Renewable and Sustainable Energy Reviews 167 (2022) 112719

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Comparison methods of energy system frameworks, models and scenario results

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ARTICLE INFO

Keywords:
Energy system modeling
Comparison
Framework
Model
Scenario results

ABSTRACT

Energy system modeling has a central role in assessing the future energy system and helping policy makers to set targets and subsidizing mechanisms. In the years, different energy system models have been developed with the aim of supporting political decision-makers in the design of energy policies. It is relevant to compare and cross-validate these models in order to add robustness to the final results and technical feasibility of the identified transition pathways. Two main methods to compare these models exist i) comparison of the technical features and characteristics of the models and ii) comparison of the final results. While there are several reviews focusing on the comparison of models based on their technical characteristics and features, to the authors' knowledge, no review article exists on comparison techniques based on final results. The scope of this paper is to carry out a review of existing methods and techniques to compare energy system frameworks, models, and scenario results regarding their final results.

1. Introduction

Greenhouse gas (GHG) emissions are predominantly generated, at global level, by the energy sector. In particular, more than 75% of these emissions are produced by the energy system [1]. The IPCC report [2] from 2021 showed that it will only be possible to limit global temperature rise to 1.5 °C through ambitious emission reductions. Therefore, it is relevant to study the decarbonization of the future energy system and to support policy makers in identifying the best energy strategies. Energy system modeling is the discipline that pursues this goal by developing computer models to investigate the future alternatives of the energy system [3].

Increasing computing capabilities have resulted in a huge growth of the number of energy system models during the last 20 years. This also increased the number of published peer-reviewed articles presenting future scenarios and transition pathways for different case studies around the world. To adequately support policy makers, the robustness, transparency and reliability of these methods and their results need to be improved. This ensures the robustness to the technical feasibility of the analyzed scenarios and transition pathways. This is achieved through benchmarking and comparing of different assumptions, data sources, characteristics of the models, modeling suites, scenario building and final results.

The necessity of comparison exercises to add robustness to the findings in energy system modeling is certainly not new. It is demonstrated by the activities conducted by the Energy Modeling Forum (US) [4], China Energy Modeling Forum [5], Energy Modeling Platform for Europe (EMP-E) [6] and a recent European Horizon project which aims to create the European Energy and Climate Modeling Forum [7]. The latter has the aim to structure a joint modeling comparison exercise for the European energy system. In this context, it is also important to mention the Openmod initiative [8], which has collected the most relevant open-based energy system models and compared them based on their main characteristics and features.

The scope of this article is to identify through a review study the techniques used by researchers to compare energy system frameworks, models and scenario results. The term "model" is sometimes erroneously adopted in energy system modeling. Thus it is important to have in mind a clear and common definition for these three terms: frameworks, models and scenarios. An energy system framework is the set of mathematical equations written in a programming language that can be

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https://doi.org/10.1016/j.rser.2022.112719
Received 3 April 2022; Received in revised form 19 May 2022; Accepted 15 June 2022
Available online 8 July 2022

List of abbreviations

Acronyms

EMF Energy Modeling Forum
EMP-E Energy Modeling Platform for Europe
GHG Greenhouse gas
LCoE Levelized Cost of Electricity
OFV Objective Function Value
Openmod Open Energy Modeling
PCA Principal component analysis
US United States

Nomenclature

$Costs^{REF}$ System costs of reference model
$Costs_i$ System costs of model i
$GenerationMixError_i$ Indicator of the Generation mix error for model i
$GenerationShare_{i,k}$ Generation share of the source k in model i
$GenerationShare_k^{REF}$ Generation share of the source k in the reference model
$LCoE\ Deviation_i$ Indicator of the LCoE deviation for model i
$LCoE^{REF}$ LCoE of reference model
$LCoE_i$ LCoE of model i
$MisallocationMetric_{i,j}$ Misallocation metric indicator for the couple of models i and j
$OFV\ Deviation_i$ Indicator of the objective function value deviation for model i
OFV^{REF} Objective function value of reference model
OFV_i Objective function value of model i
OFV_j^i Objective function value with assumptions of the i case and lower bounds of the decision variables found solving OFV_0^i
OFV_0^i Objective function value with assumptions of the i case and no lower bounds for the decision variables of the expansion capacity optimization
$SystemCosts\ Deviation_i$ Indicator of the system cost deviation for model i
i Index which identify the generic model i
j Index which identify the generic model j different from model i
k Index which identify the generic generation source k

applied to different energy system case studies with different assumptions [9,10]. An energy system model is a specific application of a framework to a particular case study with specific assumptions [11]. A scenario result is intended to be the result of an energy system model run. In section 2 "Materials and methods" a more extended definition is provided.

While several review studies exist on the comparison of energy system frameworks based on their structural features and characteristics, none of these focuses on the comparison techniques of their final results. Van Beeck [12] (1999) compared 10 energy system frameworks based on the following characteristics: general and specific purpose, analytical approach, model structure, mathematical approach, underlying methodology, geographical coverage, sectoral coverage and time horizon. Worrell et al. [13] (2004) compared 15 different energy system frameworks on the implementation of the technology representation. The authors distinguish between explicit and stylistic technology representations. An explicit technology representation exists when the framework implements actual characteristics of individual technologies. A stylistic technology representation, on the other hand, prevails when the model captures the characteristics of a group of technologies. Mundaca et al. [14] (2010) analyzed and compared 12 energy system frameworks focusing on how these models include and implement energy efficiency of the household sector. Connolly et al. [15] (2010) presented a review of 37 different energy system frameworks focusing on the number of downloads, specific focus, and simulated renewable-energy penetrations. Hall et al. [16] (2016) compared 22 different energy system frameworks utilized in the United Kingdom based on different characteristics: model purpose, technological detail and mathematical detail. Lyden et al. [17] (2018) compared 13 different energy system frameworks based on characteristics of input data, supply technologies, design optimization, outputs, demand side management, storage and practical considerations. Ringkjøb et al. [18] (2018) compared 75 different energy system frameworks to support modelers in the process of selection of the proper tool. Gacitua et al. [19] (2018) presented a review of expansion planning models in which they compared different studies and frameworks based on the optimization methodology, programming technique, temporal resolution, included technologies and policy considerations. Savvidis et al. [20] (2019) analyzed 40 energy system frameworks and compared them using a classification scheme based on the following criteria: model-theoretic specifications, detail of modeling, market representation, and general information. Prina et al. [21] (2020) compared 22 different energy system frameworks focusing on the concept of resolution and identifying four resolution fields: resolution in time, space, techno-economic detail and sector-coupling.

The novel approach of the present research, focusing on comparison techniques instead of modeling frameworks themselves, will analyze the topic from a completely new perspective providing thus new insights and information.

The article has the following structure. Section 2 presents the definitions of frameworks, models and scenario results. In addition, the section highlights the main differences between these three categories and identifies the indicators and methodological approaches used in the literature to conduct comparisons within the three categories. Section 3 is divided in three sub-sections. The first sub-section presents the comparison techniques used to compare frameworks, the second part the techniques used for model comparisons, and the third part the techniques for scenario results comparisons. The final section summarizes insights from the review and provides conclusive remarks.

2. Materials and methods

At first, definitions for the terms framework, model and scenario result are presented. An energy system framework is a modeling environment to inspect the best future alternatives of the energy system from a techno-economic perspective. A framework is formulated in general terms and not reduced to a specific case, which allows replicability under different assumptions and input data [9,10]. Furthermore, frameworks are characterized by certain mathematical formulations and structural boundaries. In contrast, an energy system model is defined as a specific application of a framework to a particular case study under specific assumptions and system boundaries. It is characterized by defined input data, assumptions (such as the level of resolution in time, space, techno-economic detail and sector-coupling) and system boundaries [11]. A scenario is typically defined not only as model output, but also as the set of parameters and qualitative assumptions that influence model outcomes. Whereas, a scenario result in energy system modeling is the result of an energy system model run.

In a first stage, all literature on comparison of energy system modeling outputs has been collected. Afterward the categorization into (i) comparison of frameworks, (ii) comparison of models, (iii) comparison of scenario results has been identified. Moreover, the literature review has allowed for the identification and classification of the main approaches adopted in the existing comparison exercises and the main indicators used for the quantitative comparison.

Table 1 shows the main characteristics, differences and commonalities of the comparison techniques of energy system frameworks, models and scenario results. Keeping in mind the term model has been previously often and widely used in several meanings, the comparison of energy system frameworks corresponds to the formerly called inter-model comparison [22]. It is characterized by a pre-processing phase to harmonize the input data and the capabilities of the frameworks. The compared energy system frameworks differ in terms of the mathematical formulation implemented in each of them. The scope of this technique is: i) to examine the impact of the mathematical formulation on the final results and ii) to identify the commonalities and areas of disagreement between the final results. The stakeholders interested in the results of this comparison technique are both modelers and policy makers. Modelers are interested in both the impact of the mathematical formulation and the common findings and differences in the final results. Policy makers are more interested in the latter outcome.

The comparison of energy system models is formerly known as intra-model comparison [22]. It consists in the comparison of different model configurations developed starting from a unique framework. It is characterized by the highest level of harmonization, where both the input data and the mathematical formulation are harmonized. The mathematical formulation because it refers to the unique framework. The input data should be harmonized among the different models. In general, referring to the terminology of [22] intra-model comparisons are more straightforward than inter-model comparisons of frameworks because the different models of a unique framework share the same input data format. Moreover, the comparison of energy system models, formerly known as intra-model comparison, is usually adopted to examine the impact of different resolution levels on the final results. This is especially useful for modelers who need to understand the degree of approximation introduced by a certain simplification and the improvement in terms of computational effort.

Finally, the comparison of scenario results consists in the comparison of different results of energy system model runs, based on different frameworks and models. It is characterized by the lowest level of harmonization. The frameworks are different thus different mathematical formulations are taken into account. Additionally, the models are dissimilar as different input data, assumptions and levels of resolutions are included in the comparison analysis. The scope of this comparison technique is to identify the similarities and areas of disagreement between the final results obtained through different frameworks and models. The stakeholders interested in the results of this comparison technique are mainly the policy makers. Policy makers aim to identify the key findings of energy system modeling and add robustness to the technical feasibility of the identified pathways. Comparing scenario results obtained from different frameworks, models, assumptions, and sometimes also different case studies allow for the identification of the must-have and must-avoid of future energy systems [23].

Therefore, the comparison of frameworks (also known as inter-model comparison [22]) is the technique that requires the most effort in harmonizing inputs, since the structure of input data varies substantially between frameworks. The effort for models comparison (intra-model comparison [22]) is lower, due to the fact that these models are created starting from a unique framework and thus the structure of the input data is the same. In contrast, there is no effort for input harmonization regarding the technique of comparing scenario results as the results are based on different frameworks and models whose inputs are not harmonized.

Different approaches can be used within the comparison process. The main identified ones are the qualitative and the quantitative approaches. In the qualitative approach the comparison is based on the theoretical characteristics of each framework, model or scenario. For example comparing the mathematical formulation of different frameworks without actually running the different frameworks and analyzing the final results. In the quantitative approach, final results are compared against a set of indicators.

The quantitative comparison techniques used for frameworks, models and scenario results typically involve the use of multiple indicators to quantify and compare the outcomes obtained through the different methods. The analyzed literature have allowed the authors to collect several of these indicators that have been classified in different areas and categories in order to facilitate the analysis.

Table 2 shows the proposed classification. Four areas are identified: economy, energy, environment and computation. For each of these areas different indicator categories are listed. These can be further divided in two sub-groups: a) the indicators evaluating the deviation of the results and b) the direct comparison. Some examples of the indicators in category a) are reported in section 3.2. The category b) direct comparison is characterized by the simple comparison of indicators or outputs of the modeling process. Some examples for the sub-category ii) “costs” are the total system costs [22,24], the variable operational costs [25],

Table 2
Indicators for results comparison grouped in four areas and eleven categories.

Areas	Indicator category	a) Deviation	b) Direct comparison
Economy	Costs	i)	ii)
Energy	Generation and demand	iii)	iv)
	Installed capacities of generation sources	–	v)
	Installed capacities of storages and transmission units	–	vi)
	Curtailments and excess energy	–	vii)
	Hourly generation and storage profiles	–	viii)
Environment	CO_2 emissions	ix)	x)
Computation	Computational process indicators	–	xi)

Table 1
Comparison of energy system frameworks, models and scenario results: differences and commonalities.

Proposed definitions	Terminology previously used in [22]	Subject of the comparison	Harmonization degree of input data and mathematical formulation	What is the scope of the comparison?	Who could be interested in the results of the comparison?
Comparison of frameworks	Inter-models comparison	Different frameworks	Same input data (pre-processing phase of data) Different mathematical formulations	The impact of mathematical formulation, Commonalities and areas of disagreement	Modellers and policy makers
Comparison of models	Intra-models comparison	1 framework Different models	Same input data Same mathematical formulation	The impact of resolution	Modellers
Comparison of scenario results	–	Different scenario results obtained by different frameworks and different models	Different input data Different mathematical formulations	Commonalities and areas of disagreement	Policy makers

technology expansion costs [26]. Some examples for the sub-category iv) "generation and demand" are the annual electricity generation from different sources [27], the variable renewable energy (VRE) share [28], the electricity generation of dispatchable sources [25] or the change in sectoral electricity demand [29]. Some examples for the sub-category v)" installed capacities of generation sources" are VRE capacity [28], conventional power plant capacity [30], capacity expansion of peak load and based load power plants [26]. Some examples for the sub-category vi) "installed capacities of storages and transmission units" are storage capacity [31], storage expansion capacity and transmission grid expansion capacity [26]. Some examples for the sub-category vii) "curtailments and excess energy" are annual VRE curtailment [32], curtailment [24] and critical excess electricity production [33]. Some examples for the sub-category viii) "hourly generation and storage profiles" are the hourly mean of discharge and charge flows [30], hourly energy balances of the week with the highest residual load [30], hourly electricity generation and demand response load reduction [32]. The annual CO_2 emissions [29] is an example of indicator adopted in the sub-category x) "CO_2 emissions". Some examples for the sub-category xi) "computational process indicators" are the number of constraints, Wallclock time and used random-access memory (RAM) [11].

After reviewing the existing studies on the comparison of frameworks, models and scenario results, another type of comparison approach can be added. It is named "Quantitative Plus" and is applied when not only each result is compared against a set of indicators, but also the deviation of the results is further analyzed through statistical analysis, clustering, etc. This additional step is particularly relevant to understand the reasons why the deviations are originated and which common characteristics of the modeling approach, such as the mathematical formulation, the optimization approach etc., are the main causes of the deviations of the results. Statistical analysis provides valuable information on the nature of the deviations. Clustering techniques allow to identify groups of frameworks, models and scenario results that present similar deviations in the final results and determine the common characteristics that originate this similar behavior.

3. Results

This section presents the results of the review analysis on the comparison techniques for frameworks, models and scenario results. Each sub-section focuses on a different comparison technique, exploring the state of the art and main challenges.

3.1. Comparison of frameworks

Table 3 represents the reviewed studies on the comparison of energy system frameworks. It should be noted that the articles, with the exception of Lund et al. [27], are quite recent. The current interest of the articles highlights two main barriers to overcome for this comparison technique: i) the first barrier is the required collaborative approach between various institutions, as diverse frameworks are usually developed by different institutions; ii) a second barrier for studies exploring comparison of frameworks is the required harmonization of input data between multiple frameworks with different input data structures. Only recently have projects (such as the German Modex project [34] and an European H2020 project [7]) and modeling forums (US [4], China [5] and Europe [6]) started to address the topic of comparing energy system frameworks and publishing studies.

Lund et al. [27] in 2007 published a paper on the comparison of the

Table 3
Studies on comparison of energy system frameworks classified by publication year, number of compared frameworks, covered energy sectors, comparison approach, indicators used for the comparison of the results (defined in Table 2) and type of techniques adopted in the Quantitative Plus approach.

Authors	Ref.	Year	Number of compared frameworks	Covered energy sectors (electricity, heating, transport and industry)	Comparison approach: qualitative, quantitative, quantitative Plus	Indicators used for the comparison of the results		Quantitative Plus, which methods are used to further analyze the results?
						Areas	Indicator categories	
Lund et al.	[27]	2007	2	Electricity	Quantitative	Energy	iv)	
Bistline et al.	[29]	2018	16	Electricity	Quantitative Plus	Economy, Energy, Environment	iv), v), x)	Median and average of the results from different frameworks
Mai et al.	[28]	2018	3	Electricity	Quantitative	Energy, Environment	iv), v), x)	
Gils et al.	[25]	2019	4	All sectors	Quantitative	Economy, Energy	ii), iv), v), vi), x)	
Muschner	[11]	2020	2	Electricity	Quantitative	Computation	xi)	
Herc et al.	[33]	2021	2	All sectors	Quantitative	Energy, Environment	v), vii), x)	
Giarola et al.	[31]	2021	4	Electricity	Quantitative Plus	Energy, Environment	iv), vi), x)	Deviation of power generation
Misconel et al.	[30]	2022	3	Electricity	Quantitative	Energy, Environment	iv), v), vi), viii), x)	
Ruhnau et al.	[49]	2022	5	Electricity	Quantitative	Economy, Energy, Environment	ii), iv), x)	
Gils et al.	[32]	2022	9	All sectors	Quantitative Plus	Economy, Energy	ii), iv), v), vi), vii), viii)	Clustering analysis tool to identify systematic result deviations.
Ouwerkerk et al.	[26]	2022	6	Electricity	Quantitative	Energy	v), vi)	
Siala et al.	[22]	2022	5	Electricity	Quantitative	Economy, Energy, Environment	ii), iv), v), vi), x)	
Ouwerkerk et al.	[24]	2022	5	Electricity	Quantitative	Economy, Energy, Environment	ii), iv), v), vi), vii), x)	
Gils et al.	[73]	2022	8	All sectors	Quantitative Plus	Economy, Energy,	ii), iv), v), vi), vii)	Box plot, median, lower, upper quartiles and deviation ranges.

following two frameworks: EnergyPLAN [35,36] and H_2RES [37]. In order to compare the final results, this paper adopted a quantitative approach and used the direct comparison of electricity generation from different sources of the electricity system. Bistline et al. [29] in 2018 published the results of the comparison of 16 different frameworks. These results have been carried out within the project Energy Modeling Forum (EMF) 32 [38] from the Energy Modeling Forum (US) [4]. The authors not only compared final results using the direct comparison approach of costs, generation and demand, installed capacities of generation sources, and CO_2 emissions, but also calculated the median and average of the results from different frameworks for these indicators. This is a first example of how the comparison technique based on a quantitative approach can go a step further and evaluate the deviations between the results. As stated in section 2, this approach is defined as "Quantitative Plus" in this paper.

The majority of the reviewed studies concentrate, as the above mentioned two, on the comparison of energy system frameworks covering only the electricity sector. Mai et al. [28] present a comparison of three frameworks (NEMS [39], REGEN [40] and ReEDS [41]) concentrating on the electricity sector, using a quantitative approach based on the direct comparison of the following indicators: generation and demand, installed capacities of generation sources and CO_2 emissions. Muschner [11] compares the OSeMOSYS [42] and oemof [43,44] frameworks focusing on the electricity sector, using a quantitative approach based on the direct comparison of computational process indicators. Misconel et al. [30] compare three frameworks, ELTRAMOD [45], PowerACE [46], IDILES-JMM [47,48], applying them on the German power sector and using a quantitative approach for the outcomes comparison based on the direct comparison of the following indicators: generation and demand, installed capacities of generation sources, installed capacities of storage and transmission units, hourly generation and storage profiles, and CO_2 emissions. Ruhnau et al. [49] compare five electricity market models: PowerFlex [50], the Joint market model [51], SCOPE [52,53], EMMA [54] and the DIMENSION model [55]. The authors use a quantitative approach based on direct comparison of the following indicators: costs, generation and demand, CO_2 emissions. Ouwerkerk et al. [26] compare six power system frameworks (DIETER [56], E2M2 [57], GENESYS-MOD2 [58], ISAaR [59], oemof [43,44], REMix [60]) using a quantitative approach based on direct comparison of the following indicators: installed capacities of generation sources, storage and transmission units. Siala et al. [22] compare five power system frameworks using a quantitative approach based on direct comparison of the following indicators: system costs, generation and demand, installed capacities of generation sources, storage and transmission units, and CO_2 emissions. Giarola et al. [31] compare four energy system frameworks (GENeSYS-MOD [61], MUSE [62,63], NATEM [64], urbs-MX [65]) with a "quantitative Plus" approach. They adopt a direct comparison on generation, installed capacity of storage and CO_2 emissions. They also calculate the deviance on the power generation between the case with and without storage to evaluate the role of energy storage in the integration of renewable energy. Ouwerkerk et al. [24] compare five open source power system frameworks (Balmorel [66], GENESYS-2 [67], GENeSYS-MOD [58], oemof [43,44], and urbs [65]) with a quantitative approach based on direct comparison of the following indicators: system costs, generation and demand, installed capacities of generation sources, storage and transmission units, curtailments and excess energy and CO2 emissions.

The implementation of sector-coupling in energy system modeling is very important to investigate the synergies between different energy sectors and to exploit additional flexibility options as demonstrated in several studies [68,69]. Three of the studies reviewed on the topic of comparison of energy system frameworks consider sector-coupling. Gils et al. [25] consider all sectors and the case study of Germany in their framework comparison (four frameworks: REMix [60], PowerFlexEU [70], SCOPE [52,53], ELMOD [71]). The authors apply a quantitative approach based on direct comparison of the following indicators: system costs, generation and demand, installed capacities of generation sources, storage and transmission units, and CO_2 emissions. Herc et al. [33] also consider all sectors within their framework comparison between the H_2RES [37] and PLEXOS [72] frameworks. The authors use a comparison technique based on quantitative approach and direct comparison of the following indicators: installed capacities of generation sources and CO_2 emissions.

Gils et al. [32] present a comparison of nine frameworks considering sector-coupling and using a "Quantitative Plus" approach. The quantitative approach for the comparison is based on the direct comparison of the following indicators: system costs, generation and demand, installed capacities of generation sources, storage and transmission units, and hourly generation and storage profiles. The improvement in this specific framework comparison is achieved by developing a clustering analysis to identify systematic result deviations. The clustering algorithm takes the model results at the regional and indicator levels as input and groups them based on their similarities and differences. The approach is especially useful for comparing more than five frameworks. Gils et al. [73] compare eight open source power system frameworks considering sector-coupling (DIETER [56], E2M2 [57], GENESYS-2 [67], ISAaR [74], JMM [75], MarS [76], oemof [43,44], and REMix [60]) and using a quantitative plus approach. They adopt the direct comparison of indicators such as: system costs, generation and demand, installed capacities of generation sources, storage and transmission units, curtailments and excess energy. In addition, they apply simple statistic methods to evaluate the deviation of the final results, among the different frameworks, such as the box plots, median, lower, upper quartiles and deviation ranges.

From the studies reviewed, the following conclusions can be drawn:

a) The quantitative approach for frameworks comparison is the most commonly used.
b) The technique is typically based on the comparison of decision variables, energy generation mixes, CO_2 emissions, and costs. The comparison of hourly generation and storage profiles and the comparison of optimization process variables (computational time, number of constraints, number of objectives, number of variables, RAM use, etc.) are less frequently included in the comparison.
c) Most studies comparing frameworks focus on the Electricity sector, while few cover all sectors of the energy system.
d) The statistical analysis regarding deviations between the final results from different frameworks ("Quantitative Plus" approach) is very useful to better understand the outcomes, but is only possible if the sample of energy system frameworks is large enough. In fact, the studies using this approach are the ones with the highest number of frameworks considered within the comparison.

The research challenges, therefore, are to conduct comparisons of energy system frameworks using a large sample of frameworks, including sector-coupling and applying a "Quantitative Plus" approach. This approach should include not only a direct comparison of final outcomes using indicators of the four identified areas: economy, energy, environment and computation, but also the application of statistical techniques, clustering analysis to better understand the deviations between final results.

3.2. Comparison of models

This section presents the state of the art of the comparison techniques for energy system models and its main challenges. Table 4 shows the reviewed studies in chronological order and classifies them by case study, type of optimization and indicators used for the comparison of the results. Compared to the reviewed studies on the topic of comparison of frameworks, it can be noted that there exist a higher number of studies on the comparison of energy system models and that this research field has a longer tradition.

Table 4
Reviewed studies on comparison of energy system models classified by publication year, case study, type of optimization and indicators used for the comparison of the results (defined in Table 2).

Authors	Ref.	Year	Case study	Operational (O) vs operational and investment optimization (O&I)	Indicators used for the comparison of the results	
					Areas	Indicator categories
Palmintier et al.	[77]	2011	Electric Reliability Council of Texas (ERCOT)	O&I	Economy, Energy, Computation	i), iv), xi)
Haydt et al.	[78]	2011	Flores island (Azores)	O	Energy	iv)
Ludig et al.	[79]	2011	Eastern Germany and Hamburg	O&I	Energy	iv)
Pina et al.	[80]	2011	São Miguel (Azores, Portugal)	O&I	Energy	iv)
Kannan et Turton	[81]	2012	Switzerland	O&I	Economy, Energy	ii), iv)
Deana et al.	[82]	2012	Ireland	O	Energy	iv)
Nweke et al.	[83]	2013	South Australia	O&I	Economy, Energy	ii), v), vi)
Ommen et al.	[84]	2014	Eastern Denmark	O	Energy	iii)
Welsch et al.	[85]	2014	Ireland	O&I	Energy, Environment	iv), v), vi), ix)
Poncelet et al.	[86]	2016	Belgium	O	Energy	iii)
Trutnevyte	[87]	2016	United Kingdom	O&I	Economy	i)
Nahmmacher et al.	[88]	2016	EU-29	O&I	Economy, Energy	ii), iv)
Frew and Jacobson	[89]	2016	WECC regions (US)	O&I	Economy	i)
Pfenninger	[90]	2017	United Kingdom	O	Economy, Energy, Computation	i), iii), xi)
Kotzur et al.	[91]	2018	CHP system, Residential system, island system	O&I	Economy	i)
Kotzur et al.	[92]	2018	CHP system, Residential system, island system	O&I	Economy	i)
Brown et al.	[93]	2018	EU-30	O&I	Economy	ii)
Priesmann et al.	[94]	2019	Germany	O&I	Economy	i)
Diaz et al.	[95]	2019	Chile	O&I	Economy, Energy	ii), v), vi)
Teichgraeber and Brandt	[96]	2019	Battery and gas turbine application	O	Economy	i)
Siala and Mahfouz	[97]	2019	EU-28	O&I	Energy	v), vi)
Victoria et al.	[98]	2019	EU-30	O&I	Economy	ii)
Frysztacki and Brown	[99]	2020	Germany	O	Energy	vii)
Raventós	[100]	2020	German federal state of Schleswig-Holstein	O	Economy, Computation	i), xi)
Schyska et al.	[101]	2021	EU-30	O&I	Economy	i)
Mier and Azarova	[102]	2021	EU	O&I	Energy, Environment	iv), v), vi), x)

Fig. 1 shows the indicators used for the comparison of energy system models within the reviewed studies. It highlights that the most frequently used indicators belongs to the areas of economy and energy. Among the indicator categories, cost deviation is the most commonly used, followed by direct comparison of generation and demand, costs, installed capacities, and deviations in generation and demand as well as of direct comparison of computational process indicators. Less commonly used indicators include CO_2 emissions deviation, direct comparison of curtailments and excess energy, and direct comparison of CO_2 emissions.

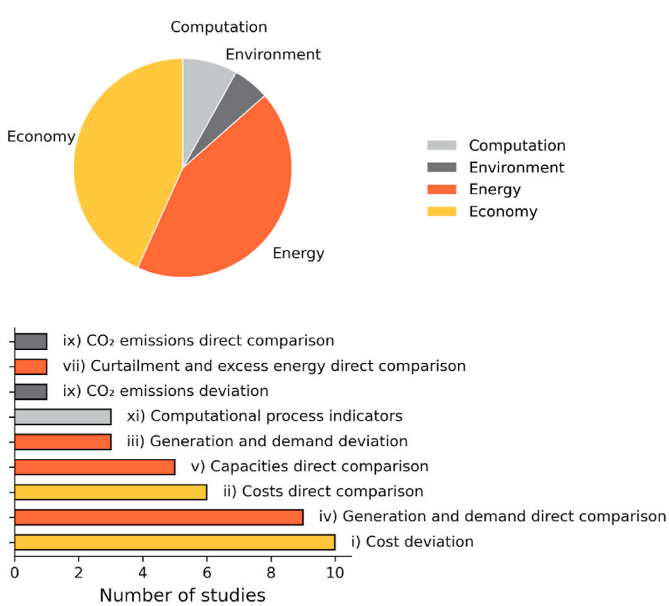

Fig. 1. Indicators used for the comparison of energy system models in the reviewed studies. The various indicator areas are highlighted at the top, and the indicators categories are presented at the bottom.

A list of indicators used in these studies to assess deviations (category a) Deviation) is provided to allow the readers to make appropriate choices according to their needs. The first indicators presented all fall under the category of cost deviation. Trutnevyte [87] applies the system cost deviation, which is shown in Eq. (1). Kotzur et al. [91] use the same indicator under the name cost share error, which is also described by Eq. (1). $Costs_i$ are the system costs of the model i, for which the $SystemCosts\ Deviation_i$ is calculated, and $Costs^{REF}$ are the system costs of a model taken as reference. Typically, the model with the highest temporal and spatial resolution, the highest degree of techno-economic detail and sector-coupling is chosen as the reference.

$$SystemCosts\ Deviation_i = \frac{|Costs_i - Costs^{REF}|}{Costs^{REF}} \tag{1}$$

Priesmann et al. [94] instead use a more general deviation in Objective Function Value (OFV), $OFV\ Deviation_i$ [%] (Eq. (2)), which is also called Objective Function Accuracy Loss by Frew and Jacobson [89]. In both cases, the OFV corresponds to the system cost and for this reason are both assigned to the cost deviation category.

$$OFV\ Deviation_i = \frac{|OFV_i - OFV^{REF}|}{OFV^{REF}} \tag{2}$$

Pfenninger [90] applies the deviation in Levelized Cost of Electricity

(LCoE), $\textbf{LCoE Deviation}_i$, defined as the percent deviation [%] from the reference model (Eq. (3)).

$$\textbf{LCoE Deviation}_i = \frac{|\textbf{LCoE}_i - \textbf{LCoE}^{REF}|}{\textbf{LCoE}^{REF}} \quad (3)$$

Schyska et al. [101] introduce a different approach: the misallocation metric (Eq. (4)), $\textbf{MisallocationMetric}_{i,j}$. In general, it is formulated by using the OFV. In Ref. [101], the authors use the system LCoE as the objective function and for this reason it is categorized as a cost deviation indicator. The innovative feature is that for the use of this indicator it is not necessary to define a reference model. This indicator can be applied in the context of comparing models characterized by the optimization of investment or expansion capacity.

$$\textbf{MisallocationMetric}_{i,j} = \frac{\Delta \textbf{OFV}^i + \Delta \textbf{OFV}^j}{2} \quad (4)$$

Where $\Delta \textbf{OFV}^i = \textbf{OFV}^i_j - \textbf{OFV}^i_0$

For instance, i indicates a model with certain assumptions (e.g. hourly resolution), j indicates a model with different assumptions (e.g. 2 h temporal resolution). $\textbf{OFV}^i_j$ is the objective function value with assumptions for case i and the lower bounds on the decision variables found when solving $\textbf{OFV}^i_0$. $\textbf{OFV}^i_0$ is the objective function value with assumptions for case i and no lower bounds for the expansion capacity optimization decision variables.

Another typology of deviation indicators is identified by the category generation and demand deviation. Poncelet et al. [86] propose the Generation Mix Error indicator (Eq. (5)) where $\textbf{GenerationMixError}_i$ is the indicator for model i. $GenerationShare_{i,k}$ is the generation share of the source k in model i. Whereas, $GenerationShare^{REF}_k$ is the generation share of the source k in the reference model.

$$\textbf{GenerationMixError}_i = \sum_k \frac{|\textbf{GenerationShare}_{i,k} - \textbf{GenerationShare}^{REF}_k|}{2} \quad (5)$$

In general, as mentioned in section 2, model comparisons are carried out to examine the impact of resolution on the final results. Prina et al. [21] identify four different fields of resolution in energy system modeling: resolution in time, in space, in techno-economic detail and sector coupling. In this article, the authors also propose a challenges scheme in which they distinguish three different levels of resolution for these four fields. Prina et al. [21] conclude that one of the main challenges in energy system modeling is to implement models with high resolution in these four fields simultaneously.

The evaluation of the approximations introduced by lowering the resolution in one of these four fields and the benefits of this action in terms of computational effort is a wide research field. Model comparisons are performed in most cases for this purpose. Table 5 shows the studies reviewed as part of the model comparison and, for each of these, the types of resolution fields that are dealt with and examined through the model comparison techniques. Table 5 also indicates if the adopted models within the comparison are based on an operational (O) or operational and investment optimization (O&I) approach. A model implementing an operational optimization approach aims to find the optimal way to operate the resources of the considered system. A model implementing an operational and investment optimization approach not only optimizes the use of resources over the year but also implements the expansion capacity optimization.

The temporal resolution depends on the chosen time-step which divides the simulation year, year matter of the analysis of the model. A low temporal resolution is characterized by a low number of different time-slices, usually in the order of 12, one per season and three per day (Day, night and peak). A high temporal resolution in energy system modeling is characterized by an hourly time-step. Spatial resolution depends on the number of different nodes in which is divided the energy system model. The resolution in techno-economic detail depends on the level of flexibility constraints and costs implemented in the energy system model. Some example of these constraints are flexibility requirements of conventional power plants such as ramp constraints, decay of efficiency at partial load and start-up costs. The resolution in sector coupling depends on the level of integration of different energy sectors in the model.

Table 5
Reviewed studies on comparison of energy system models classified by publication year, type of optimization and resolution fields examined in the analysis.

Authors	Ref.	Year	Operational (O) vs operational and investment optimization (O&I)	Resolution in time	Resolution in space	Resolution in techno-economic detail	Resolution in sector coupling
Palmintier et al.	[77]	2011	O&I	–	–	X	–
Haydt et al.	[78]	2011	O	X	–	–	–
Ludig et al.	[79]	2011	O&I	X	–	–	–
Pina et al.	[80]	2011	O&I	X	–	–	–
Kannan et Turton	[81]	2012	O&I	X	–	–	–
Deana et al.	[82]	2012	O	X	–	X	–
Nweke et al.	[83]	2013	O&I	–	–	X	–
Ommen et al.	[84]	2014	O	–	–	X	–
Welsch et al.	[85]	2014	O&I	X	–	X	–
Poncelet et al.	[86]	2016	O	X	–	X	–
Trutnevyte	[87]	2016	O&I	–	–	–	–
Nahmmacher et al.	[88]	2016	O&I	X	–	–	–
Frew and Jacobson	[89]	2016	O&I	X	X	–	–
Pfenninger	[90]	2017	O	X	–	–	–
Kotzur et al.	[91]	2018	O&I	X	–	–	–
Kotzur et al.	[92]	2018	O&I	X	–	–	–
Brown et al.	[93]	2018	O&I	–	X	–	X
Priesmann et al.	[94]	2019	O&I	X	X	X	–
Diaz et al.	[95]	2019	O&I	X	–	X	–
Teichgraeber and Brandt	[96]	2019	O	X	–	–	–
Siala and Mahfouz	[97]	2019	O&I	–	X	–	–
Victoria et al.	[98]	2019	O&I	–	–	–	X
Frysztacki and Brown	[99]	2020	O	–	X	–	–
Raventós	[100]	2020	O	X	–	–	–
Schyska et al.	[101]	2021	O&I	X	X	–	–
Mier and Azarova	[102]	2021	O&I	X	X	–	–

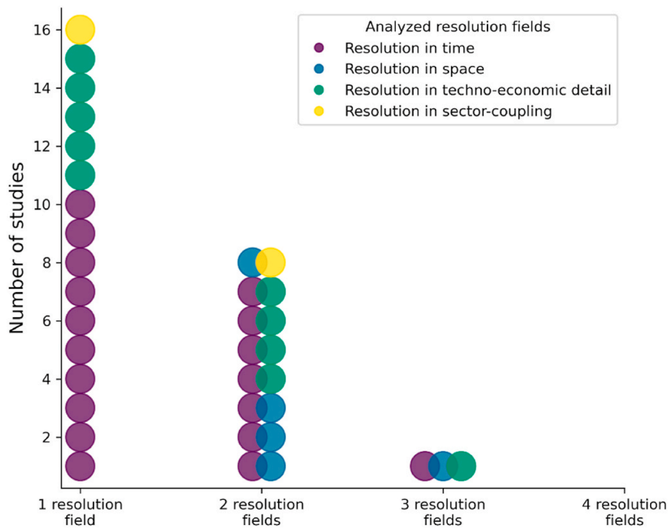

Fig. 2. Resolution fields analyzed in the reviewed studies.

This is particularly important to exploit the synergies and flexibility options given by the coupling of different sectors such as electricity, gas, heat, transport and industry. For a better understanding and characterization of the four resolution fields in the energy system modeling research field please refer to Prina et al. [21].

The following Fig. 2 shows the resolution fields analyzed in the reviewed studies. 16 different studies focus on one single resolution field. The majority of these focuses on the resolution in time, five on the resolution in techno-economic detail and one on the resolution in sector-coupling. Eight studies concentrate on two resolution fields. Three focus on the resolution in time and the resolution in space, four on the resolution in time and resolution in techno-economic detail and only one study analyzes the impact of different resolutions in space and sector-coupling. Only one study examines three resolution fields and their impact on final results. No one consider all the four resolution fields when comparing energy system models.

Therefore, one challenge in models comparison is to analyze all four resolution fields simultaneously. This would require the comparison of a model with a simultaneous high resolution in all these four fields with different models which lower the resolution in one or more than one of these fields. The aim is to evaluate the accuracy and computational burden of each of these models. The main challenge of producing an analysis of this type is connected to the complexity of a model with simultaneous high resolution in all these four fields. However, considering the four resolution fields and evaluating the consequences of reducing resolution for each of them in terms of the approximations introduced and the computational benefits would be very relevant to the research field. This would provide a better understanding of what priorities modelers should give to different resolution fields to maximize accuracy at a reasonable computational effort.

3.3. Comparison of scenario results

This section presents the state of the art of the comparison techniques for energy system scenario results and its main challenges. Table 6 shows the reviewed studies regarding the comparison of energy system scenario results classified by publication year, case study, number of scenarios analyzed, energy sectors covered, comparison approach, and indicator methods used in the "Quantitative Plus" approach. The number of scenario results analyzed varies widely, ranging from 4 to 405. It should be noted that, in contrast to the comparison of frameworks, the number of items to be compared can increase significantly. This is

Table 6
Reviewed studies on comparison of energy system scenario results classified by publication year, case study, number of scenarios analyzed, covered energy sectors, comparison approach, indicators methods used in the Quantitative Plus approach.

Authors	Ref.	Year	Case study	Number of analyzed scenarios	Covered energy sectors (Electricity, heating, transport and industry)	Comparison approach: qualitative, quantitative, quantitative Plus	Indicators used in the quantitative comparison	Quantitative Plus, which methods are used to further analyze the results?
Keles et al.	[108]	2011	Germany	4	Electricity	Quantitative	iv), x)	–
Reedman	[109]	2012	Australia	23	Electricity	Quantitative	iv), v)	–
Schmid et al.	[110]	2013	Germany	10	Electricity	Quantitative	ii), iv), v)	–
Cochran et al.	[111]	2014	Different countries with high levels of renewables	12	Electricity	Quantitative	iv)	–
Densing et al.	[104]	2016	Switzerland	29	Electricity	Quantitative Plus	iv)	Principal component analysis (PCA), distance measure (squared Euclidian distance)
Lunz et al.	[105]	2016	Germany	9	Electricity	Quantitative Plus	iv), v)	Residual load curve re-calculation
Cebulla et al.	[106]	2018	US, Europe, Germany	405	Electricity	Quantitative Plus	iv), v), vi)	Linear interpolation
Deason	[112]	2018	Different countries with high levels of renewables	15	Electricity	Quantitative	v), vi)	–
Ruhnau et al.	[113]	2019	Germany	22	Electricity	Quantitative	iv)	–
Candas et al.	[114]	2019	15 EU countries	126	Electricity	Quantitative	iv)	–
Georgios et al.	[115]	2020	Switzerland	82	Electricity	Quantitative	iv)	–
Naegler et al.	[103]	2021	Germany	26	All sectors	Quantitative	iv), v)	–
Thimet et al.	[107]	2022	Switzerland, Germany, France and Italy	171	Electricity	Quantitative Plus	iv)	Median, 25th and 75th percentiles for electricity generation from gas, solar and wind power, Electric demand deviation

mainly due to the lower effort in harmonizing input data and modeling features. The majority of the studies concentrates on the electricity sector. Only Naegler et al. [103] extend the analysis considering scenarios with sector-coupling for Germany.

Most of the studies reviewed utilize a quantitative approach. The most commonly used indicators are from the energy area: direct comparison of generation and demand, direct comparison of installed capacities of generation sources, and storages and transmission units. Less utilized are indicators with regard to the area economy and environment.

Four studies conduct a “Quantitative Plus” approach. Densing et al. [104] use principal component analysis (PCA), a dimension reduction technique that captures the variability of a given result across different scenarios and approximates it with lower dimensions. After this first phase, the authors use the squared Euclidian distance to evaluate the deviation between scenario results. Lunz et al. [105] adopt an algorithm to re-calculate the residual load and the generation sources to cover it. Thus, the scenarios are harmonized towards the same CO_2 emission reduction. Cebulla et al. [106] evaluate the impact of power mixes on electrical energy storage power capacity [GW] and energy capacity [GWh] by comparing scenarios. The authors use linear interpolation techniques to determine storage requirements in scenarios with a particular dominance of photovoltaic or wind power. Thimet et al. [107] review power sector scenarios for Switzerland, Germany, France and Italy. They compare the scenarios for electricity generation from different sources and demand. The authors also apply different statistical techniques to evaluate the deviations between the final results. Thimet et al. use the median, lower, upper quartiles to capture the deviations in the results on future electricity generation from gas, solar and wind power. Additionally, they assess the differences of the electricity demand as a percentage deviation from the 2019 reference value for each selected country.

4. Conclusions

This article reviews the techniques used by researchers to compare energy system frameworks, models, and scenario results.

The comparison of energy system frameworks is the technique that requires the largest effort in terms of harmonizing input data. Further, the comparison of energy system frameworks is used to examine the impact of the mathematical formulation on the final results and to identify the commonalities and dissimilarities among the final results. For this reason, it is of interest for both modelers and policy makers.

The comparison of energy system models is used to investigate the impact of different levels of resolution on final results. This is particularly useful for modelers who need to understand the degree of approximation introduced by a certain simplification and the improvement in terms of computational effort.

In contrast, the comparison of energy system scenarios is used to identify the commonalities and areas of disagreement on the final results, which is mainly of interest for policy makers.

Different approaches can be used as part of the comparison process. The qualitative, quantitative and a third identified approach, which is called “Quantitative Plus” in this study. In the qualitative approach the comparison is based on the theoretical characteristics of each framework, model or scenario. The quantitative approach is used when comparing the final results based on a set of different indicators that quantify some results of the modeling. The “Quantitative Plus” approach is applied when not only is each result compared against a set of indicators, as in the quantitative approach, but also the deviation between results is further examined through statistical analysis.

The literature review have allowed the authors to collect several indicators adopted in the quantitative approach. These have been classified in different areas and categories in order to facilitate the analysis within this article. Four areas and eleven indicator categories have been identified. These categories can be divided in two sub-groups (i) deviation between final results and (ii) direct comparison of final results. The identified areas are economy, energy, environment and computation.

The comparison of frameworks shows the following results: the quantitative approach is the most commonly used and is usually based on the comparison of decision variables, energy generation mixes, CO_2 emissions and costs. Most studies deal with frameworks’ comparisons that focus on the electricity sector, while few cover all sectors of the energy system. The statistical analysis on the deviations between the final results of the different frameworks (“Quantitative Plus” approach) is very useful to better understand the final results but it is only possible if the sample of energy system frameworks is large enough.

The challenges of the frameworks’ comparison research field are therefore to conduct comparisons of energy system frameworks using a large sample of frameworks, including sector-coupling and applying a “Quantitative Plus” approach. This approach should include not only a direct comparison of final results using indicators for the four identified areas of economy, energy, environment and computation, but also the use of statistical techniques, clustering analyzes to better understand the deviations between the final results and the reasons why the deviations are originated.

The comparison of models has highlighted that the most frequently used indicators belongs to the economy and energy areas. Among the indicators categories, cost deviations are most commonly applied, followed by direct comparison of generation and demand, direct comparison of costs and capacities, generation and demand deviations, and computational process indicators. The comparison of models is mostly performed to test a certain resolution (usually the temporal resolution is tested). However, there is no study that examines the four resolution fields (temporal and spatial resolution, techno-economic detail, and sector-coupling) simultaneously. Considering all the four resolution fields and evaluating for each of them the consequences of reducing resolution in terms of the approximations introduced and the computational benefits would be very relevant to the research field. Moreover, this would provide a better understanding of what priorities modelers should give to different resolution fields to maximize accuracy at a reasonable computational effort.

By comparing scenario results, a higher number of compared results can be achieved. This is mainly due to the fact that no harmonization of input data or mathematical formulations is required. Therefore, there are more possibilities for statistical analysis of the deviations between the final results.

This article has highlighted the main current challenges of the comparison of framework, models and scenario results in energy system modeling. Addressing these challenges would increase the robustness, transparency and reliability of the developed scenarios and transition pathways and allow modelers to better support policy makers. Therefore, addressing these challenges would result in a more robust evidence of the must haves and must avoids technologies relevant for the development of near-term and long-term energy policies.

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.

Acknowledgements

The authors thank the Department of Innovation, Research and University of the Autonomous Province of Bozen/Bolzano for covering the Open Access publication costs.

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