the three dimensions: (1) geographical scope, (2) number of sectors and (3) bottom-up/top-down models. The authors of [21] identify a lack of comprehensive evaluation methods to assess the suitability of models to tackle present modeling challenges. They suggest a new qualitative evaluation approach and illustrate it with the oemof. The approach is based on a matrix approach with comparison dimensions focusing on *open-source philosophy, collaborative development and structural properties*.

The review of existing literature highlights that the comparisons of ESMFs focus on the overall capabilities of ESMFs rather than a detailed comparison of underlying mathematical approaches and equations. This paper contributes to filling that research gap by examining the core mathematical equations for five open-source energy system frameworks. Starting from the main mathematical equations, the paper aims to provide a comprehensive overview of the frameworks' core competencies and specifics in their implementation. Thus, the paper improves on previous comparisons of ESMFs by delving into the mathematical machinery underlying five ESMFs. The approach is of durable benefit as the core equations of frameworks rarely change. This is, however, in contrast to existing comparisons that mainly relate to specific features of ESMFs in a factsheet-like manner, which may mislead readers to believe that two frameworks may cover a specific feature in equal detail.

Additionally, the identified theoretical differences are audited through a model experiment with harmonized input data to investigate their effects in practice. In this experiment, we optimize both capacity expansion and dispatch planning and quantify result differences that stem from mathematically different feature implementations.

Remarkably, we provide open access to the comparison terminology, addressing a research gap highlighted in [17]. In combination with the open access input data and a comparison infrastructure from the open MODEX project, from which this paper emerged, a basis is created to enable the participation of other frameworks in this comparison.

2. Methodology

2.1. Framework overview and method

In this work, five OS-ESMFs are considered, which take part in the research project open_MODEX. These are:

1. *urbs*,
2. *The Baltic Model of Regional Electricity Liberalization (Balmorel)*,
3. *Genetic Optimization of a European Energy Supply System (GENESYS-2)*,
4. *Global Energy System Model (GENeSYS-MOD)*,
5. *Open Energy Modeling Framework (oemof)*,

and will be denoted as the *frameworks* in this work. These OS-ESMFs are commonly used for optimal capacity and dispatch planning of large-scale energy systems, but are not limited to this use case. All OS-ESMFs are licensed under various open-source licenses (see Table 1 for a basic overview on the OS-ESMFs, and https://openenergy-platform.org/factsheets/frameworks/ for further information about each OS-ESMF). The open-source availability and transparent documentation of the OS-ESMFs facilitate a comprehensive comparison of their features on an equation-to-equation basis. Hereby, the analysis of the frameworks' features and their mathematical formulations is performed in a multi-step process. This process can be broken down into four steps:

2 https://urbs.readthedocs.io/en/latest/.
3 https://oemof.readthedocs.io/en/latest/.

Table 1
Overview of the contributing frameworks.

	urbs	Balmorel	GENeSYS-MOD	GENESYS-2	oemof
Modeling language	Python (Pyomo)	GAMS	GAMS	C++	Python (Pyomo)
Institution	TUM ENS	RAM-løse, DTU and others	TU Berlin	ISEA RWTH Aachen	EU Flensburg, HS Flensburg, TU Berlin, DLR Oldenburg and others
Release	2015	2001	2017	2017	2016
License	GNU General Public License v3.0	ISC	Apache license 2.0	GNU Lesser General Public License Family	MIT
Objective	Minimum cost (or CO_2)	Minimum cost	Minimum cost	Minimum cost	Minimum cost
Method	(MI)LP	(MI)LP	LP	Heuristic	(MI)LP
Documentation	[2]	[a]	[b]	[22,23]	[3]

[a] http://www.balmorel.com/index.php/balmorel-documentation.
[b] https://git.tu-berlin.de/genesysmod/genesys-mod-public/-/blob/main/Docs/GENeSYS_MOD_Manual_Technical_Guide_v1.0.pdf.

1. The **feature selection** is closely related to the scenario development and aims to comprise the maximal functionality overlap of the participating frameworks. This leads to a minimal intersection of meaningfully comparable features that are considered in a basic scenario. (for the chosen modeling scopes, see Section 2.2).
2. A **common terminology** is established to analyze feature-relevant equations without studying framework-specific semantics. This terminology facilitates the comparability of sets, indices, parameters and variables across the frameworks. The nomenclature describing this terminology may also help readers through this work and can be found in Appendix.
3. A qualitative **theoretical comparison** (Section 3) is performed for the selected features with the aim of identifying different modeling approaches. The framework maintainers applied the common terminology and documented their equations accordingly. We conducted qualitative interviews to receive feedback on the results of the analysis and concluded the theoretical comparison after its implementation.
4. A quantitative **model experiment** was conducted with a fully harmonized input dataset (Section 4). All framework maintainers modeled two scenarios in their respective framework. Selected results were evaluated and compared with the mathematical background of the frameworks.

2.2. Modeling scopes and selected features

Within the open_MODEX project, on which this work is based, three modeling scopes were defined, around which the compared features were selected and categorized. The first scope consisted of three single-year models for the German electricity system, where the system operation is optimized for year the 2016 and a co-optimization of the operation and expansion is made for the years 2030 and 2050. The second one dealt with an intertemporal model with support years[4] $\mathcal{Y} = \{2016, 2020, 2030, 2040, 2050\}$, whereas the third scope introduced the heating sector so that a co-optimization of both sectors takes place.

Along the lines of these modeling scopes, the following feature categories were identified:

- **Basic energy system model features:** (a) time representation, (b) cost types and annuity calculation, (c) energy balance, (d) power plants, (e) grid models, (f) storages and (g) imports/exports,
- **Intertemporality features:** (a) intertemporal costs, (b) capacity transfer between support years, (c) CO_2 budgets
- **Multi-sector features:** (a) emission limitation by sectors, (b) multiple input-multiple output technologies

[4] In contrary to single-year models, intertemporal modeling allows investments in multiple points in time, which are denoted as *support years* in this work. Support years typically consist of only a subset of the entire time horizon of the model to reduce computational complexity. The remainder of the years will be denoted as *intermediate years*.

3. Mathematical comparison of the OS-ESMFs

In this section, the selected features and their mathematical formulations are compared against each other for each framework. The distinctions of each framework will be highlighted in more detail in the context of the three modeling scopes.

3.1. Basic energy system model features

3.1.1. Time representation

A variable timestep length Δt can be set in some of the compared frameworks. This parameter is then used for conversions between the power and energy units (which are, by default, given in MW and MWh, respectively). However, for simplification reasons, a timestep length of 1 hour is assumed in the following comparison, and thereby the Δt parameter is removed from the respective equations wherever present.

Additionally, while all frameworks can work with hourly timesteps, they are represented differently to facilitate certain functionalities such as automatized temporal aggregation. This is the case for *Balmorel*, which by default divides a year into 52 weeks, each consisting of 168 hours, resulting in 8736 hours. Similarly, in *GENeSYS-MOD* and *Genetic Optimisation of a European Energy Supply System (GENESYS-2)*, some model features inherently assume a 8760-hours year. Consequently, *Balmorel*, *GENeSYS-MOD* and *GENESYS-2* are not able to handle leap years without considerable changes on the source codes of the frameworks. Therefore, for the scenarios concerning the year 2016, the first 8760 hours are considered by *GENeSYS-MOD* while the Balmorel model has been adjusted to facilitate the full year in the model run covering only the single year. When solving a sequence of years in *Balmorel*, only the first 8736 hours are used of each included year. However, this specific timestep handling allows *GENeSYS-MOD* and *Balmorel* to have an incorporated time aggregation functionality, enabling the user to solve a model for representative timesteps instead of the entire time horizon. For *Balmorel*, this is done by selecting a user-defined subset of hours per year. All associated calculations are then performed automatically and the results are scaled up to match those of non-aggregated models. In *urbs*, a similar automatic time aggregation functionality is currently under development using *tsam* [24].

3.1.2. Cost types per technology

Each framework aims to minimize costs, i.e. the costs emerging from operation, investments or emissions. Since the scope of the objective function dictates the optimal solution, it is important to analyze the differences among the objective functions to be able to explain potential differences in the solutions.

Across all frameworks, various costs types are associated with each *system component*, represented as *processes* (*power plants*),[5] *storages* or *transmission lines*. In general, the cost types are categorized as *annuitized investment costs* ζ_y^{inv}, *fixed costs* ζ_y^{fix}, *variable costs* ζ_y^{var}, *fuel costs* ζ_y^{fuel} and *environmental costs* ζ_y^{env}. The economic parameters required to calculate these costs are defined as model inputs on specific terms. The specific investment cost c^{inv} of a component represents the costs of a new investment for 1 MW (and MWh for storage) of the respective component. The specific fixed costs c^{fix} are in turn paid annually for each MW (and MWh for storage) of the total installed capacity. Thus, they represent any costs related to the operation and maintenance that are not dependent on the actual utilization of the technology. In contrast, the specific variable costs c^{var} are paid for each MWh that a given technology is used and represent the operational costs of e.g. power plants besides fuels. The specific fuel costs c^{fuel} represent the procuring costs for 1 MWh of input fuel that are used by the processes. Similarly, the specific environmental costs c^{CO_2} are only relevant to the processes and they represent the costs (in the form of carbon prices or externalities) each ton of emission (e.g. CO_2 as considered here) has on the environment. For a given model year y, a generic formulation of annual costs for a non-intertemporal energy system can then be described as follows:

$$
\begin{aligned}
\zeta_y &= \zeta_y^{\text{inv}} + \zeta_y^{\text{fix}} + \zeta_y^{\text{var}} + \zeta_y^{\text{fuel}} + \zeta_y^{\text{CO}_2} \\
&= \sum_{r\in\mathcal{R}} \Bigg(\sum_{p\in\mathcal{P}_r} c_{yrp}^{\text{inv}} \cdot \kappa_{yrp}^{\text{new}} \cdot af_{yrp} + \sum_{s\in\mathcal{S}_r} c_{yrs}^{\text{inv,con/pow}} \cdot \kappa_{yrs}^{\text{con/pow,new}} \cdot af_{yrs} \\
&\quad + \sum_{f\in\mathcal{F}_r} c_{y(rr')f}^{\text{inv}} \cdot \kappa_{y(rr')f}^{\text{new}} \cdot af_{y(rr')f} \Bigg) \\
&\quad + \sum_{r\in\mathcal{R}} \Bigg(\sum_{p\in\mathcal{P}_r} c_{yrp}^{\text{fix}} \cdot \kappa_{yrp}^{\text{total}} + \sum_{s\in\mathcal{S}_r} c_{yrs}^{\text{fix,con/pow}} \cdot \kappa_{yrs}^{\text{con/pow,total}} \\
&\quad + \sum_{f\in\mathcal{F}_r} c_{y(rr')f}^{fix} \cdot \kappa_{y(rr')f}^{\text{total}} \Bigg) \\
&\quad + \sum_{t\in\mathcal{T}} \sum_{r\in\mathcal{R}} \Bigg(\sum_{p\in\mathcal{P}_r} c_{yrp}^{\text{var}} \cdot \epsilon_{yrpct}^{\text{out}} + \sum_{s\in\mathcal{S}_r} c_{yrs}^{\text{var}} \cdot \epsilon_{yrsct}^{\text{ch/disch}} \\
&\quad + \sum_{f\in\mathcal{F}_r} c_{y(rr')f}^{\text{var}} \cdot \epsilon_{y(rr')fct}^{\text{send/recv}} \Bigg) \\
&\quad + \sum_{t\in\mathcal{T}} \sum_{r\in\mathcal{R}} \Bigg(\sum_{p\in\mathcal{P}_r} c_{yrp}^{\text{fuel}} \cdot \epsilon_{yrpct}^{\text{in}} + c_{yrp}^{\text{CO}_2} \cdot \epsilon_{yrp(\text{CO}_2)t}^{\text{out}} \Bigg) \quad \forall y \in \mathcal{Y}, \qquad (1)
\end{aligned}
$$

where the generalized parameters $\kappa_{\dots}^{\text{new}}$ denote the newly installed component capacities, af the annuity factor where applies (see Section 3.1.3), $\kappa_{\dots}^{\text{total}}$ the total capacities, ϵ the energy carrier flows in and out of the system components (processes, storages and transmissions). Table 2 gives an overview of the framework support for cost parameters and related energy system components. Generally, a high similarity across the frameworks is seen, especially within the process category. In particular, *GENESYS-2* differs from the other frameworks by not considering any variable costs. Additionally, *Balmorel* and *GENeSYS-MOD* differentiate from *urbs* and *oemof* by not considering fixed costs for the transmission lines, fixed costs for the storage content capacities and variable costs associated with the storage state. For investment planning models built with *oemof*, the specific fixed costs are manually annualized and added on top of the investment costs by the user as an additional cost term after a model run. As the only framework, *Balmorel* does not differentiate investment costs between storage content and charging/discharging capacity. By imposing the same economic parameters as inputs on all frameworks, these modeling differences may thus reflect differences in the optimal solution.

[5] Although the terms *process* and *power plant* are often used interchangeably throughout this paper, the former stands for a generic conversion unit whereas the latter is a term specifically used for electricity-generating units.

3.1.3. Annuity calculation for investments

As mentioned above, investment costs appear on the objective functions of ESMFs in their annuitized form, corresponding to the yearly payments distributed over the duration of their respective lifetime. The frameworks use two different approaches for modeling this functionality, henceforth referred to as annuity factor method (**AF**) and salvage value method (**SV**). The following section explains these approaches in detail and highlights their differences.

Annuity factor method (AF)

The annuity factor method is used to calculate the constant yearly payments that correspond to a loan taken for an investment, assuming a constant annual interest and a payment period. This annual interest rate is typically reflected by the weighted average cost of capital (WACC) i that corresponds to the investment to a certain technology, and the payment period can be assumed to be equal to the economic lifetime n of the process. The annualized investment cost for a certain process yrp can be then given by:

$$\zeta_{yrp}^{\text{inv}} = c_{yrp}^{\text{inv}} \cdot \kappa_{yrp}^{\text{new}} \cdot af_{yrp} \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall p \in \mathcal{P}, \qquad (2)$$

where af_{yrp} is the process-specific annuity factor, c_{yrp}^{inv} the specific investment costs of process p per unit capacity and $\kappa_{yrp}^{\text{new}}$ stands for the newly installed capacity.

The annuity factor is calculated by:

$$af_{yrp} = \frac{(1+i_{yrp})^{n_{yrp}} \cdot i_{yrp}}{(1+i_{yrp})^{n_{yrp}} - 1} \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall p \in \mathcal{P}, \qquad (3)$$

where i_{yrp} and n_{yrp} stand for the WACC and economic lifetime of the process yrp respectively.

Salvage value method (SV)

In the salvage value method, a correction of the investment costs is made by deducting a salvage value if the lifetime of an investment exceeds the modeling horizon. A salvage value is obtained by subtracting the rest of the values of the technology of residual lifetime from investment costs. The salvage values in *GENeSYS-MOD* are calculated using a *linear depreciation approach*:

$$\zeta_{yrp} = c_{yrp}^{\text{inv}} \cdot \kappa_{yrp}^{\text{new}} \cdot \left(1 - \frac{y_{\max} - y + 1}{n_{yrp}}\right) \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall p \in \mathcal{P}, \qquad (4)$$

where $y_{\max}$ is the last year of the modeling period (note that $y_{\max} = y$ for a single-year model). This equation is only applied if the current year y plus the lifetime n_{yrp} of the technology is larger than the last year of the modeling period.

Table 3 shows which approach applies to which framework, along with additional differences related to the parameter values. As seen from Table 3, *GENeSYS-MOD* differs from the remaining frameworks in being the only framework following the salvage value approach, hence the WACCs of technologies do not play a role. Thus, in *GENeSYS-MOD*, investment costs of technologies with high WACCs would be less pronounced compared to the other frameworks. Another difference among the frameworks is the technology- or region-dependence of the lifetime and WACC parameters. In contrast to the other models, *GENESYS-2*, does not consider region-specific WACC and assumes the same value for each technology in all regions.

3.1.4. Energy balance equation

One of the most central constraints in energy system models is the energy balance equation, which ensures that the consumption and production of an energy commodity are balanced in a given timestep. For multi-regional models, this constraint also has to hold for each

Table 2
Overview on the cost types supported by the frameworks.

	Cost type	urbs	Balmorel	GENESYS-2	GENeSYS-MOD	oemof
Processes (power plants)	Investment (€/MW new capacity)	x	x	x	x	x
	Fixed (€/MW total capacity/year)	x	x	x[a]	x	x[g]
	Variable (€/MWh output)	x	x[b]	–	x	x
	Fuel (€/MWh input)	x	x[h]	x	x[c]	x
	Environmental (€/tons of emission)	x	x[h]	x	x[c]	x
Storage	Investment (€/MWh new storage capacity)	x	x	x	x[d]	x
	Investment (€/MW new charging/discharging capacity)	x	–	x	x	x
	Fixed (€/MWh/year)	x	x	x[a]	–	x[g]
	Fixed (€/MW storage and charging/discharging capacity/year)	x	–	x[a]	x[e]	x[g]
	Variable (€/MWh charging/discharging)	x	x[f]	–	x	x
	Variable (€/MWh current storage state)	x	–	–	–	x
Transmission	Investment (€/MW new transmission capacity)	x	x	x	x	x
	Fixed (€/MW total transmission capacity/year)	x	–	x[a]	–	x[g]
	Variable (€/MWh flow on line)	x	x	–	x	x

Explanations
[a]Percentage of annualized investment costs.
[b]Additionally, costs relative to fuel consumption rate (MW) and costs related to power produced from hydro with reservoir.
[c]Incur in the fuel production process.
[d]Possible, but not used since E2P's are assumed to be constant.
[e]Only related to total storage content capacity.
[f]Only related to discharging.
[g]In investment planning models, the fixed O&M costs are included on top of the annualized investment costs in *oemof*.
[h]Conversion factor PJ/GJ to MWh.

model region. A generic form of the energy balance Eq. (5) is given in the following:

$$
\begin{aligned}
&\epsilon^{\text{stock}}_{yrct} + \sum_{p\in\mathcal{P}_r} \epsilon^{\text{out}}_{yrpct} + \sum_{s\in\mathcal{S}_r} \epsilon^{\text{disch}}_{yrsct} + \sum_{f\in\mathcal{F}_r} \pi^{\text{recv}}_{y(r'r)fct} + \epsilon^{\text{buy}}_{yrct} + \epsilon^{\text{slack}}_{yrct} \\
&= d_{yrct} + \sum_{p\in P_r} \epsilon^{\text{in}}_{yrpct} + \sum_{s\in S_r} \epsilon^{\text{ch}}_{yrsct} + \sum_{f\in F_r} \pi^{\text{send}}_{y(rr')fct} + \epsilon^{\text{sell}}_{yrct} + \epsilon^{\text{curt}}_{yrct}, \qquad (5)\\
&\forall r\in\mathcal{R},\ \forall c\in\mathcal{C},\ \forall y\in\mathcal{Y},\ \forall t\in\mathcal{T},
\end{aligned}
$$

where

- $\mathcal{P}_r, \mathcal{S}_r, \mathcal{F}_r$ denote the set of processes, storages and transmission lines in a given region r,
- $\epsilon^{\text{stock}}_{yrct}$ stands for the procured amount of a (fuel) commodity c at a given timestep t,
- $\epsilon^{\text{in}}_{yrpct}, \epsilon^{\text{out}}_{yrpct}$ the input and output amount of that commodity from process p that belongs to region r,
- $\epsilon^{ch}_{yrsct}, \epsilon^{disch}_{yrsct}$ the charged and discharged amount of that commodity from storage s that belongs to region r,
- $\pi^{\text{recv}}_{y(r'r)fct}, \pi^{\text{send}}_{y(rr')fct}$ the incoming and outgoing amount of the commodity c through the transmission line f that are between the modeled regions r and r',
- $\epsilon^{\text{buy}}_{yrct}, \epsilon^{\text{sell}}_{yrct}$ the bought/sold amount of the commodity in and out of the model boundaries,
- d_{yrct} the demand in region v for the said commodity,
- $\epsilon^{\text{curt}}_{yrct}$ the curtailed amount of the commodity (e.g. for overproduction of electricity from volatile renewable energies), and
- $\epsilon^{\text{slack}}_{yrct}$ is the "slack" production[6] of the commodity c which the model resorts to in case the demand cannot be covered otherwise.

In *urbs* and *Balmorel*, an up/downshift term for demand-side management (DSM) can be added to the energy balance equation to modify the demand term. In oemof and Balmorel, the energy balance equation can also be also defined in different temporal resolutions for certain energy carriers (such as the yearly sums instead of hourly).

[6] To prevent the slack production when the demand can be covered in another way, a very high variable cost is usually attached to it.

3.1.5. Power plant features

In this section, a comparison is made between the frameworks regarding the modeling approaches for power plant operation and expansion. The relevant comparison aspects are grouped in three categories: (a) plant efficiencies, (b) output limitation by capacities and (c) output limitation by ramping rate.

(a) Efficiencies. There are multiple possibilities for modeling plant efficiencies for each framework.

(1) constant efficiencies: All frameworks support defining constant efficiency factors for power plants, which set the ratio between the energy content of output commodities (e.g. electricity) and input commodities (e.g. fuels). *Balmorel*, *GENESYS-2* and *oemof* realize this with a plant efficiency parameter $\eta_{yrp(c_{\text{elec}})}$:

$$
\epsilon^{\text{in}}_{yrp(c_{\text{fuel}})t} = \frac{\epsilon^{\text{out}}_{yrp(c_{\text{elec}})t}}{\eta_{yrp(c_{\text{elec}})}} \qquad \forall y\in\mathcal{Y}, \forall r\in\mathcal{R}, \forall p\in\mathcal{P}, \forall t\in\mathcal{T}, \qquad (6)
$$

whereas *urbs*, *GENeSYS-MOD* and *oemof* deal with decoupled input and output ratios, in form of generic multiple-input and multiple-output (MIMO) processes. In *GENeSYS-MOD*, the total energetic content of the input commodities (fuels) are converted to each output commodity via the following relationship:

$$
\begin{aligned}
&\frac{\epsilon^{\text{out}}_{yrp(c_{\text{out}})t}}{\eta^{\text{out}}_{yrp(c_{\text{out}})}} = \sum_{c\in C_{in}} \epsilon^{\text{in}}_{yrpct} \cdot \eta^{\text{in}}_{yrpc} \qquad \forall y\in\mathcal{Y}, \forall r\in\mathcal{R}, \forall p\in\mathcal{P}, \forall t\in\mathcal{T}, \qquad (7)\\
&\qquad \forall c_{out} \in C^{\text{out}}_p,
\end{aligned}
$$

where η^{in}_{yrpc} and η^{out}_{yrpc} represent the input and output efficiencies of the power plant, and C^{out}_p standing for the set of output commodities of the plant p. *urbs* and *oemof* on the other hand use a commodity-neutral throughput variable τ that quantifies a plant's level of activity at a given time. Each input and output commodity flow is then independently tied to the throughput variable via the input and output efficiencies:

$$
\epsilon^{\text{in}}_{yrpct} = \eta^{\text{in}}_{yrpc} \cdot \tau_{yrpt} \qquad \forall y\in\mathcal{Y}, \forall r\in\mathcal{R}, \forall p\in\mathcal{P}, \forall t\in\mathcal{T}, \forall c_{out}\in C^{\text{in}}_p, \qquad (8)
$$

$$
\epsilon^{\text{out}}_{yrpct} = \eta^{\text{out}}_{yrpc} \cdot \tau_{yrpt} \qquad \forall y\in\mathcal{Y}, \forall r\in\mathcal{R}, \forall p\in\mathcal{P}, \forall t\in\mathcal{T}, \forall c_{out}\in C^{\text{out}}_p, \qquad (9)
$$

where C^{in}_p is the set of the input commodities of the plant p.

(2) part-load efficiencies: As an alternative to model the processes with a constant efficiency, a load-dependent, part-load efficiency (PLE)

Table 3
Overview on the methods for calculating annuities in the frameworks.

Annualization method		urbs	Balmorel	GENESYS-2	GENeSYS-MOD	oemof
		AF	AF	AF	SV	AF[a]
Parameter dependence	Technology-dependent lifetime	x	x	x	x	x
	Region-dependent lifetime	x	x[b]	–[c]	x	x
	Technology-dependent WACC	x	x[b]	–	–	x
	Region-dependent WACC	x	x[b]	–	–	x

[a]In *oemof*, the annuity calculation is made by the user outside of the model and the investment costs are input in their annualized forms.
[b]In *Balmorel*, the annuity factor values are not calculated by the model but instead are input directly by the user for each technology.
[c]In *GENESYS-2*, region-dependent lifetimes can be modeled by defining distinct technologies.

can also be modeled in some of the frameworks. In *urbs*, using a linear relationship between the electricity output, throughput and the process capacity, a load-dependent efficiency behavior is achieved. *oemof* also supports part-load efficiencies using a piecewise-linear formulation.

(3) exogenous time-variable efficiencies: Another way to model power plant efficiencies is through an exogenously provided timeseries. This way, the ambient temperature-dependent efficiencies can be modeled, especially for thermal power plants. This feature is present and can be set optionally for any set of processes in *urbs* and *oemof*.

(4) volatile renewable energies: For intermittent renewable electricity generators such as PV and wind turbines, a time-variable capacity factor σ is used as a multiplier to the plant capacity to determine the power output at a given timestep.

$$\epsilon^{\text{out}}_{yrp(c_{\text{elec}})t} = \kappa^{\text{total}}_{yrp} \cdot \sigma_{yrpct} \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall p \in \mathcal{P}, \forall t \in \mathcal{T}, \forall c \in \left(\mathcal{C}_{\text{VRE}} \cap \mathcal{C}^{\text{in}}_{p}\right). \tag{10}$$

Some frameworks, such as *Balmorel*, feature either an equality or an inequality constraint dependent on the allowance of curtailment.

(b) Capacity limitations. Across all frameworks, the operation of each energy system component is limited by its capacity. For power plants, this is achieved by a simple inequality:

$$\epsilon^{\text{out}}_{yrpct} \leq \kappa^{\text{total}}_{yrp} \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall p \in \mathcal{P}, \forall t \in \mathcal{T}, \tag{11}$$

for the reference commodity of the plant c. In case of multiple output commodities in a process, this capacity usually limits the main output commodity, which is typically electricity. Additionally, in *urbs*, *Balmorel* and *oemof*, it is also possible to include a minimum allowable part-load:

$$\epsilon^{\text{out}}_{yrpct} \geq \underline{P}_{yrp} \cdot \kappa^{\text{total}}_{yrp} \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall p \in \mathcal{P}, \forall t \in \mathcal{T}, \tag{12}$$

where $\underline{P}_{yrp}$ is the normalized, minimal operational state of the process.

(c) Ramping limitations. With the help of the ramping constraints, abrupt changes in consecutive production levels of power plants can be limited:

$$-\overline{\rho}_{yrp} \cdot \kappa^{\text{total}}_{yrp} \leq \epsilon^{\text{out}}_{yrpct} - \epsilon^{\text{out}}_{yrpc(t-1)} \leq \overline{\rho}_{yrp} \cdot \kappa^{\text{total}}_{yrp}, \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall p \in \mathcal{P}, \forall t \in \mathcal{T}, \tag{13}$$

where $\overline{\rho}_{yrp}$ the normalized, maximal gradient of the operational state of the plant per timestep of the model. Modeling ramp constraints are possible for *Balmorel*, *urbs*, *GENeSYS-MOD* and *oemof*.

Table 4 gives a summary of mentioned plant features that each framework can implement. In general, generic power plant operations are identical across all frameworks. On the other hand, modeling of advanced process features such as time-variable efficiencies or multi-commodity operation is offered by some of the ESMFs.

3.1.6. Storage features

In this section, a comparison of the modeling of the storage technologies is made. These features consist of how the storage content is modeled, storage capacity limitations, and cyclicity/initialization of the storage (Table 5).

(a) Change of storage content. A typical form of the governing equation for the changes in the storage content between consecutive timesteps is given as follows:

$$\epsilon^{con}_{yrsct} = \epsilon^{con}_{yrsct} \cdot (1-\delta_{yrs}) + \eta^{\text{in}}_{yrs} \cdot \epsilon^{ch}_{yrsct} - \frac{\epsilon^{disch}_{yrsct}}{\eta^{\text{out}}_{yrs}} \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall s \in \mathcal{S}, \forall t \in \mathcal{T}. \tag{14}$$

Here, ϵ^{con}_{yrsct} stands for the energy content of a storage unit s in a given year y and in a region r, at a given timestep t and $\epsilon^{ch}_{yrsct}, \epsilon^{out}_{disch}$ the charging/discharging power of the storage unit at a given timestep t. The efficiencies for charging and discharging are given by η^{in}_{yrs} and η^{out}_{yrs} respectively, whereas the δ_{yrs} is the hourly relative self-discharge rate.

Each framework has a storage balance equation in the form given above. However, the feature of self-discharge is present only in *urbs* and *oemof*.

(b) Storage capacity limitations and energy-to-power ratio. Similar to other energy system components, the operation of storage is limited by its capacity. For instance, the charging and discharging of a storage are limited by the power capacity $\kappa^{\text{pow,total}}_{yrs}$:

$$\epsilon^{\text{ch}}_{yrsct} \leq \kappa^{\text{pow,total}}_{yrs} \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall s \in \mathcal{S}, \forall t \in \mathcal{T}, \tag{15}$$

$$\epsilon^{\text{disch}}_{yrsct} \leq \kappa^{\text{pow,total}}_{yrs} \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall s \in \mathcal{S}, \forall t \in \mathcal{T}. \tag{16}$$

While all frameworks restrict storage operation with such power capacity, charging and discharging power capacities ($\kappa^{\text{pow,ch}}_{yrs}$ and $\kappa^{\text{pow,disch}}_{yrs}$) may assume different values in *oemof*, *GENESYS-2*, and *Balmorel*.

Additionally, the storage content is limited by the total storage energy capacity $\kappa^{\text{con,total}}_{yrs}$:

$$\epsilon^{\text{con}}_{yrsct} \leq \kappa^{\text{con,total}}_{yrs} \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall s \in \mathcal{S}, \forall t \in \mathcal{T}. \tag{17}$$

Depending on the framework that is used, energy and power capacities of storages may be independent or coupled to each other. In *urbs*, an energy-to-power ratio (E2P) ($k^{\text{E/P}}_{yrs}$) can be optionally set for a storage unit to enforce a linear dependency in the form of $\kappa^{\text{con}}_{yrs} = \kappa^{\text{pow}}_{yrs} k^{\text{E/P}}_{yrs}$.

In *GENeSYS-MOD* and *Balmorel*, E2Ps are applied by default and for *Balmorel*, different E2Ps for charging and discharging can also be set. In default operation of *oemof* the charging, discharging and energy capacities are sized independently from each other. Nevertheless, a fixed E2P can also be set to couple to power (charging/discharging) and energy capacities to each other, or alternatively, only the charging and discharging capacities can be coupled to each other by a factor. *GENESYS-2* does not support an exogenous E2P; in this case, the power and energy capacities of storage are invested independently, by which separate investment costs are incurred for each of them.

(c) Storage cyclicity and initialization. The cyclicity and initialization constraints are another set of equations that imposes boundary conditions to the storage content. To avoid windfall profits for the energy system, e.g. by emptying a fully-initialized storage over the model horizon, the initial and final storage content can be linked by the following cyclicity constraint:

$$\epsilon^{\text{con}}_{yrsct_1} \leq \epsilon^{\text{con}}_{yrsct_N} \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall s \in \mathcal{S}, \tag{18}$$

where t_1 and t_N are the initial and final modeled timesteps, respectively. This constraint ensures that the total discharged energy from storage cannot exceed the total charged energy.

Furthermore, an initialization constraint of the following form fixes the energy content at the beginning of the modeled time horizon:

$$\epsilon^{\text{con}}_{yrsct_1} = \kappa^{\text{con}}_{yrs} \cdot I_{yrs}, \qquad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall s \in \mathcal{S}, \tag{19}$$

where I_{yrs} is the fraction of the total storage capacity that is filled at the beginning of the modeling period.

In *oemof* and *urbs*, the cyclicity constraint is active by default and the initialization constraint can be optionally activated with any given value of I_{yrs}. In case the initialization is not active, the initial value of the storage is optimized endogenously. In *Balmorel*, the cyclicity constraint is active for short term (intra-seasonal) storage systems; here, the storage content is cyclical for each week. In *GENESYS-2* and *GENeSYS-MOD*, the storages are initialized in an empty state ($I_{yrs} = 0$) by default, and thus, the cyclicity constraint is not necessary.

Different flexibilities in which the storage capacities are modeled and different degrees of freedom in the storage initialization potentially influence the economic value of storage in the overall system. Thus, given the same input data for modeling a scenario, different tendencies of storage utilization across frameworks could be sourced to these particularities.

3.1.7. Grid features

Considering how each framework models grids for the transportation of commodities, two main differences are observed. For all frameworks besides *GENESYS-2*, the grid is modeled as a lossy transport model and incorporated into the optimization. In contrast, *GENESYS-2* employs a heuristic approach towards handling the decisions regarding transmission. This heuristic focuses on shortest distances and may yields significantly different results compared to the frameworks that globally optimize the transmission according to costs and environmental impacts. The two approaches are outlined below.

Optimization

Transmission between any two regions r and r' are incorporated within the optimization model through constraints that account for the losses on the line and the capacity of the lines. The amount of the commodity that is imported from a neighbor r' has a positive contribution to the balance of that commodity in region r. The imported amount $\pi^{\text{recv}}_{y(r'r)fct}$ corresponds to the amount that has been exported from the neighboring region, $\pi^{\text{send}}_{y(r'r)fct}$, after accounting for an efficiency factor $\eta_{y(r'r)fc}$. This is achieved through the constraint:

$$\pi^{\text{recv}}_{y(r'r)fct} = \pi^{\text{send}}_{y(r'r)fct} \cdot \eta_{y(r'r)fc} \qquad \forall y \in \mathcal{Y}, \forall f \in \mathcal{F}, \forall t \in \mathcal{T}, \tag{20}$$

where r is the region receiving the commodity, r' the exporting region, t for timestep and c the commodity transported. Additionally, the transferred amount must respect the capacity of the respective line:

$$\pi^{\text{send}}_{y(r'r)fct} \leq \kappa^{\text{total}}_{y(r'r)f} \qquad \forall y \in \mathcal{Y}, \forall f \in \mathcal{F}, \forall t \in \mathcal{T}, \tag{21}$$

where $\kappa^{\text{total}}_{y(r'r)f} = \kappa^{\text{exist}}_{y(r'r)f} + \kappa^{\text{new}}_{y(r'r)f}$ denotes the total transmission capacity and $\kappa^{\text{inst}}_{y(r'r)f}, \kappa^{\text{new}}_{y(r'r)f}$ standing for the existing and new transmission capacities respectively.

Frameworks: urbs, Balmorel,[a] *GENeSYS-MOD and oemof*

Pre-defined dispatch order

The framework's transmission model aims to balance out remaining positive residual load with exceeding generation of interconnected regions. This way, each region tries to first cover their demand with its own assets. The goal of the grid is then to dissipate the positive and negative residual loads from different regions to reach an overall balance. For every region and timestep, the grid algorithm tries to exchange power with a certain distance level of neighbors, that can be set by the user. In the order of highest unsatisfied demands (or random order), all the regions are balanced per level. The iterative balancing algorithm selects a starting node with an electricity demand, and the user defines the distance level of neighboring nodes that can be requested for their surplus. Then, the algorithm checks if electricity can be transferred to neighboring nodes by considering the existing demand and the allowance of transfer capacity between the two regions. If the transfer is possible, it is executed. If all electricity demand is satisfied or no suitable neighbor offers a surplus, the algorithm moves to the next node and the process is repeated with this node. When all nodes have been considered or no more surplus electricity can be transferred, the algorithm terminates and the resulting transmission are returned to the main model. Note, that the transmission balancing is incorporated into the pre-defined dispatch order such that local use of energy is preferred over transmitting energy. The regional demand can also be satisfied by dispatchable power plants in neighboring region according to the dispatch order.

Frameworks: GENESYS-2

[a] *Balmorel* has a single variable accounting for transferred amount, rather than having separate variables for the incoming and outgoing flows. Consequently, the losses expressed in Eq. (20) are handled directly in the balance equation (5) and an additional symmetry constraint is added making sure that import in r_i from r_e corresponds to export from r_e to r_i

Table 4
Overview on the power plant features in the frameworks.

	Power plant feature	urbs	Balmorel	GENESYS-2	GENeSYS-MOD	oemof
Efficiencies	Constant efficiency	x	x	x	x	x
	Volatile RE production	x	x	x	x	x
	Part-load efficiency	x	–	–	–	x
	Time-variable efficiency	x	–	–	–	x
Cap.	Upper limit for production	x	x	x	x	x
	Minimum part-load	x	x	–	–	x
	Minimum ramp-up/down	x	x	–	–	x

Table 5
Overview on the storage features in the frameworks.

	Storage feature	urbs	Balmorel	GENESYS-2	GENeSYS-MOD	oemof
	Self-discharge	x	–	–	–	x
Storagecapacities	Fixed E2P	x	x	–	x	x
	Variable E2P	x	–	x	–	x
	Different charging/discharging capacities	–	x	x	–	x
Initialcontent	Empty start	x	x	x	x	x
	Arbitrary start	x	x	x	x	x
	Optimized start	x	x	–	–	x
Cyclicity	Cyclicity between days/weeks	–	x	–	x	–
	Cyclicity between start/end of model	x	x	–[b]	–[b]	x[a]
	Continuity between years	–	–	–	–	x

[a]The cyclicity constraint can be optionally relaxed in *oemof*.
[b]Empty start by default ensures an at least cyclical behavior.

In addition to the presented transport model, *urbs*, *Balmorel*, and *oemof* feature a lossless DC power flow model, which is achieved through a linear approximation of the AC load flows. The DC power flow on a transmission line is modeled as follows:

$$\pi^{\text{send}}_{y(r'r)fct} = \pi^{\text{recv}}_{y(r'r)fct} = \frac{(\theta_{yr't} - \theta_{yrt})}{57.3} \cdot \frac{V^2_{\text{base}}}{X_{yr'rf}}, \quad \forall y \in \mathcal{Y}, \forall f \in \mathcal{F}, \forall t \in \mathcal{T}, \tag{22}$$

where θ_{yrt} and $\theta_{yr't}$ are the voltage angles of the connected sites r and r' respectively. These are converted to radians from degrees by dividing by 57.3. $X_{yr'rf}$ is the reactance of the connecting transmission line f in Ohms and $\frac{1}{X_{af}}$ is the admittance of the transmission line.

3.1.8. Imports/exports

Importing and exporting energy commodities (e.g. electricity) in and out of the modeled region can be realized in several different ways in each framework. In each framework, pre-defined import and export amounts can be implemented by adjusting the demands in each model region accordingly. Additionally, model-endogenous import/export decisions with time-variable prices and capacity limitations can be modeled in *urbs*, *Balmorel* and *oemof*. In *GENeSYS-MOD*, this feature is also present, however, with a constant yearly price. *In GENESYS-2*, imports and exports are not incorporated.

3.2. Intertemporality features

This section focuses on intertemporality and, along with it, three additional model features. These are (1) the handling of intertemporal costs, (2) intertemporal capacities and (3) a CO_2 budget over the modeling horizon. Therefore, the different modeling approaches for these features across the frameworks will be explained in this section.

3.2.1. Modeling intertemporal costs

This section explores the different approaches of the frameworks to deal with costs in intertemporal models, where the models encompass multiple years in which investment decisions can be made. For a summary of the intertemporal cost calculation approaches taken by each framework, see Table 6.

For calculating the costs that emerge in intermediate years, *urbs* repeats the costs of the last occurring modeled support year, each consecutive year discounted by a constant discount rate j. In other words, the fixed, variable, fuel and environmental costs are repeatedly charged for each intermediate year (assuming the same operation as in the last support year) until the next support year y^+ (which has a distance to the preceding support year of $\Delta y = y^+ - y$ years) and discounted cumulatively by the factor $\frac{1}{1+j}$ for each year in between. For each support year y, the summation of this series then leads to the intertemporal cost factor D_y:

$$\begin{aligned} D_y &= \sum_{l=y}^{y+\Delta y-1} (1+j)^{-l} = (1+j)^{-y} \sum_{l=0}^{\Delta y-1} (1+j)^{-l} \\ &= (1+j)^{1-y} \frac{1-(1+j)^{-\Delta y}}{j} \quad \forall y \in \mathcal{Y}. \end{aligned} \tag{23}$$

This factor is then used to calculate the costs associated with the year y as follows:

$$\zeta^{\{\text{fix, var, fuel, env}\}}_{[y,\rightarrow y+\Delta y-1]} = D_y \cdot \zeta^{\{\text{fix, var, fuel, env}\}}_y \quad \forall y \in \mathcal{Y}. \tag{24}$$

The investment costs, on the other hand, are first annuitized by the annuity factor described in Section 3.1.3. This leads to the following manner of calculating their intertemporal costs (for an investment made in year y) for any process p (analogously for storages and transmission lines):

$$\begin{aligned} \zeta^{\text{inv}}_{[y,\rightarrow y+\Delta y-1]} &= \sum_{r\in\mathcal{R}} \left(\sum_{p\in\mathcal{P}_r} D_y \cdot \zeta^{\text{inv}}_{yrp} \right) \\ &= \sum_{r\in\mathcal{R}} \left(\sum_{p\in\mathcal{P}_r} \underbrace{D_y \cdot af_{yrp}}_{=:I_{yrp}} \cdot c^{\text{inv}}_{yrp} \cdot \kappa^{\text{new}}_{yrp} \right) \forall y \in \mathcal{Y}, \end{aligned} \tag{25}$$

where I_{yrp} is the intertemporal investment cost factor for a process p in region r in a given support year y. Note that the involvement of D_y in this expression leads to the consideration of only the number of years of an investment's lifetime that fall into the model horizon. This way, the payments for an investment that exceed the model horizon are deducted from the model's objective function.

Table 6
Overview on the intertemporal cost calculation in the frameworks.

Intertemporal costs		urbs	Balmorel	GENESYS-2	GENeSYS-MOD	oemof
Discounting of intermediate years	Fixed for a given support year	–	x	–	–	-[a]
	Different for each intermediate year	x	–	x	x	-[a]
Weighting of support years	Arbitrary	–	x	–	–	-[a]
	Distance-based	x	x	x	x	-[a]

[a]Possible, but has to be manually implemented.

GENESYS-2 intertemporal cost calculations also consider a constant discount rate j, however, due to the internal representation of investment pathways, a year-by-year calculation is performed. Any payments that fall outside the model horizon are omitted in *GENESYS-2*. For pathway calculations, *GENESYS-2's* input values are linearly or constantly interpolated for intermediate years, which also applies to other techno-economical parameters where no individual values are given between support years. From the start until the end of the simulation, all years are optimized based on the individual dispatch with an hourly resolution for the entire time-span.

In *Balmorel*, discounting of costs is applied to the objective function, making distant future years in the model weigh less than near years. However, in *Balmorel*, in contrast to *urbs*, each intermediate year belonging to a support year is discounted with the same factor $(1+j)^{-\Delta y}$ as the respective support year. Hence, Balmorel neglects varying discount factors for those intermediate years. By manually setting the annuity factors for each support year, the weighting of support years can still be made flexibly.

GENeSYS-MOD discounts the total system costs, including investment (after applying the salvage value), fixed, variable, trade and emissions costs.

In *oemof*, intertemporal economic and technical constraints spanning multiple, non-consecutive years are not considered a core feature. It is possible to manually add these constraints to an *oemof* model but the process is more involved than building a model with an equidistant time index. Alternatively, calculating support years individually and transferring capacity decisions between support years is also supported.

3.2.2. Capacity transfer between support years

This section focuses on how existing technology capacities are transferred to subsequent years and how the phasing out of technologies is handled in each framework (with Table 7 providing an overview). All frameworks, except for *GENESYS-2*, are able to generate a single problem with perfect foresight so that the capacity expansion can be performed for each support year while making use of the information of future years and unit lifetimes. The optimization approach in *GENESYS-2*, however, uses an iterative approach to find a suitable solution for the necessary capacity investments over the whole time-span. It also considers automatic capacity decommissioning based on the technical lifetime of pre-installed and installed capacities within the model horizon. In *urbs*, pre-installed capacities for technologies are given with a remaining lifetime for the first support year of the model. For new installations, the economic lifetime also behaves as the technical lifetime. The units exceeding their technical lifetimes are then automatically decommissioned. If capacities expire between two support years, they are only added to the succeeding support year if their expiration occurs in the second half of the period between the years.

In *Balmorel*, first, a "global" time horizon is defined and a subset of which is then set for a specific model run. The support years with perfect foresight can be hence user-defined. The framework offers three decommissioning strategies that can be applied to the existing capacity of newly invested capacity. The options are (1) decommission due to exceeding the lifetime, (2) decommission due to profitability and (3) the option to buy back decommissioned capacity.

In *GENeSYS-MOD* the remaining share of the pre-existing capacities is provided by the user for each support year. For new installations, the economic lifetime also behaves as the technical lifetime and the units exceeding their technical lifetimes are decommissioned. If the capacities expire between two support years, they are only included in the first support year. Moreover, an optional constraint limits the production of technologies by a given percentage compared to a previous optimized support year, restricting its expansion indirectly and hence aims to avoid unrealistic expansion pathways.

In *GENESYS-2*, the installed capacities remain in operation until the end of their lifetime. Initial capacities defined in the starting year of the modeling horizon or at the support years can be optionally set.

Except for *GENESYS-2's* approach, it would technically be possible to emulate the other frameworks approaches using *oemof*, but only at a very significant overhead in model development time. For this reason, a much simpler approach can be implemented, where the support years are consecutively optimized as individual models. The optimized capacity expansion per year is automatically transferred between consecutive models. The economic lifetime is treated as technical lifetime and units are automatically decommissioned at the end of their technical lifetime so that capacities are only present in support years that are within their lifetime.

3.2.3. CO_2 budget and emission limits

Besides the annual emission limits, which can be defined by all ESMFs, this section analyzes the differences in the implementation of an overall CO_2 budget feature between the frameworks. Table 8 offers an overview. In general, two groups regarding the budget implementation can be identified from the five ESMFs. The first group includes the CO_2 budget as a feature to allow an optimized distribution of the emissions over the modeling horizon. The second group has not yet implemented the CO_2 budget as a built-in feature in the reviewed framework version, but options exist to implement it alternatively. *urbs* and *GENeSYS-MOD* belong to the first group. For instance in *urbs*, a CO_2 budget of $\overline{E}_{\mathrm{CO}_2}$ can be defined over the entire modeling horizon:

$$\sum_{y\in Y} w_y \left(\sum_{t\in T} \left(\sum_{r\in R} \left(\sum_{p\in P_r} \left(\epsilon^{\mathrm{out}}_{yrp(\mathrm{CO}_2)t} - \epsilon^{\mathrm{in}}_{yrp(\mathrm{CO}_2)t} \right) \right) \right) \right) \leq \overline{E}^{\mathrm{CO}_2}, \tag{26}$$

where w_y stands for the weight of a given support year y (distance in years until the next support year, and a user-input value for the last support year in the model). In *GENeSYS-MOD*, emissions of the intermediate years are not repeated but rather linearly interpolated between the two support years.

In *oemof* and *Balmorel* the budget is pre-allocated to the support years.

Balmorel provides yearly limits and costs of emission in the objective function but no emission budget across the modeling horizon can be set. Rather, year- and country-specific limits on the annual CO_2-emission and country are set as follows:

$$\sum_{t\in T} \left(\sum_{r\in X} \left(\sum_{p\in P_r} \left(\epsilon^{\mathrm{out}}_{yrp(\mathrm{CO}_2)t} - \epsilon^{\mathrm{in}}_{yrp(\mathrm{CO}_2)t} \right) \right) \right) \leq \overline{E}^{\mathrm{CO}_2}_{y,X}, \qquad \forall y \in Y, \forall X \in \mathcal{X}, \tag{27}$$

where $\mathcal{X}$ are the set of countries, each (X) defined as a distinct subset of the model regions and $\overline{E}^{\mathrm{CO}_2}_{y,X}$ the allocated yearly emission allowance for each of these countries in the support year y.

Table 7
Overview on the methods for handling the intertemporal capacities of components in the frameworks.

Intertemporal capacities	urbs	Balmorel	GENESYS-2	GENeSYS-MOD	oemof
Perfect foresight	x	x	–	x	-[a]
Decomissioning due to lifetime	x	x	x	x	x
No intertemporal capacity constraints	–	–	–	–	x

[a]Possible, but has to be manually implemented.

Table 8
Overview on the frameworks' capabilities for defining an intertemporal emission budget.

Emission budget	urbs	Balmorel	GENESYS-2	GENeSYS-MOD	oemof
Budget for all intertemporal years	x (repeated)	–	–	x (interpolated)	–
Manually allocating budget to years	–	x	x	–	x

However, due to the lack of perfect foresight in the reviewed *oemof* version for multi-year models (see Section 3.2.2), some model adaptions are necessary. In *oemof*, the CO_2-emissions between the support years are linearly interpolated and emission limits for specific years can be implemented. The limit for each support year (if not set manually) is defined as the remaining budget divided by the number of years to the next support year—this way, the overall budget constraint is not exceeded during interpolation. After optimization of the first support year, the remaining budget is allocated to the second support year. However, if the optimal solution of the second calculated support year uses less than its allocated maximal budget, the emission between the first and second support year are interpolated again and the unused budget in this period is provided to the next, not yet optimized, third support year.

GENESYS-2's implementation of a CO_2 budget is similar to *Balmorels*. If an emission budget is provided, it is split into annual limits over the modeling horizon. The possible emissions per year are user-defined, but when annual emissions limits for selected support years are already in place, the budget is distributed linearly between the existing limits. In contrast to the other frameworks *GENESYS-2* optimizes each year between two support years and the emission limit for every single year forms an upper limit that cannot be exceeded. Conversely, there is no carry-over of unused annual emission volumes, such that unused emission volumes per year expire and are not available to subsequent years.

3.3. Multi-sector features

The third scope extends the second one in order to also include a heat sector representation. Some of the essential features categorizing this scenario are therefore how the different frameworks handle sector-wise emission limits as well as how sector coupling technologies are modeled.

3.3.1. Emission limits by sector

Additional to these emission restriction features mentioned above, some frameworks facilitate a limitation also on a sectoral level. However, as illustrated in Table 9, currently, only *GENeSYS-MOD* and *oemof* supports a sector-specific CO_2 limit, which, for both frameworks, is achieved by incorporating the following constraint into the optimization model:

$$\sum_{t\in T}\left(\sum_{r\in R}\left(\sum_{p\in P_{r,n}}\left(\epsilon^{\text{out}}_{yrp(\text{CO}_2)t}-\epsilon^{\text{in}}_{yrp(\text{CO}_2)t}\right)\right)\right)\leq \overline{E}^{\text{CO}_2}_{y,n}, \qquad \forall y\in Y,\forall n\in\mathcal{N} \quad (28)$$

where N is the set of defined sectors (n) in the model (e.g. electricity, heat), $\overline{E}^{\text{CO}_2}_{y,n}$ is the yearly CO_2 limitation in a given sector and $P_{r,n}$ the set of processes that are defined for a sector n in a given region r. Additionally, in *GENeSYS-MOD*, such sectoral limitation of CO_2 can also be defined for each region separately.

For the remaining frameworks, both *urbs* and *Balmorel* features a structure that allows for such a limitation to be incorporated with minor adjustments (e.g. via defining different CO_2 commodities for each sector), while this is not possible for *GENESYS-2*. Keeping this in mind, results obtained from frameworks featuring this limitation may therefore be more expensive compared to the results obtained without the limitation due to these acting as additional constraints on the model.

3.3.2. Sector-coupling processes

Modeling sector-coupled energy systems frequently requires representations of MIMO technologies such as combined heat and power plant (CHP)s. The different frameworks deviate in how detailed the MIMO technologies are modeled with the main differences being the amount of different CHPs being modeled spanning from zero to two. *GENESYS-2* does not support modeling of MIMO technologies at all, whereas both *urbs* and *GENeSYS-MOD* model these with an approach similar to the *backpressure* approach explained below. Lastly *Balmorel* and *oemof* divide the CHPs into either *backpressure* or *extraction* technologies, and therefore cover different modeling of the two types of technologies. Table 10 illustrates whether a framework supports MIMO technologies and to which extend it is modeled.

In more detail, *urbs* and *GENeSYS-MOD* model the MIMO technologies similarly to how the single input/output technologies are modeled with either constant or exogeneously variable efficiencies (e.g. dependent on temperature) determining the relation between input and output of the technologies. In these frameworks, modeling the dependency between the thermal and electrical efficiency is not possible, which essentially is what differentiates them from *Balmorel* and *oemof*. In *Balmorel* and *oemof*, each CHP technology p is associated with three types of efficiencies, namely $\eta^{\text{out}}_{yrp(c_{\text{elec}})}$, ζ^{CB}_{yrp} and η^{CV}_{yrp} relating to the technology specific power to heat ratio and the efficiencies derived from the CB and the CV line (detailed explanations in [12,25]). Fuel usage for both types of technologies are then described through:

$$\zeta^{\text{woExt}}_{yrp}\cdot\epsilon^{\text{in}}_{yrp(c_{\text{fuel}})t}=\epsilon^{\text{out}}_{yrp(c_{\text{elec}})t}+\zeta^{\text{CV}}_{yrp}\cdot\epsilon^{\text{out}}_{yrp(c_{\text{heat}})t}$$
$$\forall y\in\mathcal{Y},\forall r\in\mathcal{R},\forall p\in\left(\mathcal{P}^{\text{EX}}\cup\mathcal{P}^{\text{BP}}\right),\forall t\in\mathcal{T}, \quad (29)$$

where $\mathcal{P}^{\text{EX}},\mathcal{P}^{\text{BP}}$ are the sets of extraction and backpressure CHPs respectively, $\epsilon^{\text{in}}_{yrp(c_{\text{fuel}})t}$ is the fuel input needed to generate a certain amount of electricity $\epsilon^{\text{out}}_{yrp(c_{\text{elec}}t)}$ and heat $\epsilon^{\text{out}}_{yrp(c_{\text{heat}}t)}$, with the given electrical efficiency in condensing mode $\zeta^{\text{woExt}}_{yrp}$, and ζ^{CV}_{yrp}. In *oemof*, $\zeta^{\text{CV}}_{yrp}=1$ for the backpressure mode and for both CHP types, every efficiency parameter can be set in a time variable manner to account for the influence of varying ambient temperatures on the performance.

For backpressure technologies, the power/heat generation is then limited by the CB-line as follows:

$$\epsilon^{\text{out}}_{yrp(c_{\text{elec}})t}=\epsilon^{\text{out}}_{yrp(c_{\text{heat}})t}\cdot\eta^{\text{CB}}_{yrp} \qquad \forall y\in\mathcal{Y},\forall r\in\mathcal{R},\forall p\in\mathcal{P}^{\text{BP}},\forall t\in\mathcal{T}, \quad (30)$$

which leads to a similar modeling approach as *urbs* and *GENeSYS-MOD*, in which a constant ratio between the heat and electricity production can be defined via the output ratios of the two commodities.

Table 9
Overview on the implementability of sector-specific limitation of CO_2 in frameworks.

Sector-specific CO_2 limit	urbs	Balmorel	GENESYS-2	GENeSYS-MOD	oemof
Already implemented	–	–	–	x	x
Possible to implement	x	x	–	–	x

Table 10
Overview on the multiple input-multiple output process modeling in the frameworks.

	urbs	Balmorel	GENESYS-2	GENeSYS-MOD	oemof
MIMO	x	x	–	x	x
Backpressure CHP	x	x	–	x	x
Extraction CHP	–	x	–	–	x

For the extraction CHPs, the power/heat generation is also limited by the CB-line but in a more relaxed form, i.e. not necessarily satisfying the equality, creating room for varying power-to-heat ratios:

$$\epsilon^{\text{out}}_{yrp(c_{\text{elec}})t} \geq \epsilon^{\text{out}}_{yrp(c_{\text{heat}})t} \cdot \eta^{\text{CB}}_{yrp} \quad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall p \in \mathcal{P}^{\text{EX}}, \forall t \in \mathcal{T}, \tag{31}$$

In addition to the above inequality, the power and heat generation is also limited by the CB-line with the following constraint:

$$\epsilon^{\text{out}}_{yrp(c_{\text{elec}})t} \leq \kappa^{\text{total}}_{yrp} - \epsilon^{\text{out}}_{yrp(c_{\text{heat}})t} \cdot \eta^{\text{CB}}_{yrp} \quad \forall y \in \mathcal{Y}, \forall r \in \mathcal{R}, \forall p \in \mathcal{P}^{\text{EX}}, \forall t \in \mathcal{T}. \tag{32}$$

Apart from the difference in supporting MIMO technologies, the main differences between the frameworks can be summarized as how and to which degree the power/heat generation is limited. From a mathematical perspective, *Balmorel* and *oemof* allow for technologies having a variable ratio between heat and power generation, whereas this is not possible in *urbs* and *GENeSYS-MOD*. *Balmorel* and *oemof* however have additional constraints, because of which it might be hard to foresee the exact impact that these differences could have on the results.

3.4. Discussion of modeling differences

Based on the preceding comparison, this section summarizes each frameworks' modeling strengths and limitations. Their capabilities and weaknesses in modeling energy systems are briefly discussed, based on the selected features and identified differences. Besides the framework-specific strengths and limitations as shown in Table 11, the joint strength of all frameworks is their flexibility to allow custom constraints besides their out-of-the-box functionalities. Their implementation, however, should be executed with caution to avoid unwanted effects in model behavior. Still, the frameworks' application showed that they allow many interpretations of their built-in functionalities to support particular energy system behavior even without adjusting the shipped code. Exemplary to mention are implementing resource limits of varying regional scope through dummy technologies and chaining sets of generic technologies to model specific technology behavior. Particular attention should also be paid to the different time representations and their limitations in Balmorel, GENESYS-2 and GENeSYS-MOD, especially when modeling storage in hourly resolution and consecutive years. On the other hand, in research questions that lay the focus on the exact pathway of investments in power systems, the insights from the high-resolution expansion pathways in GENESYS-2 could be preferred over the limited approach of repeating the support years until the next support year in Balmorel, GENeSYS-MOD and urbs. Yet, a trade-off exists as sector-coupling functions lack in GENESYS-2 due to the resulting computational complexity.

4. A model experiment

In this section, we showcase selected results from a model experiment implemented by each of the analyzed frameworks. The experiment relates to the German energy system (represented in sixteen federal states and two offshore regions) in 2016 and 2050. Both of these years represent a stand-alone scenario. The former deals with an isolated optimization of operation and the latter deals with a co-optimization of the operation and capacity expansion. Some key figures of these scenarios can be seen in Table 12. As this investigation aims to identify possible impacts of modeling differences on the model results, rather than deriving any policy statement from these, further scenario description is omitted for the sake of brevity. Moreover, this section will focus only on the parts of the results where explanations are possible to make with respect to the framework features. As some of the frameworks can either not implement intertemporal models or include other sectors apart from electricity, the features relevant in this analysis are limited to the basic model features presented in Section 3.1. The selected results are generated using the open_MODEX Dashboard.[7]

Heuristic method of GENESYS-2. The Figs. 1 and 2 respectively show the optimized power plant capacities and the corresponding amounts of electricity generation in each framework and year. For both years, we observe very similar results for all frameworks. On the other hand, due to GENESYS-2's fundamentally different heuristic method (pre-defined dispatch order) which prioritizes electricity generation within regions over cross-regional trade, the results differ slightly from the other, optimization-based frameworks. For instance in 2016, the locally available natural gas-fired power plants are utilized in GENESYS-2, while for the other four frameworks, the global optimization takes advantage of the cheaper coal resources and the transmission grid to cover the base-load electricity. Similar behavior is present in 2050, where the geothermal resources are not used since they only have local availabilities.

Salvage value method instead of the annuity factor method. As mentioned before, the salvage value method used in GENeSYS-MOD leads to an under-representation of the investment costs compared to the annuity factor method of the other frameworks. This economic factor, possibly combined with the empty storage initialization constraint (all storages start empty in 1. January) leads to a noticeably different capacity mix in GENeSYS-MOD for 2050. In particular, systems that provide daily storage consisting of PV and batteries are preferred over seasonal storage systems (provided by production from wind and hydrogen). Lower preference of wind installations leads to lower importance of transmission expansion as these are mostly used to balance the high-demand in southern regions with high generation from wind from the north. Additionally, as the variable costs have a relatively higher significance, the production from biogas plants is relatively lower in GENeSYS-MOD.

Noncyclic storage overloading as curtailment. Fig. 3 shows the total charged and discharged storage energy for each framework in 2050. Unlike the other frameworks, GENeSYS-MOD and GENESYS-2 are observed to charge a much higher amount of energy through batteries than they discharge. This implies that these frameworks, which do not impose a storage cyclicity constraint and have a free-of-charge storage operation, allow for a net-positive charging phenomenon as an alternative to the curtailment of excess production of volatile renewable electricity. While analyzing model results, this might misleadingly result in an underestimation of the curtailment in the system. Attaching a non-zero, however insignificant cost for storage operation, would help remedy this behavior.

[7] https://modex-results.rl-institut.de/.

Table 11
Comparison table.

	Modeling capacities	Limitations
urbs	-Detailed cost representation -Detailed power plant operation -CO_2 budget limit in intertemporal models	-No CHP-specific features -No sector-specific CO_2 limits by default -No preset feature for renewable share targets
Balmorel	-Detailed cost representation and power plant operation -Focus on sector-linkages and CHP-specific features -Rolling time horizon possibilities -Flexible year weighting in intertemporal models	-Fixed E2P ratio for storages -Detailed long-term investment models with sector coupling features are only possible to compute at reduced time resolution -Manually allocating emission budgets to years
GENESYS-2	-Very high (yearly) resolution for investment pathways over several decades -(Dis)-charging and capacity unit for storage is modeled individually -Interpolation between support-years can be chosen constant or linearly -Fixed dispatch structure promotes the regional use of energy	-Limited, rule-based transmission model because of dispatch structure -Only electricity sector can be modeled -Foresight between years cannot be modeled -Modeling of leap-years not possible
GENeSYS-MOD	-Integrated timeseries aggregation -Possibility of implementing numerous political targets -Sector specific targets and constraints possible -Focus on sector-linkages, covers electricity, transport, industry, and buildings by default	-Detailed long term models only possible to compute at reduced time resolution -Fixed E2P ratio for storages
oemof	-Detailed power plant operation -CHP-specific features -Very flexible/built in components integrate seamlessly with user-written ones	-No detailed cost representation/costs have to be tracked manually -Capacity limits across multiple components are difficult to implement -No GUI; model has to be coded in Python

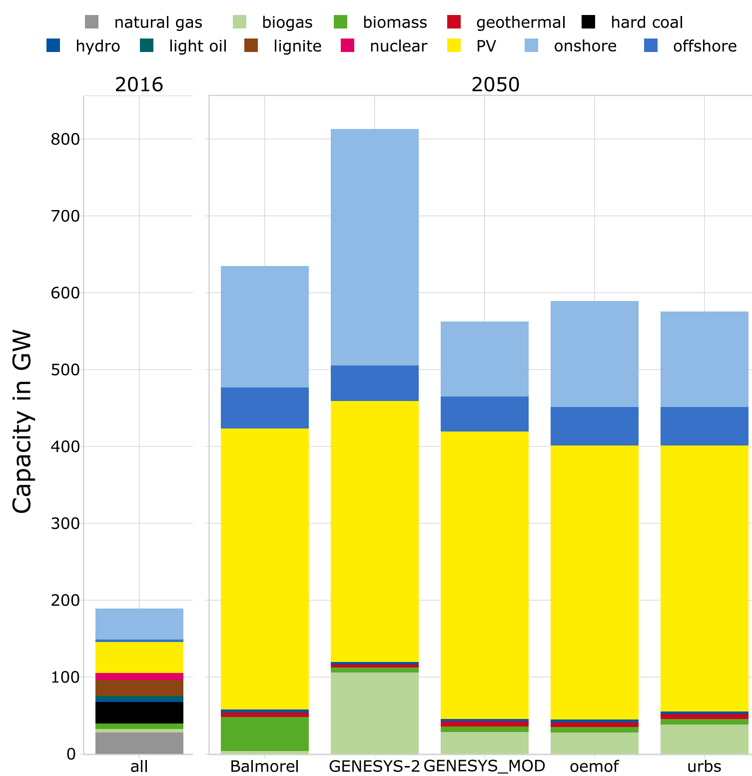

Fig. 1. Capacity results across frameworks (fixed for 2016, optimized for 2050).

5. Conclusion

In this work, five OS-ESMFs have been comprehensively compared regarding their mathematical functional implementation to generate scenarios for optimal energy systems. Although all frameworks have a relatively high standard in transparency and documentation, a common terminology was developed to further facilitate the comparison.

The comparison has shown that the core equations are mathematically very similar and only few framework formulations differ. With the model experiment, an impact quantification of these differences was made and several results were able to be traced back to the underlying formulations.

Both framework users and developers can benefit from this comparative overview of frameworks. By acknowledging concrete formulations

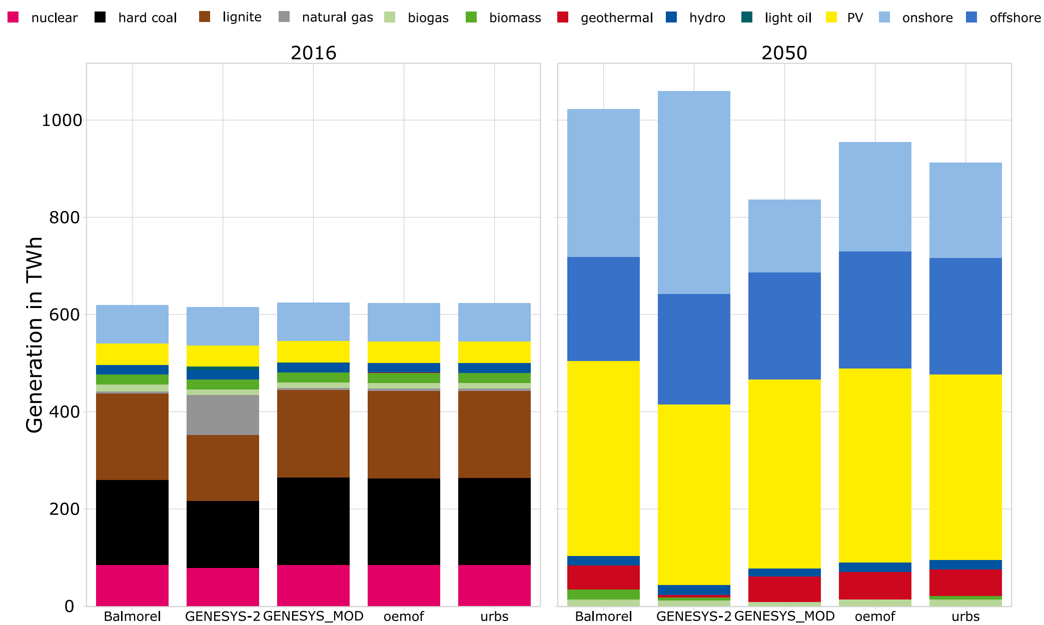

Fig. 2. Optimal electricity generation results across frameworks.

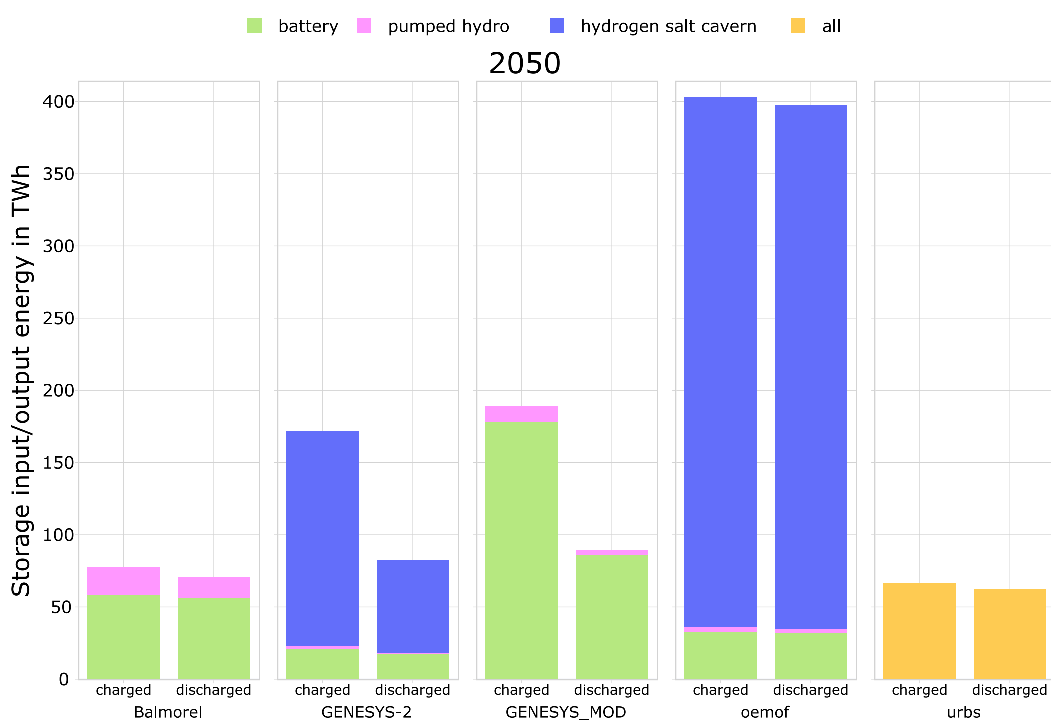

Fig. 3. Total charged and discharged amounts of electricity in 2050 for each framework.

of missing features, framework developers will be able to identify avenues of improvement regarding their frameworks and ease the implementation of those. Moreover, experienced framework users can reflect on their framework-specific implementations and enhance their model building. Other users are given a head-start in the frameworks' specifics and differences, and thereby save resources in selecting an OS-ESMF for their needs. Subsequent OS-ESMF reviews can build upon the findings and a common terminology for further analysis.

The transparency achieved in this study also contributes to reducing redundant development of new OS-ESMFs with identical approaches. Furthermore, we have assessed the impact of different mathematical approaches through comparative scenario calculations, both qualitatively and quantitatively, by analyzing to what extent differences in mathematical expressions were reflected logically in the calculation results. Overall, this study assists energy system modelers to understand existing approaches and frameworks better, and we aim to strengthen the collaboration between OS-ESMFs with this comparison study.

5.1. Future work

The outlook on future research is manifold. A useful extension of this work would be establishing a common terminology standard and

Table 12
Factsheet of the two scenarios for Germany in 2016 and 2050.

	2016	2050
Spatial	Germany with 16 federal states	
Temporal	2016, hourly	2050, hourly
Sectors	Electricity	Electricity
Capacity expansion	No	Yes
Electricity demand	568 TWh	794 TWh
CO_2 price	26.8 €/t	115 €/t
Emission budget	Unlimited	0 Mt CO_2
Net electricity exports	49.1 TWh	−79.2 TWh
Phase out	None	Nuclear, coal

extending the comparison covering additional features that energy system modeling deals with. This could be done by broadening this terminology or linking and extending it to an existing one (such as the Open Energy Ontology [26]). A terminology standard would increase interoperability between ESMFs and make researchers and policymakers better understand where the differences between ESMFs lie. It would be supportive to explain differences arising in scenario studies that were modeled with different frameworks. This study lays the ground for quantitative evaluations of different modeling approaches and their effects in the next step. For this purpose, we recommend calculating the scenarios with an incremental model run plan to understand the impacts at a satisfactorily granular level. Through such analysis, the robustness of the individual approaches could be improved, discrepancies better understood, and the strengths and limitations of the OS-ESMFs investigated here could be enhanced.

Additionally, research on whether the frameworks are fit for purpose and to what extent the approaches serve the OS-ESMFs' purpose, scope and philosophy could be performed. Especially, whether there are already other, more suitable approaches that would improve the quality of the respective OS-ESMFs could be identified. Framework developers and policy makers could benefit from such analysis, as the development process of OS-ESMFs could evolve towards a non-arbitrary diversity of approaches and a tightening of the purpose, scope and philosophy of the respective OS-ESMF. As a result, the range of outcomes from comparative scenario calculations could be increased. Still, confidence in the results could be strengthened because causal chains of assumptions and impacts could be profoundly explained and evaluated in a more sophisticated way.

CRediT authorship contribution statement

Soner Candas: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Supervision, Writing – review & editing. **Christoph Muschner:** Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Supervision, Writing – review & editing. **Stefanie Buchholz:** Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Supervision, Writing – review & editing. **Rasmus Bramstoft:** Investigation, Writing – original draft, Writing – review & editing. **Jonas van Ouwerkerk:** Data curation, Writing – review & editing. **Karlo Hainsch:** Data curation, Writing – review & editing. **Konstantin Löffler:** Data curation, Writing – review & editing. **Stephan Günther:** Data curation, Writing – review & editing. **Sarah Berendes:** Conceptualization, Investigation, Writing – review & editing. **Stefanie Nguyen:** Data curation, Writing – review & editing. **Aparna Justin:** Data curation, Writing – review & editing.

Declaration of competing interest

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

Data availability

A more extensive documentation of framework-specific modeling of features can be accessed in the following ReadTheDocs link: https://open-modex-mathdoc.readthedocs.io/en/latest/index.html. The underlying dataset for the calculations can be accessed at zenodo: https://zenodo.org/record/5854411.

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Appendix. Common terminology

Nomenclature

Parameters

$\bar{\rho}_{yrp}$	Maximum hourly ramping gradient for a process p
$\bar{E}^{CO_2}$	Total CO_2 budget of an intertemporal model
$\bar{E}^{CO_2}_{y}$	CO_2 limit for a support year y for all model regions
$\bar{E}^{CO_2}_{y,n}$	CO_2 limit for a support year y for a given sector n
$\bar{E}^{CO_2}_{y,X}$	CO_2 limit for a support year y for a given country X
δ_{yrs}	Hourly relative self-discharging rate of a storage s
η^{in}_{yrs}	Charging efficiency of a storage s
η^{out}_{yrs}	Discharging efficiency of a storage s
η^{CB}_{yrp}	CB efficiency of a CHP process p (Balmorel and oemof)
η^{CV}_{woExt}	Electrical efficiency of a CHP process p in condensing mode (Balmorel and oemof)
η^{CV}_{yrp}	CV efficiency of a CHP process p (Balmorel and oemof)
η^{in}_{yrpc}	Input efficiency of a process p (GENESYS-MOD and urbs)
η^{out}_{yrpc}	Output efficiency of a process p (GENESYS-MOD and urbs)
$\eta_{y(r'r)fc}$	Efficiency of a transmission line f
$\eta_{yrpc_{elec}}$	Electrical efficiency of a process p (Balmorel, GENESYS-2 and oemof)
σ_{yrpct}	Time-variable capacity factor for a volatile renewable process p
$\underline{\eta}^{out}_{yrpc}$	Output efficiency of a process p at its minimum part-load (urbs)
$\underline{P}_{yrp}$	Minimum allowable part-load of a process p
$y(r'r)f$	Reactance of a transmission line f (relevant for DC-OPF grid models)
$af_{y(rr')f}$	Annuity factor of a transmission line f
af_{yrp}	Annuity factor of a process p

af_{yrs}	Annuity factor of a storage s
$c^{\text{fix}}_{y(r'r)f}$	Annual fixed costs per MW total capacity of a transmission line f
$c^{\text{inv}}_{y(r'r)f}$	Investment costs per MW new capacity of a transmission line f
$c^{\text{var}}_{y(r'r)f}$	Variable running costs per MWh flow through a transmission line f
c^{fix}_{yrp}	Annual fixed costs per MW total capacity of a process p
c^{fuel}_{yrp}	Fuel costs per MWh input associated with a process p
c^{inv}_{yrp}	Investment costs per MW new capacity of a process p
c^{var}_{yrp}	Variable running costs per MWh output of a process p
$c^{\text{env}_2}_{yrp}$	Environmental costs per ton CO2 emission associated with a process p
$c^{\text{fix,con}}_{yrs}$	Annual fixed costs per MWh of a storage s
$c^{\text{fix,pow}}_{yrs}$	Annual fixed costs per MW of a storage s
$c^{\text{inv,con}}_{yrs}$	Investment costs per MWh new energetic capacity of a storage s
$c^{\text{inv,pow}}_{yrs}$	Investment costs per MW new charging/discharging capacity of a storage s
c^{var}_{yrs}	Variable running costs per MWh charging and discharging of a storage s
D_y	Intertemporal cost factor for a support year y
d_{yrct}	Hourly demand for commodity c
f^{out}_{yrpct}	Time-variable efficiency multiplier for a process p
I_{yrp}	Intertemporal investment cost factor of a process p
i_{yrp}	Weighted average cost of capital (WACC) of a process p
I_{yrs}	Initial state of charge of a storage s
$k^{\text{E/P}}_{yrs}$	Energy-to-power ratio of a storage s
n_{yrp}	Economic lifetime of a process p
V_{base}	Base voltage of the modeled transmission grid (relevant for DC-OPF grid models)
w_y	Weight of a support year y

Sets and indices

$\mathcal{C}$	Set of commodities (energy carriers)
$\mathcal{C}_{\text{VRE}}$	Set of volatile renewable resources e.g. solar and wind
$\mathcal{C}^{\text{in}}_p$	Set of input commodities (energy carriers) entering a process p
$\mathcal{C}^{\text{out}}_p$	Set of output commodities (energy carriers) leaving a process p
$\mathcal{F}$	Set of transmission line types
$\mathcal{F}_r$	Set of transmission lines connected to region r
$\mathcal{N}$	Set of modeled sectors
$\mathcal{P}$	Set of process (plant) types
$\mathcal{P}^{\text{BP}}$	Set of backpressure CHP processes
$\mathcal{P}^{\text{EX}}$	Set of extraction CHP processes
$\mathcal{P}_r$	Set of processes defined in region r
$\mathcal{P}_{r,n}$	Set of processes defined in region r and sector n
$\mathcal{R}$	Set of model regions
$\mathcal{S}$	Set of storage types
$\mathcal{S}_r$	Set of storages defined in region r
$\mathcal{T}$	Set of model timesteps
$\mathcal{Y}$	Set of support years
c	Index for a commodity (energy carrier)
f	Index for a transmission line
n	Index for a sector
p	Index for a process (plant)
r	Index for a model region
s	Index for a storage unit
t	Index for a model timestep
y	Index for a support year (relevant for intertemporal models)
$y_{\max}$	Index for the latest support year in the model (relevant for intertemporal models)

Variables

$\epsilon^{\text{buy}}_{yrct}$	Amount of energy bought (imported) from the external market
$\epsilon^{\text{curt}}_{yrct}$	Curtailed amount of the commodity c
$\epsilon^{\text{sell}}_{yrct}$	Amount of energy sold (exported) to the external market
$\epsilon^{\text{slack}}_{yrct}$	Slack production of the commodity c
$\epsilon^{\text{stock}}_{yrct}$	Procured amount of a (fuel) commodity c
$\epsilon^{\text{in}}_{yrpct}$	Input commodity flow into a process p
$\epsilon^{\text{out}}_{yrpct}$	Output commodity flow from a process p
$\epsilon^{\text{ch}}_{yrsct}$	Charging energy into a storage s
$\epsilon^{\text{con}}_{yrsct}$	Energy content of a storage unit s at a timestep t
$\epsilon^{\text{disch}}_{yrsct}$	Discharging energy from a storage s
$\kappa^{\text{exist}}_{y(rr')f}$	Existing capacity of a transmission line f
$\kappa^{\text{new}}_{y(rr')f}$	New capacity of a transmission line f
$\kappa^{\text{total}}_{y(rr')f}$	Total capacity of a transmission f
$\kappa^{\text{exist}}_{yrp}$	Existing capacity of a process p
$\kappa^{\text{new}}_{yrp}$	New capacity of a process p
$\kappa^{\text{total}}_{yrp}$	Total capacity of a process p
$\kappa^{\text{con,exist}}_{yrs}$	Existing energetic capacity of a storage s
$\kappa^{\text{con,new}}_{yrs}$	New energetic capacity of a storage s
$\kappa^{\text{con,total}}_{yrs}$	Total energetic capacity of a storage s
$\kappa^{\text{pow,exist}}_{yrs}$	Existing charging/discharging capacity of a storage s
$\kappa^{\text{pow,new}}_{yrs}$	New charging/discharging capacity of a storage s
$\kappa^{\text{pow,total}}_{yrs}$	Total charging/discharging capacity of a storage s
$\pi^{\text{recv}}_{y(r'r)fct}$	Energy flow over a transmission f from r' to r, arriving r
$\pi^{\text{send}}_{y(rr')fct}$	Energy flow over a transmission f from r' to r, leaving r
τ_{yrpt}	Throughput of a process p (urbs)
θyrt	Voltage angle of a model region r (relevant for DC-OPF grid models)
ζ^{CO_2}	Total environmental costs
ζ_y	Total annualized system costs in year y
ζ^{fix}_y	Total fixed costs in year y
ζ^{fuel}_y	Total fuel costs in year y
ζ^{inv}_y	Total annualized investment costs in year y
ζ^{var}_y	Total variable costs in year y
$\zeta^{\text{CO}_2}_y$	Total environmental costs in year y

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