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Review

Considering Socio-Technical Parameters in Energy System Models—The Current Status and Next Steps

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Abstract: The energy transition is a complex development towards a climate-neutral, economic, safe, and fair energy system. Therefore, numerical energy system models, among others, can make a significant contribution by simulating, optimizing and thus demonstrating possible transition pathways. Representative models and forecasting tools are needed to illustrate the next necessary steps and measures for the various target groups. In the literature, such energy system models have been studied and evaluated many times. This paper presents the approaches of previous reviews and analyses of how technical, economic, and social aspects of energy system models have been investigated so far. It is shown that especially recent studies already address this topic, but still receive insufficient recognition. Besides the general structural features, the technical modeling details were evaluated in the previous literature. Thereby, a part of the examined general reviews assesses the representation of consumer behavior in the models as a representative for social system aspects. Only a minor amount of the energy system models analyzed there per se represent consumer behavior. Furthermore, this article identifies possible linking strategies of social science parameters and energy system models from the literature based on their opportunities and challenges. This analysis forms a basis on which the already established majority of techno-economic energy system models can be extended in order to provide a more holistic view of the energy system. To do so, further research and development to improve future interdisciplinary processes are required.

Keywords: energy system modeling; socio-technical energy transition; renewable energy; review

Citation: Liegl, T.; Schramm, S.; Kuhn, P.; Hamacher, T. Considering Socio-Technical Parameters in Energy System Models—The Current Status and Next Steps. *Energies* **2023**, *16*, 7020. https://doi.org/10.3390/en16207020

Academic Editors: Fabrizio Zuccari, Adriano Santiangeli and Fabio Orecchini

Received: 31 August 2023
Revised: 28 September 2023
Accepted: 7 October 2023
Published: 10 October 2023

1. Introduction

The advance of climate change demands a rapid decarbonization of energy production and the rational use of energy. In order to successfully implement the energy transition, strategic planning of measures in different levels of the energy systems is necessary. The substantial transformation towards a more decentralized and renewable energy system requires not only the acceptance of technical developments, but also the active participation of the population in the process of change. Modeling and simulation tools play an important role in this process: On the one hand, technically detailed models can be used to investigate, for example, the integration of renewable power plants into the grid. On the other hand, the simulation of future energy systems can also support energy policy decisions. There are many tools for the different requirements of various energy systems and their stakeholders. The results of these investigations are currently mainly used for technical questions and address experts or scientists. In recent years, a large number of review papers have already been published on current energy system models, their application, and other technical issues as shown in several reviews. The reviews provide a quick and targeted overview of the existing models and their evaluation. So far, there is no overview of the existing reviews concerning their evaluation methods.

What criteria do the reviews use to evaluate the models? In addition to structural quality and technical features, are the scope of societal parameters in energy system models also analyzed? After all, these characteristics are becoming increasingly relevant regarding the social complexity of the energy system transition and should be considered [1]. Therefore, this paper presents and investigates reviews focused on energy system models and analyzes which criteria are used for evaluation. In this context, multi-energy systems are characterized by the fact that different sectors such as electricity, heat, transport, etc., interact at different levels, which can also be represented in models [2].

The energy system models analyzed in the reviews will be shown as well. With this knowledge, possible further steps in this research area should also be concluded. Possible linking strategies of these social parameters and energy system models from the literature are shown and assessed based on their opportunities and challenges.

2. Method and Analyzed Reviews

For the literature search, reviews from the last years were searched for by using relevant keywords in Scopus (https://www.scopus.com/, accessed on 18 September 2023) in the period June to September 2023. The aim of the search was to find reviews of publications on the modeling of multi-energy systems in which the general characteristics of energy systems are analyzed. The selection of keywords in Scopus was based on thematic categories. The keywords were chosen according to the exclusion procedure in order to obtain the broadest possible base set of reviews on energy system models: TITLE (energy AND system $ AND (tool * OR model *)) AND TITLE-ABS-KEY (review OR overview OR analysis AND energy PRE/1 system$) AND (LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (SUBJAREA, "ENER")).

That means that technology specific reviews, for example for energy storage system models or wind energy systems were intentionally left out of the search. In addition, papers concerning energy system models which only consider a part of a multi-energy system, such as building models or off-grid energy systems, were not considered by suitable keywords. Especially recent publications analyze energy systems (models) in the context of artificial intelligence or machine learning. These topics are more concerned with a new approach for finding technical solutions, and hardly make any new contributions in terms of the focused content here: TITLE (. . .AND NOT storage AND NOT building AND NOT thermal AND NOT solar AND NOT wind AND NOT bio * AND NOT gas AND NOT hydrogen AND NOT off grid AND NOT artificial AND NOT machine).

Using these keywords, a basic total quantity of 96 publications in the field of energy system modeling could be found (last update 18 September 2023). As the literature search shows, there is already a large volume of multi-energy system model reviews with different focuses. The following figure shows the publication years of the reviews. It is remarkable that the number of publications under the given keywords has increased significantly, see Figure 1. Last year, 2022, the number of publications in this field was the highest.

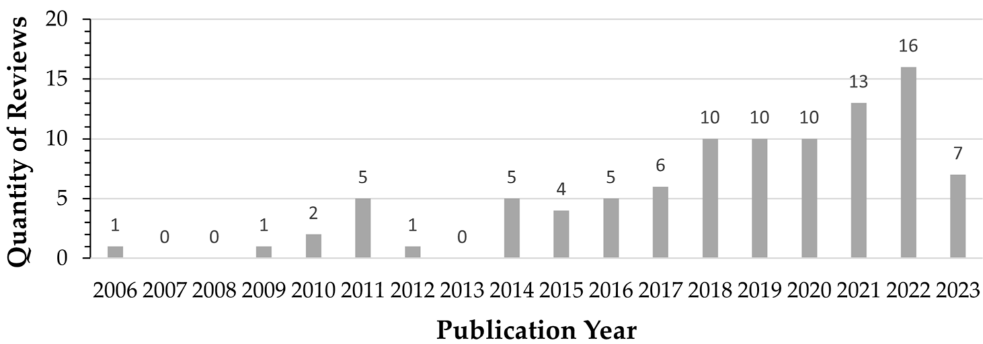

Figure 1. Overview of the publication year of the reviews found in the literature search.

To further limit the number of reviews for the research questions posed here, the relevance of the reviews is assumed based on their citation. Specifically, the citation per year is crucial in order to reflect the relevance of recent publications more effectively. Figure 2 shows all reviews found sorted by citation per year.

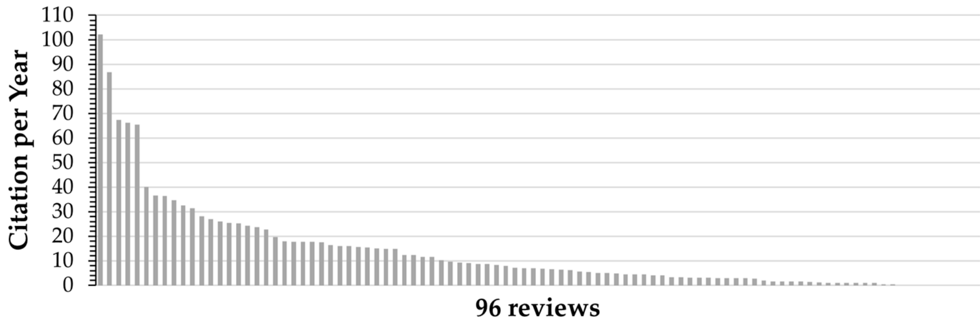

Figure 2. Overview of citation per year of the reviews found in the literature search.

In average, the papers are cited 13.5 times per year. This threshold is chosen to further select the reviews for a more detailed analysis. This leaves 33 papers with high citations per year, with a brief summary of their content below, and an evaluation of their thematic relevance to the research question pursued here. Despite careful selection of keywords, the publications that are thematically distant are sorted out below.

Mancarella [2] rather gives an overview of the assessment criteria of multi-energy systems and thus addresses the characteristics of energy system models with a focus on energy, environmental, and techno-economic viewpoints. For this purpose, multi-energy systems as well as modeling and aggregation concepts are first explained in detail. As an example, 4 energy system models are then analyzed based on 14 (here summarized to 5) assessment criteria. The review by Connoly et al. [3] analyzes 37 different computer tools with 9 evaluation criteria to support the identification of suitable energy system models for various applications. After a tabular overview, the models are described individually in the review. For a better detailed information about the models, the tool developers were interviewed based on a survey. Sinha and Chandel [4] also has a high citation per year and focus on the evaluation of hybrid energy system models. A total of 19 software tools and models are presented individually, and their input and output parameters are summarized schematically. They are then analyzed based on 5 evaluation criteria, and subsequently the advantages and disadvantages are elaborated. In the paper by Ringkjøb et al. [5], a detailed overview of 75 energy system models is given, which should support the selection of a suitable model. For this purpose, 17 different criteria are used to evaluate this broad spectrum of modeling tools. The results are clearly presented in tabular and schematic form. The review by Pfenninger et al. [6] is frequently cited and deals with challenges and paradigms of energy system modeling. For their review, they used several analyses of energy system models with different emphases to identify these challenges. In doing so, they evaluated 14 models, divided them into 4 groups based on the challenges they address: time and space, uncertainty and transparency, complexity, and human behavior and social risks [6]. Allegrini et al. [7] reviews the modeling approaches for district-scale energy systems and therefore presents a capability matrix with 17 criteria and 24 different cross-interdisciplinary energy system models. The review considers building-specific models in addition to classical energy system models and has a strong focus on the technical details in the assessment of the models.

The review by Beaudin and Zareipour [8] found in the literature search does not fit thematically into the questions of this paper, as it deals with home energy management systems and their modeling approaches. In addition Keirstead et al. [9] focuses on studies for urban energy systems and addresses different categories of models: Technology design, Building design, Urban climate, System design, and Policy assessment The broad review analyzes 219 studies, but the models used there are not discussed in detail. The work of Deng and Lv [10] gives a sound overview of techno-economic parameters used in integrated planning models and focus on studies for power sector planning. However, the comparison aimed here is to include reviews for multi-energy systems models that can represent the complex energy system with multiple energy sectors. Zendehboudi et al. [11] on the other hand, show the applications of hybrid models in chemical, oil, and gas processes. While they relate the methods of hybrid models to technical components used in energy systems, they do not evaluate energy system models per se.

Prina et al. [12] categorize 22 energy system models according to their approach and model horizon and analyze bottom-up models based on 5 criteria and therefore provide a new classification scheme. They also identify challenges based on model resolution (time, space, techno-economic, and energy). DeCarolis et al. [13] fits well into the topic of energy system modeling, but is specifically concerned with the application of energy system models. Clear recommendations (guiding principles) and key steps for the application are given in the review. There is no discussion of individual energy system models. Loipon et al. [14], in contrast, focuses on 24 national energy system models that include all energy sectors as well support governmental decision making processes. After a preselection, these are characterized and quantitatively evaluated on the basis of 9 features. Additionally, revealed trends in modeling are set in the context of current energy system modeling challenges [14]. In their review Manfren et al. [15] are looking for suitable tools for distributed generation projects with a focus on urban energy systems and identify different viewpoints of the paradigm shift at the community level of energy systems. They examine a total of 14 models on the basis of 7 evaluation criteria and then present a new optimization methodology and a computational framework. Klemm and Vennemann [16] provide an overview of the characteristics of energy system models and focus on modeling tools for mixed-use districts. In their analysis, they evaluate 13 of the 145 tools (after preselection) in more detail on the basis of 12 assessment criteria.

Collins et al. [17] also deal with energy system modeling in their work. Thereby, methods for the integration of power supply models into integrated energy system models are analyzed, as well as their strengths, limitations, and applicability. The individual models are not evaluated, but the authors distinguish between operational power system models, long-term energy system optimization models, and integrated assessment models, and list representatives of each category. The simplifications in the temporal, spatial, and technical details of the previous power system models are also briefly explained [17]. The review on numerical modeling of wave energy converters by Windt et al. [18] is an overview of technology-specific computational fluid dynamics. Despite suitable keywords in Scopus, it does not fit thematically into this work. Bazmi and Zahedi [19] comprehensively reviewed the literature on the developments in the power sector at the state of the art at the time, focusing on the power sector. The relevance of system modeling is also emphasized as key to system optimization and policy decisions. However, a model evaluation is not carried out in the process. Similarly, the next review by Hoffmann et al. [20] focuses on the methods of time aggregation of energy system models. In the paper, various possible evaluation criteria for energy system models are mentioned only briefly, but then time aggregation is deliberately discussed in depth. In addition, the mentioned models are not evaluated in general. The review of Uslar et al. [21] provides an overview of the Smart Grid Architecture Model approach used for System-of-Systems in the energy domain. Since a specific model approach is explained here using application examples, this paper is also not suitable for the issue of multi-energy system models here.

In Fattahi et al. [22], a total of 19 integrated energy system models (ESMs) are analyzed and evaluated using 8 weighted key criteria in a multi-criteria analysis. In addition, they identify 7 current and future challenges in modeling low-carbon energy systems, including the role of social behavior in the energy system transition. Mendes et al. [23] investigate available tools for Integrated Community Energy Systems as a combination of Integrated Energy Systems and Community Microgrids. In total, 6 energy models are considered based on 8 evaluation criteria. The review also provides a SWOT analysis of the analyzed tools. Liu et al. [24] explicitly analyze model frameworks for isolated areas based on 4 evaluation criteria in addition to classical energy system models. In addition, they elaborate the taxonomy of forecasting methods and address the application of the models in case studies for isolated areas. Similar to Beaudin and Zareipour [8], Ibrahim and Jiang [25] are investigating energy management systems instead of energy system models—here for electric vehicles. They explain in detail the energy system in electric vehicles and batteries. Weinand et al. [26] rather investigates the application of energy system models. In detail, 123 case studies on decentralized autonomous energy systems are analyzed and evaluated in terms of methodology and application. Most papers used the HOMER [27] model for their studies.

The work of Fodstad et al. [28] analyzes the current challenges and uses 5 of them to characterize well-established modeling frameworks, with a total of 13. In addition to the usual evaluation criteria, it also deals with the modeling of energy behavior and draws attention to the fact that there is more than one approach to integrate models with the impact of energy policy. Ahmadi et al. [29] looks at energy systems in terms of their resilience and compares existing literature and modeling approaches on this subject. Kotzur et al. [30] investigates the increasing complexity of energy system models in their review and derive reduction strategies. Although the review evaluates some general model properties and their impact on the complexity of energy system models, the actual models are only listed according to their type and application. Bolwig et al. [31] addresses the question of how quantitative modeling of energy scenarios for sustainable energy transition paths can be made more realistic by integrating insights from sociotechnical research. He does not evaluate existing classical energy system models but puts the sociotechnical insights in context with the system dynamic modeling approach. This recent publication shows that there are already considerations to incorporate sociotechnical insights into models in addition to classical energy system models. Groissböck [32] on the other hand, compares other reviews and focuses especially on the technological details of the energy system models such as type of electricity flow or consideration of reserve margin. In the process, 31 mostly open-source tools are analyzed for their degree of maturity based on 81 detailed functions. Included in the Scopus hits is the paper by Palzer and Henning [33], which does not fit into the review category since it provides a detailed description of the modeling of the German energy system using the REMOD model. Bhattacharyya and Timilsina [34] at least give a comparative overview of energy system models and focus on the application in developing countries. A total of 10 energy system models are evaluated using 14 criteria. Modeling of societal characteristics such as the rural urban divide and economic transition are also evaluated in the process.

As shown by the manual sorting and summarizing of the reviews, several studies are not directly relevant to the question discussed here. Table 1 summarizes the relevant reviews concerning multi-energy system models investigated here. In summary, it should be emphasized that most of the reviews to be analyzed here examine energy system models in considerable detail with clearly defined evaluation criteria. These reviews analyze energy system models that consider multiple energy sectors. On average, 21 models are examined in a review, with Ringkjøb et al. [5] representing the broadest examination with 75 models. In addition to classifying and evaluating energy system models, some reviews also provide an overview of the current challenges of energy system models and how the individual models address these; see Refs. [5,6,12,16,22,28]. The challenges of the energy system models identified in the reviews have already been pointed out by Fodstad et al. [28]. The most frequently mentioned challenges are time and space, uncertainty, multi-energy (i.e., mapping of different energy sectors), energy behavior and energy transition (consideration of consumer), and transparency [28]. This result also highlights the hypothesis of this paper.

Table 1. Overview of the analyzed energy system model reviews.

Ref.	Authors	Title	Year	Citation per Year	Models Analyzed
[2]	Mancarella	MES (multi-energy systems): An overview of concepts and evaluation models	2014	102.3	4
[3]	Connolly et al.	A review of computer tools for analysing the integration of renewable energy into various energy systems	2010	86.9	37
[4]	Sinha and Chandel	Review of software tools for hybrid renewable energy systems	2014	67.5	19
[5]	Ringkjøb et al.	A review of modelling tools for energy and electricity systems with large shares of variable renewables	2018	66.3	75
[6]	Pfenninger et al.	Energy systems modeling for twenty-first century energy challenges	2014	65.4	14
[7]	Allegrini et. al.	A review of modelling approaches and tools for the simulation of district-scale energy systems	2015	40.0	24
[12]	Prina et al.	Classification and challenges of bottom-up energy system models—A review	2020	31.5	22
[14]	Lopion et al.	A review of current challenges and trends in energy systems modeling	2018	26.0	24
[15]	Manfren et al.	Paradigm shift in urban energy systems through distributed generation: Methods and models	2011	25.5	14
[16]	Klemm and Vennemann	Modeling and optimization of multi-energy systems in mixed-use districts: A review of existing methods and approaches	2021	25.3	13
[22]	Fattahi et al.	A systemic approach to analyze integrated energy system modeling tools: A review of national models	2020	17.8	19
[23]	Mendes et al.	On the planning and analysis of Integrated Community Energy Systems: A review and survey of available tools	2011	17.7	6
[24]	Liu et al.	Modeling, planning, application and management of energy systems for isolated areas: A review	2018	17.5	12
[28]	M. Fodstad et al.	Next frontiers in energy system modelling: A review on challenges and the state of the art	2022	16.0	13
[32]	Groissböck	Are open-source energy system optimization tools mature enough for serious use?	2019	15.0	31
[34]	Bhattacharyya and Timilsina	A review of energy system models	2011	14.8	10

Among the 96 reviews were also recent papers, which have significantly lower citations per year, but are thematically relevant to the social aspects in energy system modeling.

McGookin et al. [35] focus on participatory methods in energy system modeling and throughout the planning process. They emphasize the advantages of participatory methods: the legitimacy and robustness of results, mutual learning about the complex system and consensus, and shared solutions. The researchers highlight the limitations of the energy system models in terms of societal implications [35]. Moreover, Vågerö and Zeyringer [36] describe energy system models in the context of energy justice. They investigate different dimensions of equity and their representation in energy system models. In addition, their review (published 2023) shows that the consideration of societal aspects such as participation is gaining more and more attention in energy systems that have so far been optimized from a technical and economic point of view. Infrequently cited is the review by Huckebrink and Bertsch [37], published in 2021, which focuses on the behavioral aspects in energy system models. In addition to evaluating energy system models, challenges to better integrate acceptance and consumer behavior will be discussed in detail.

In addition, further reviews that are not encountered in the literature search due to the keywords are briefly explained here. Another review has already addressed the question of how social aspects are taken into account in energy system models: the consideration of social parameters in energy system models. On the one hand, the study by Krumm et al. [38] merge different social aspects and the presented linking strategies as three steps in the modeling process: storyline, scenario, and input parameter; optimization/simulation process; and discussion of the model output [38]. On the other hand, the representation of different social aspects in different model types in these process steps is shown by Ref. [38] through examples. Cuesta et al. [39] give a great overview of the technical, economic, and social inputs and outputs of hybrid renewable energy models and finds that so far the social indicator has not been given much consideration. According to the review, this represents a great opportunity for future developments.

3. Evaluation Criteria of the Energy System Models

In order to gain an overview of how energy system models work, the following will firstly show how the models are analyzed and evaluated. On the other hand, the found assessment criteria are evaluated and discussed. The focus of this paper lays on the question of whether the evaluated models consider all relevant parameters, dimensions, and thus factors of the energy system—technical, economic, ecological and social. The different reviews have used a variety of evaluation criteria to classify energy system models. The following table shows the identified criteria and their use.

The above-mentioned criteria are topically divided into groups to provide a clearer structure. These are General Model Logic, Model Structure, Criteria for Model Application, Technological Details, Economic, and Social Details of the modelled energy system. The individual groups are explained below.

3.1. General Model Logic

General logic is used to summarize criteria that describe the meta-level or general properties of the model. The following criteria were used. The Analytical Approach describes the general approach to the modeling of the energy system. The reviews distinguish between three approaches to energy models: either a top-down approach, a bottom-up approach, or the hybrid, which is a combination of both approaches. The Methodology of the energy system models describes the model type and is usually divided into two main categories: Simulation and Optimization. Almost all analyzed reviews use this criterion except for Refs. [4,7]. Klemm and Venneman [16] also define forecasting and backcasting as a model type in addition to optimization. The Mathematical Approach describes the programming implementation of the model. Mostly linear programming (LP), mixed integer linear programming (MILP), dynamic programming, and heuristic techniques for differentiation are used [16,23]. Different words are often used here in reviews. For example, in Ref. [5], this implementation is discussed in more detail in the methodology. In Ref. [12], the criteria are described with the programming technique. Refs. [6,28] discuss different mathematical approaches to face uncertainty in energy system models. In addition to the time horizon, the consideration of the Transformation Path in a model can also be assessed. A distinction is made in Refs. [12,14] between two approaches: The perfect foresight approach and the myopic approach.

3.2. Model Structure

Regarding model structure, the evaluation criteria summarized here represent the spatial and temporal resolution or the scope of the model. Geographic Coverage is used to describe the included spatial area of energy system model. This scope can vary from analyzing individual buildings or single power plants to regional, national, or even modeling the energy system of the whole world. The term Modeling Horizon is used in most of the reviews to describe the time frame of an energy system model. Concrete time periods can be used for the assessment, such as years or decades [14,16] or the models can be divided into short-term and long-term models [12,24]. In Ref. [23] both differentiations are used. In addition to the geographical coverage, the Spatial Resolution is also an important evaluation criterion for energy system models. In this context, a distinction is made in Ref. [12] and Ref. [14] (under geographical coverage) between single-node and multi-node approaches. However, the spatial resolution can also be differentiated structurally, for example into city districts, buildings, and individual consumers [16,22]. In Ref. [32], the function GIS representation is used, which is also classified in spatial resolution here. According to Ref. [28] reviews usually evaluate the geographical coverage instead of the spatial resolution. In energy system models, the simulation period is usually divided into time steps. The granularity of this Temporal Resolution is assessed in almost all reviews and specifies the time steps of the model either in temporal specifications, such as minute values or hourly values, in number of time slices [12], or in flexible or user-specific time units. Multiple temporal resolutions, as shown in Ref. [28], is rarely used. Another feature of energy system models can be the selection and combination of objective functions, as in Ref. [32]. These Assessment Criteria (AC) could be minimum total costs or minimum emissions [23] or technical and economic analysis, as in Refs. [4,15,24].

3.3. Criteria for Model Application

Some criteria describe characteristics that are relevant for the application of the models. The availability of the evaluated energy system models often depends on their licensing and can therefore also be an evaluation criterion—here called Accessibility. Most reviews differentiate between various levels of accessibility [4] up to open-source models [14–16]. Criteria such as region [14] or institution [4] of development, publication [14] and update dates [32], or countries of application [22] are combined here into Development and Application. In addition, user friendliness and model documentation [15,23], or skill requirement [34], can be an evaluation criteria in the context of application. Besides the aspect of accessibility, Ref. [22] additionally identifies different Data Sources of the energy system models—from no data to detailed country-specific data and Ref. [34] defines the data need. In Ref. [5], the Purpose of the energy system model as investment decision support or power system analysis tool is also identified. In Refs. [3,6] it is described as the specific or primary focus of the energy system model. Ref. [15] differentiates the use of models between accounting, sensitivity, database, and methodology. Another important aspect for the use of an energy system model is shown by Ref. [14] in the form of the used Programming Environment. In Ref. [23], the Software requirements for each model are listed.

3.4. Technological Details

Technological details are various criteria that describe the modeling of technical components. Above all, the numerous factors used in Ref. [32] are partly summarized here. Some reviews assess the integration of Demand Side Management (DSM) in energy system models. This concerns measures on the consumer side of the energy system [28], including energy efficiency improvement, energy conservation, and Demand Response (DR) [5,16]. The energy system model can also be evaluated based on the end-use sectors considered—the Demand Sectors. The (private/commercial) buildings, industry, and transport sectors are usually used. The criteria Sectoral coverage [16], Energy sectors [3,12] or Commodities [5], here Energy Sectors, indicate which types of energy are considered in the models. The sectors represented in the models, such as electricity, heat, hydrogen, etc., are usually specified [4,7,28] or a distinction is made between the consideration of specific and all sectors [12]. The mapping of Energy Storage and flexibilities is also presented in some reviews [4]. A distinction can be made between the representation of different storage technologies [5,7]. Several of the criteria used in reviews are summarized here under Generation Details. Mostly, the assessment refers to modeling of specific technologies [4,7,16,34], as well as the application of conventional/renewable generation components [3,5]. In addition, operation optimization [2,23] and technological learning [22] can be represented in models. In Ref. [32] the representation of start-up and shut-down constraints, effects on part load, maintenance scheduling, curtailment, and reserve margin in models is evaluated. Another criterion for classifying the technical levels of detail of a model is the question of Grid Modeling. Ref. [2] describes whether energy networks are considered or even optimized. Here, Ref. [5] differentiates the models into different levels of grid detail and Ref. [7] considers thermal, electrical, and gas network as evaluation criteria. Some models include modeling of different greenhouse gases or CO_2 equivalents [5] as well as the cost of emissions or emission constraints [32]. The models can also be categorized or evaluated based on these Emission Modeling.

3.5. Economic Details

The Economic Details item describes energy system model properties that represent the economic system. Energy system models calculate economic parameters as Costs in addition to technical ones. In doing so, Ref. [3] and Ref. [5] differentiate between investment, operating, and maintenance costs (such as fuel, carbon dioxide (CO_2), tax, or balancing costs). Energy Market modeling can also be assessment criteria. The different modeling depths or types of markets in models is presented in Ref. [5]. On the other hand, Ref. [34] looks at energy trading and the economic transition. In addition, some models may also represent energy Policy [28] or Subsidies and non-price/price-induced policies, which can have an impact on the economics [34].

3.6. Social Details

Two criteria that describe social or societal properties of the energy system are summarized here. The consideration of different criteria that reflect Consumer Behavior can be considered, as in Refs. [7,28]. In Ref. [22], social parameters ranging from mapping consumption curves to multi-agent programming are evaluated. Elasticity of demand is a measure of how demand changes in response to price fluctuations, as evaluated in Ref. [5] and Ref. [32] and is therefore assigned here in the broadest sense to consumer behavior. Due to the focus on emerging economies, Ref. [34] also evaluates the consideration of Urban-rural divide in models.

3.7. Summary

As shown, the different reviews use a variety of factors to analyze and evaluate energy system models. Figure 3 shows the mentioned criteria classification (see Table 2) in a Tree map. The rectangles represent the individual evaluation criteria, whose area is proportional to the frequency of use in reviews. The color represents the group into which they were categorized. This representation makes it easy to compare the criteria within each group, the criteria across groups, and the groups among themselves. The *Model Structure* (28%), *General Model Logic* (20%), and *Technological detail* (19%) groups have the largest share of the evaluation criteria. More precisely, the criterion Methodology is used in 75% of all examined reviews and the criteria Temporal resolution in 71%. The Generation Detail, Model Horizon, Analytical Approach, Energy Sector, and Application criteria are also commonly used to describe and evaluate energy system models. As can be seen from the ratio of the areas, *Economic Details* and *Social Details* are rarely used. However, the Consumer Behavior criterion is used in 38% of the reviews investigated. Many of the recent analyzed reviews have focused more intensively on this aspect of energy system models. The urban-rural divide is used as an evaluation criterion of energy system models in 1 of 16 reviews [34]. Other represented interrelationships of the energy system and society are not evaluated in the reviews.

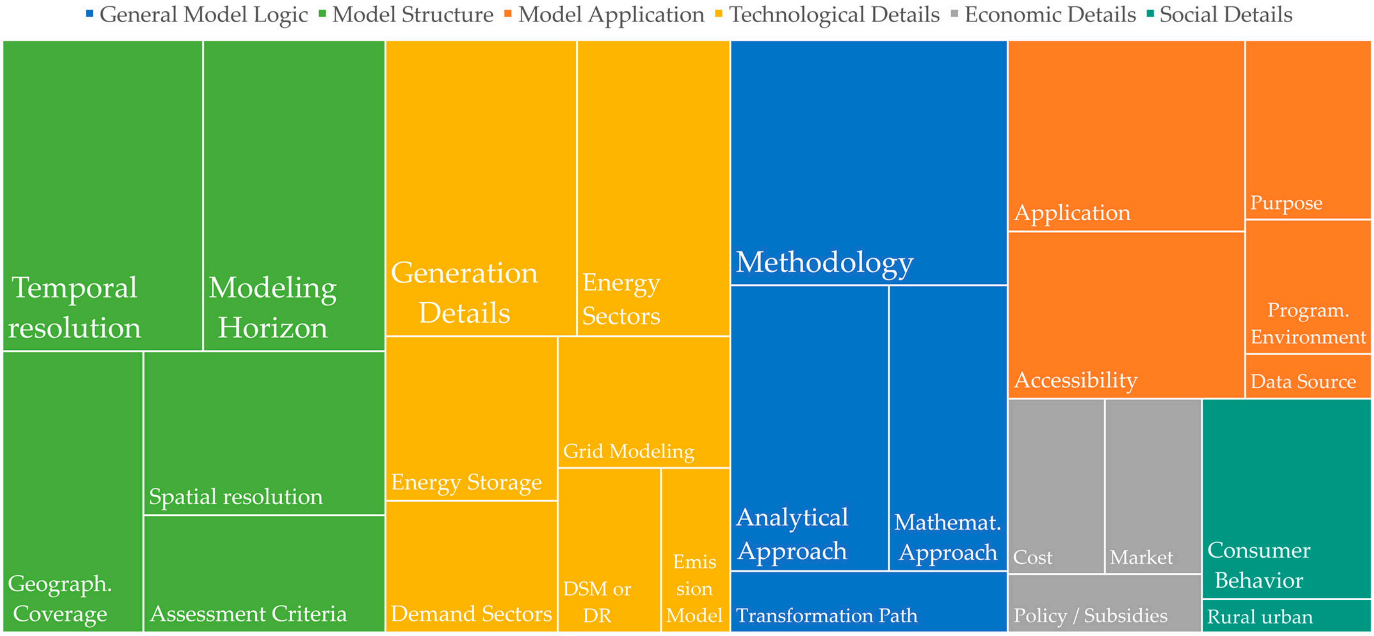

Figure 3. Frequency of the evaluation criteria of energy system models, displayed as a TreeMap.

Table 2. Overview of the evaluation criteria used by reviews, each marked with 'x'.

	Criteria	[2]	[3]	[4]	[5]	[6]	[7]	[12]	[14]	[15]	[16]	[22]	[23]	[24]	[28]	[32]	[34]
General Model Logic	Analytical Approach		x		x	x		x	x		x		x	x			
	Mathematical Approach				x	x		x			x		x		x		
	Methodology	x	x		x			x	x	x	x	x	x	x		x	x
	Transformation Path							x	x							x	
Model Structure	Geographical Coverage		x		x					x	x		x			x	x
	Modeling Horizon	x	x		x			x	x		x		x	x		x	x
	Spatial Resolution					x		x	x		x	x			x	x	
	Temporal Resolution	x	x		x	x		x	x		x	x	x		x	x	
	Assessment Criteria			x						x			x	x		x	
Model Application	Accessibility			x					x	x	x	x	x			x	x
	Application		x	x					x	x		x	x			x	x
	Data Source											x					
	Purpose		x		x	x				x							
	Programming Environment								x				x			x	
Technological Details	DSM or DR				x						x				x		
	Demand Sectors				x		x				x					x	
	Energy Sectors		x	x	x		x	x		x	x				x		
	Energy Storage		x	x	x		x									x	
	Generation Details	x	x	x	x		x				x	x	x			x	x
	Grid Modeling	x			x		x									x	
	Emission Modeling				x											x	

Table 2. *Cont.*

	Criteria	[2]	[3]	[4]	[5]	[6]	[7]	[12]	[14]	[15]	[16]	[22]	[23]	[24]	[28]	[32]	[34]
Economic Details	Cost		x		x											x	
	Market				x											x	x
	Policy/Subsidies														x		x
Social Details	Consumer Behavior				x	x	x					x			x	x	
	Urban-rural divide																x

4. Possible Integration Method for Social Aspects in Energy System Models

It could be assumed that the general underrepresentation of social aspects as an evaluation criterion for models is due to the characteristics of the evaluated models. In the following, a brief overview of models investigated in the presented reviews will be given, since other reviews [35,37,38] have already studied models intensively from this aspect, as mentioned in Section 2. All in all, the 16 mentioned reviews evaluated 178 energy system models in detail—20 of these are examined in at least 25% of the reviews, presented in Figure 4.

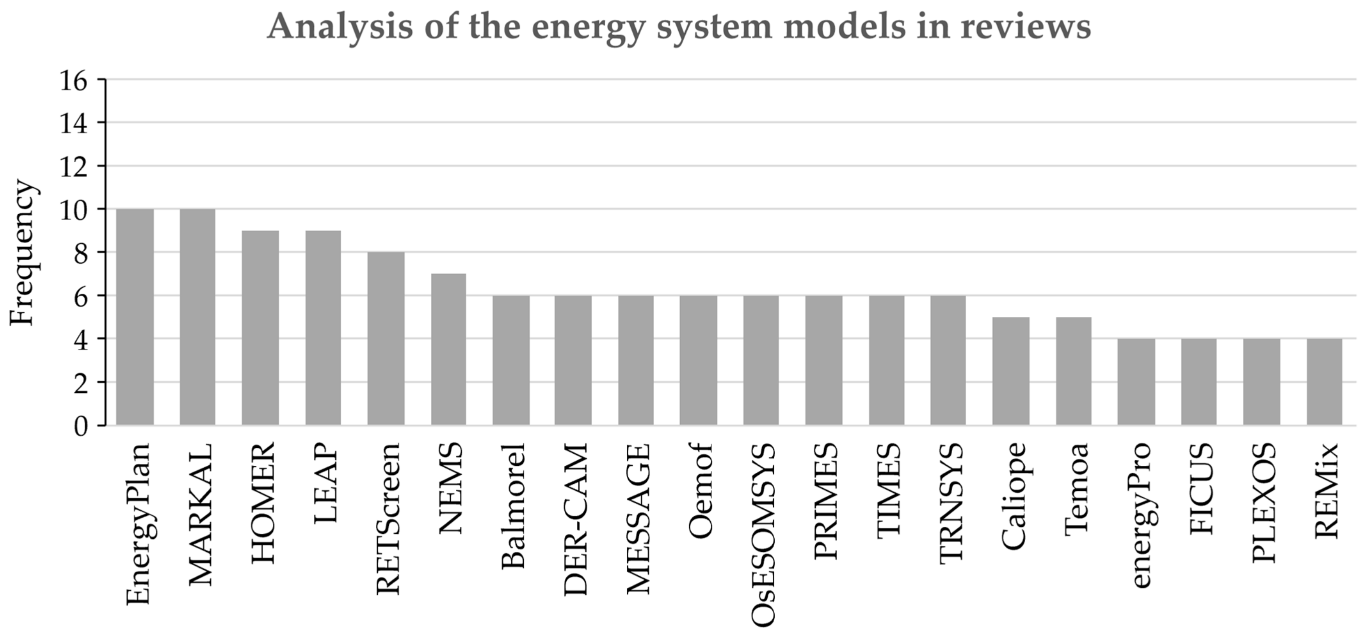

Figure 4. Overview of energy system models, sorted by frequency of analysis in the reviews.

In 10 of the reviews shown, the EnergyPlan tool [40] was examined, which is a free model for the design of future sustainable energy solutions. Commercial modeling framework MARKAL [41] is analyzed in 10 reviews. HOMER [27], the well-known simulation, optimization, and sensitivity analysis tool and LEAP, a scenario based computer tool as used in Ref. [42], are studied in more than half of the reviews shown here. The National Energy Modelling System NEMS [43] is analyzed seven times. Other frequently studied models are Balmorel [44], DER_CAM [45], Message [46], Oemof [47], OsESOMSYS [48], PRIMES [49], TIMES [50], and TRNSYS [51]. An overview of the energy system models analyzed in the reviews can be found in the Appendix A. Of the 75 models analyzed, Ringkjøb et al. [5] attribute demand elasticity to 25 models, including EnergyPlan, MARKAL, LEAP, NEMS, Balmorel, DER-CAM, MESSAGE, PRIMES, and TIMES. In Ref. [32], Balmorel and Times are categorized as demand elastic. Allegrini et al. [7] describes that 6 other models besides Energy Plus and TRNSYS can represent user behavior. PRIMES and ENSYSI additionally consider social parameters according to Ref. [22]. Of all the models examined, only 33 have the ability to model consumer behavior according to the reviews—including the most frequently analyzed models. In this regard, Refs. [2,6] are not always congruent in their classifications. In addition, Krumm et al. identified parameter dependencies in the Calliope and Destinee models [38]. Cuesta et al. [39] also describe that few models can represent social parameters. The models examined rarely consider other social aspects.

There is also already literature on the challenge of representing social aspects such as consumer behavior in energy system models. Thus, Turnheim describes a framework for bridging different approaches to the energy transition: quantitative systems modeling, socio-technical transition analysis, and initiative-based learning [52]. The energy system models analyzed here are based on the quantitative modeling approach. The socio-technical transition is described in more detail by Trutnevyte et al. [53]. According to their work, models and social science research are complementary in many ways. Energy system models represent technology, economy, environment, and politics quantitatively on the basis of data, while social scientists look at the behavior of different actors, transformation dynamics, and the heterogeneity of societies. There are three strategies for combining the findings from social sciences and models: bridging strategy, iterating strategy, and merging strategy, which will be explained and applied later [53].

This large number of models, which have already been investigated from different points of view, shows that there is already an excellent basis for the techno-economic modeling of energy systems. In the future, the socio-economic system properties such as consumer behavior or willingness to pay could be considered even more specifically in these models in order to view the system more holistically. The consideration of consumer behavior and other parameters can be further classified in the model integration strategies describing the collaboration between modelers and social science researchers of Trutnevyte et al. [53], as mentioned in Section 2. Figure 5 shows the parameters in the different linking strategies, with the degree of integration increasing towards the right.

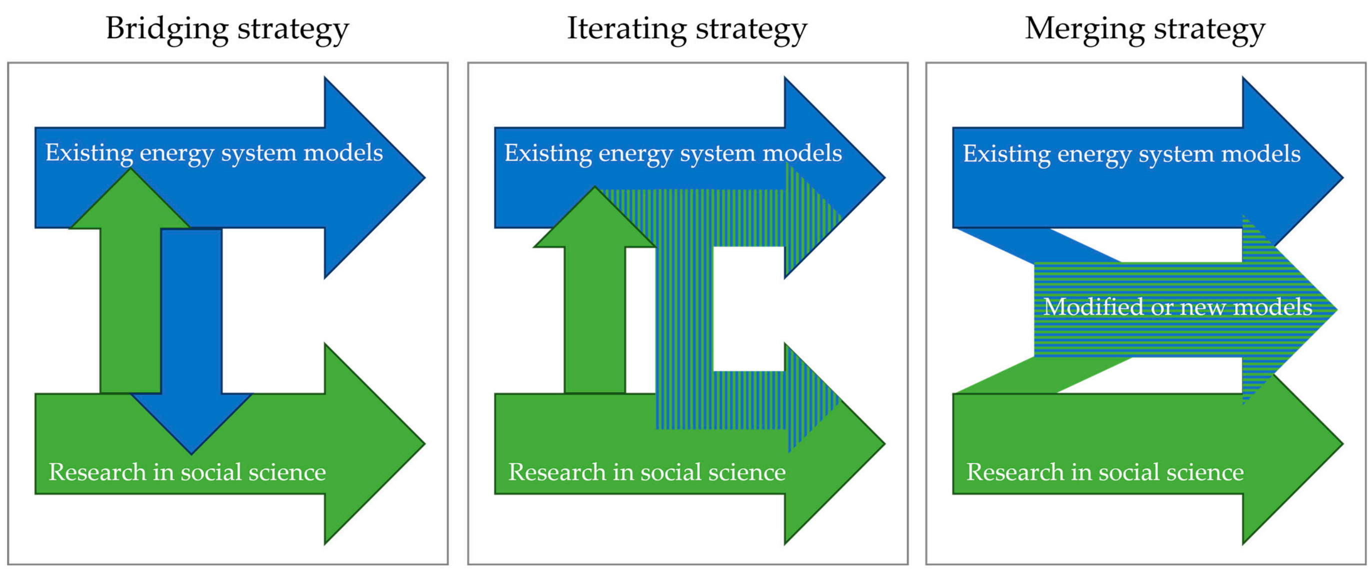

Figure 5. Integration of social aspects in energy system models by linking strategies. Own illustration based on Ref. [53].

The bridging strategy describes acts of exchange, discussing independently developed results and concepts between models and social science research. All technical and economic parameters of energy system models have the potential to be communicated to society with the help of the bridging strategy. The individual findings are relevant for different target groups, so that the modeling results can also be used again in the social sciences. In the iterating strategy, research in the social sciences defines broad exogenous narratives that can then be translated into quantitative input assumptions, such as gross domestic product or urbanization. These input parameters can then be used by the energy system models. Model characteristics such as consumer behavior and other parameters of the consumption sector or energy market could be directly expanded with findings from the social sciences. In this way, existing models that have already been studied in detail could be easily expanded by inputs from the qualitative storylines. The findings can be further utilized in energy system modeling as well as in the social sciences. In the merging strategy, quantifiable findings from the social sciences are used to structurally modify existing energy system models or to create completely new socio-technical models that can take technology, economy, environment, politics, and society into account as a whole [53].

To get a better overview of which linking strategy might be suitable for the existing energy system models, the strengths and weaknesses of the strategies are elaborated below based on use cases from the literature [53,54]. The opportunities and risks of the approaches are also compared, as shown in Figure 6.

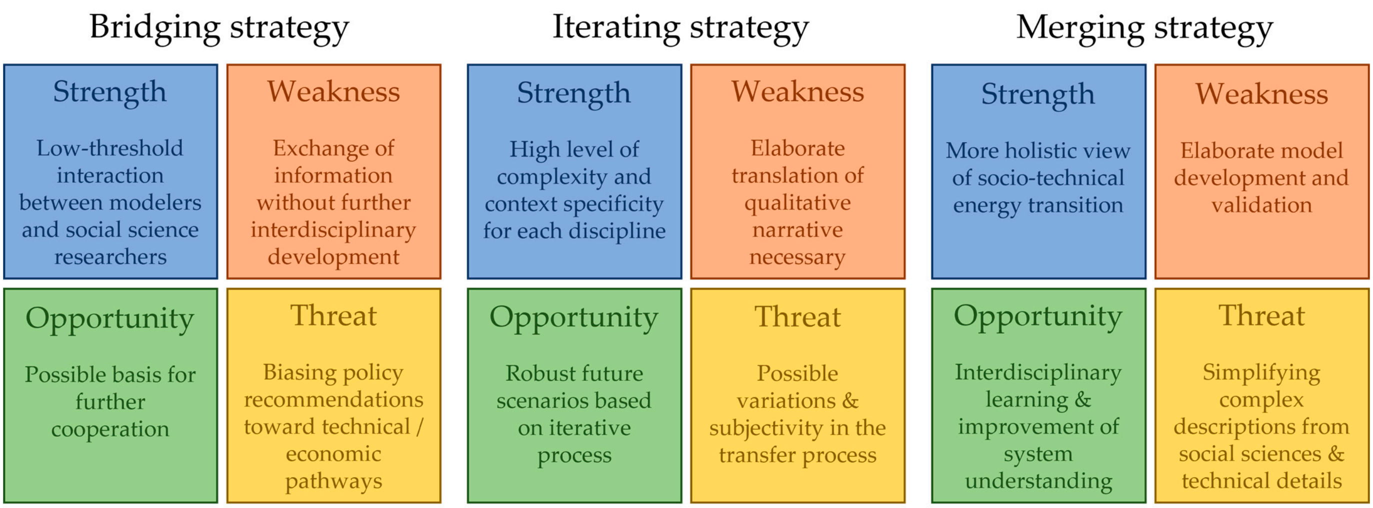

Figure 6. Strengths, weaknesses, opportunities, and threats of the linking strategies.

The bridging strategy enables low-threshold interaction between modelers and social scientists—whereby any of the above-mentioned models could be used. However, the aim here is not interdisciplinary further development, instead an exchange of information in which the depth of detail of each discipline can be preserved [53]. This strategy can pave the way for further cooperation. The resulting biased policy recommendations based only on easily quantifiable technical and economic pathways can be identified as a risk [53]. The iterating strategy also maintains the complexity of the individual disciplines through the exchange of qualitative narratives and techno-economic energy system models, which can be seen as a great strength [53]. On the one hand, this iterative process enables robust future scenarios for the energy system, which can be evaluated from the technical, socio-economic, and political sides [54]. On the other hand, the complex translation of the narratives into integrable parameters is a weakness of this strategy. The risk can also be derived from this: When translating the narratives, specific variations or even subjective interpretations can influence the quality of the results [54]. This is in contrast to the approach of the merging strategy, whose strength is to consider the energy system as a whole and to show quantitative dependencies [53]. However, this involves a great effort in terms of development and, above all, validation processes [55]. There is also the risk that complex descriptions from social science or technical details are simplified [53], which is already discussed in the literature [55]. Nevertheless, the great opportunity of interdisciplinary learning and the increase of system understanding stands for the merging strategy. The SWOT analysis shows that different strategies may be useful depending on the target of integrating social science findings into the energy system models. This must be decided for the applied model specifically and depending on the case study framework.

5. Discussion

There is already a wide range of reviews for energy system models with different focuses, which were analyzed here. The overview of the evaluation criteria of the total of 16 reviews shows several points. In general reviews, economic and social details rarely serve as evaluation criteria for energy system models. It seems obvious that mainly criteria from the group of model structure and general model logic are used to classify the different models. The consideration of consumer behavior in energy system models, one example for social aspects described in Section 3, shows that the consumer side of the energy system depends strongly on exogenous model assumptions as demographics or price signals, etc., as described in Ref. [53]. Besides consumer behavior, other aspects also have an impact on the energy system or are influenced by the energy system, such as job creation or acceptance, as Ref. [28] shows. Nevertheless, the generation side of energy systems can be represented well by quantified technical and economic factors [53] and therefore these technical details are still preferred for the detailed description of the model.

The method used here in the meta-analysis attempts to find relevant papers based on their citation without disadvantaging more recent papers. By using the citation per year, a wide range of papers could be found. However, especially in recent years reviews have been published that explicitly focus on social or societal aspects, such as energy justice [36] or participation [35]. So far, despite considering the date of publication, these publications do not have the visibility as the general reviews. Nevertheless, also in general reviews, the consideration of the human dimension in energy system models is more and more understood as a challenge for future research, even if they often do not evaluate the models according to it in depth [28].

The question of whether social aspects have so far been sufficiently considered in energy system models per se can also be answered. The large number of models examined in the reviews shows that there are already many proven tools for planning or optimizing energy systems with different approaches. As shown in Section 4, only 33 of the 178 analyzed traditional models already include first socio-technical linkages in the widest sense. In order to combine quantitative systems modeling and socio-technical transition analysis, there are already several studies dealing with the integration of social aspects into energy system models [37,38,53]. The approach of Trutnevyte et al. [53–55] was picked up here to show that there are different linking strategies with advantages and disadvantages. The consideration of the mentioned demand-side parameters in models can go beyond the bridging strategy towards a translation of quantitative storylines by the iterating strategy or even toward the quantification of relevant boundary conditions and integration with the bridging strategy. In this context, the trade-off between a detailed but one-sided (technical) system analysis and simplifying complex dependencies of the whole system for modeling must be found. The SWOT analysis developed here can help to select the appropriate linking strategy, thus adding the human dimension to existing energy models.

Many further interdisciplinary questions arise from the consideration of socio-economic variables in energy system modeling and thus planning of energy systems. Which societal and socio-technical parameters are relevant for energy system modeling? The interdependencies and correlations have to be identified using qualitative and quantitative methods. After that, the integration into the energy system model and especially the application can be done. How do the designs of energy systems change when social parameters are taken into account? These questions must be the subject of future examinations—both in fundamental and applied research. Purely techno-economic optimizations are no longer sufficient. As shown, linking social sciences and energy system modeling is only the first necessary step for interdisciplinary research, which is essential for a holistic energy transition.

6. Conclusions

In the transformation towards a more sustainable energy system, not only technical and economic aspects are important, but also social aspects such as acceptance, participation, and equity. Overall, it is important to consider social aspects in energy system models to achieve a successful transformation to a sustainable energy system. In the future, energy system models should also be assessed to evaluate how social parameters and framework conditions can be quantified and integrated.

The reviews presented here evaluate energy system models primarily on structural and technical parameters. Although social aspects in the form of consumer behavior are evaluated, only a few tools display this characteristic compared to the large quantity of the examined energy system models. It is shown that especially in recent works, non-technical aspects of the energy system model are receiving more and more recognition.

Besides the analysis of previous findings, the actual integration and application is an important step. The analyzed reviews show that there are already many different technical energy system models with different focuses available, which can be expanded further. This requires on-going development to improve the integration of social aspects in energy system models, e.g., according to the methodology of Krumm et al. [38]. Above all, the complexity of the social aspects requires a trade-off between representability and accuracy. For this purpose, existing research in social sciences can be used to represent relevant dependencies in energy system models. This collaboration between disciplines could represent an essential module for the accelerated implementation of the energy transition and thus the future-oriented realization of the set climate targets.

Author Contributions: Conceptualization, T.L. and S.S.; methodology and investigation, T.L. and P.K.; writing—original draft preparation, T.L.; writing—review and editing, S.S., P.K. and T.H.; writing—editing, T.L.; supervision, T.H. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Munich University of Applied Sciences HM and the German Research Foundation (DFG) through the "Open Access Publication Costs" program (project # 512819356).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Reviews and Analyzed Energy System Models

Review	Analyzed Models				
Mancarella [2]	DER-CAM	EnergyPLAN	eTransport	RETScreen	
Connolly et al. [3]	AEOLIUS BALMOREL BCHP Screening Tool COMPOSE E4cast EMCAS EMINENT	EMPS EnergyPLAN energyPRO ENPEP-BALANCE GTMax H2RES HOMER HYDROGEMS	IKARUS INFORSE Invert LEAP MARKAL/TIMES Mesap MESSAGE MiniCAM NEMS	ORCED PERSEUS PlaNet PRIMES ProdRisk RAMSES RETScreen SimREN	SIVAEL STREAM TRNSYS16 UniSyD3.0 WASP
Sinha and Chandel [4]	ARES Dymola/modelica HOMER	Hybrid Designer HYBRID2 HYBRIDS HybSim	HySim HYSYS iGRHYSO iHOGA	INSEL IPSYS RAPSIM RETScreen	SOLSIM SOLSTOR SOMES TRNSYS

Review	Analyzed Models				
Ringkjøb et al. [5]	AURORAxmp BALMOREL Calliope CASPOC COMPETES COMPOSE CYME DER-CAM DESTinEE DIETER* DIgSILENT EMLab-Generation EMMA EMPIRE EMPS	EnergyPlan energyPro Enertilec ENTIGRISd ETM ETSAP-TIAM EUCAD EUPower-Dispatch ficus GCAM GEM-E3 General GENESYS GridLAB-D HOMER	HYPERSIM iHOGA IIASA IMAKUS IRiE LEAP LIBEMOD LIMES-EU LOADMATCH LUSYM MARKAL MESSAGE NEMO NEMS Oemof	OS OpenDSS OSeMOSYS PLEXOS POLES PowerGAMA PRIMES* ProdRisk PyPSA RAPSim ReEDS ReMIND REMix renpass RETScreen	SIMPOW SIREN SAM SNOWi stELMOD SWITCH Temoa TIMES TIMES-Norway TIMES-Oslo TRNSYS18 urbs WEM* WeSIM WITCH
Pfenninger et al. [6]	EFOM ELMOD EMCAS	ETSAP LEAP LIMES-EUþ	MACRO MARKAL MESSAGE	MGA NEMS OSeMOSYS	PLEXOS PowerACE PRIMES
Allegrini et. al. [7]	CitySim EnerGis EnergyPlus energyPro Envi-met	EPIC-HUB ESP-r Fluent HOMER IDA ICE	KULeuvenIDEAS lib MEU Neplan NetSim	OpenFOAM Polysun Radiance RETScreen Solene	SynCity Termis TRNSYS UMI
Prina et al. [12]	Balmorel Calliope DESSTinEE eMix EnergyPLAN	EPLANopt EPLANoptTP Ficus GAMAMOD Genesys	LEAP LUT Mahbub MARKAL/ TIMES	MESSAGE Oemof OSeMOSYS PLEXOS PyPSA	REMix REMod Temoa
Lopion et al. [14]	Balmorel BESOM Calliope CIMS DynEMo	E4cast EnergyPLAN ENPEP-BALANCE ESME IKARUS	LEAP MARKAL MESSAGE NEMS OEMOF	OSEMoSYS PRIMES REMIND-D REMix REMod-D	SCOPE Temoa TESOM TIMES
Manfren et al. [15]	CO2DB DEECO DER-CAM	EnergyPLAN EnergyPlus ExternE	GEMIS GENOPTa HOMER	LEAP LEED PLACE3S	RETScreen TRNSYS
Klemm and Vennemann [16]	Calliope DER-CAM EnergyPlan	energyPro eTransport ficus	HOMER MARKAL MARKAL-MACRO	Oemof TEMOA TIMES	Urbs
Fattahi et al. [22]	DynEMo E4Cast EnergyPLAN ENSYSI	ESME ETM IKARUS IWES	LEAP MARKAL METIS NEMS	OPERA OSeMOSYS POLES PRIMES	REMix SimREN STREAM
Mendes et al. [23]	DER-CAM EAM	H2RES HOMER	MARKAL/TIMES RETScreen		
Liu et al. [24]	AIM CGE EFOM	EnergyPLAN H2RES HOMER	LEAP MARKAL MEDEE	MESSAGE NEMS TRNSYS	

Review	Analyzed Models				
M. Fodstad et al. [28]	BALMOREL DISPA_SET EnergyPLAN	ENERTILE ESME GENeSYS-MOD	METIS Nexus Security Oemof	PleXOS PRIMES REMOD	TIMES
Groissböck [32]	Balmorel Calliope DER-CAM dhmin DIETER Dispa-SET ELMOD	EMMA EnergyPLAN EnergyRt ficus HOMER MATPOWER minpower	MOST NEMO oemof OSeMOSYS pandapower ProView psst	PyOnSSET pypower pyPSA Renpass RETScreen rivus Switch	TEMOA TIMES Urbs
Bhattacharyya and Timilsina [34]	EFOM LEAP	MARKAL MESAP	NEMS POLES	RESGEN SAGE	TIMES WEM

References

1. Sovacool, B.K.; Ryan, S.; Stern, P.C.; Janda, K.B.; Rochlin, G.; Spreng, D.; Pasqualetti, M.; Wilhite, H.; Lutzenhiser, L. Integrating social science in energy research. *Energy Res. Soc. Sci.* **2015**, *6*, 95–99. [CrossRef]
2. Mancarella, P. MES (multi-energy systems): An overview of concepts and evaluation models. *Energy* **2014**, *65*, 1–17. [CrossRef]
3. Connolly, D.; Lund, H.; Mathiesen, B.V.; Leahy, M. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Appl. Energy* **2010**, *87*, 1059–1082. [CrossRef]
4. Sinha, S.; Chandel, S.S. Review of software tools for hybrid renewable energy systems. *Renew. Sustain. Energy Rev.* **2014**, *32*, 192–205. [CrossRef]
5. Ringkjøb, H.-K.; Haugan, P.M.; Solbrekke, I.M. A review of modelling tools for energy and electricity systems with large shares of variable renewables. *Renew. Sustain. Energy Rev.* **2018**, *96*, 440–459. [CrossRef]
6. Pfenninger, S.; Hawkes, A.; Keirstead, J. Energy systems modeling for twenty-first century energy challenges. *Renew. Sustain. Energy Rev.* **2014**, *33*, 74–86. [CrossRef]
7. Allegrini, J.; Orehounig, K.; Mavromatidis, G.; Ruesch, F.; Dorer, V.; Evins, R. A review of modelling approaches and tools for the simulation of district-scale energy systems. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1391–1404. [CrossRef]
8. Beaudin, M.; Zareipour, H. Home energy management systems: A review of modelling and complexity. *Renew. Sustain. Energy Rev.* **2015**, *45*, 318–335. [CrossRef]
9. Keirstead, J.; Jennings, M.; Sivakumar, A. A review of urban energy system models: Approaches, challenges and opportunities. *Renew. Sustain. Energy Rev.* **2012**, *16*, 3847–3866. [CrossRef]
10. Deng, X.; Lv, T. Power system planning with increasing variable renewable energy: A review of optimization models. *J. Clean. Prod.* **2020**, *246*, 118962. [CrossRef]
11. Zendehboudi, S.; Rezaei, N.; Lohi, A. Applications of hybrid models in chemical, petroleum, and energy systems: A systematic review. *Appl. Energy* **2018**, *228*, 2539–2566. [CrossRef]
12. Prina, M.G.; Manzolini, G.; Moser, D.; Nastasi, B.; Sparber, W. Classification and challenges of bottom-up energy system models—A review. *Renew. Sustain. Energy Rev.* **2020**, *129*, 109917. [CrossRef]
13. DeCarolis, J.; Daly, H.E.; Dodds, P.E.; Keppo, I.; Li, F.G.N.; Mcdowall, W.; Pye, S.; Strachan, N.; Trutnevyte, E.; Usher, W.; et al. Formalizing best practice for energy system optimization modelling. *Appl. Energy* **2017**, *194*, 184–198. [CrossRef]
14. Lopion, P.; Markewitz, P.; Robinius, M.; Stolten, D. A review of current challenges and trends in energy systems modeling. *Renew. Sustain. Energy Rev.* **2018**, *96*, 156–166. [CrossRef]
15. Manfren, M.; Caputo, P.; Costa, G. Paradigm shift in urban energy systems through distributed generation: Methods and models. *Appl. Energy* **2011**, *88*, 1032–1048. [CrossRef]
16. Klemm, C.; Vennemann, P. Modeling and optimization of multi-energy systems in mixed-use districts: A review of existing methods and approaches. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110206. [CrossRef]
17. Collins, S.; Deane, J.P.; Poncelet, K.; Panos, V.; Pietzcker, R.; Delarue, E.; Gallachoir, B.O. Integrating short term variations of the power system into integrated energy system models: A methodological review. *Renew. Sustain. Energy Rev.* **2017**, *76*, 839–856. [CrossRef]
18. Windt, C.; Davidson, J.; Ringwood, J.V. High-fidelity numerical modelling of ocean wave energy systems: A review of computational fluid dynamics-based numerical wave tanks. *Renew. Sustain. Energy Rev.* **2018**, *93*, 610–630. [CrossRef]
19. Bazmi, A.A.; Zahedi, G. Sustainable energy systems: Role of optimization modeling techniques in power generation and supply—A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3480–3500. [CrossRef]
20. Hoffmann, M.; Kotzur, L.; Stolten, D.; Robinius, M. A Review on Time Series Aggregation Methods for Energy System Models. *Energies* **2020**, *13*, 641. [CrossRef]

21. Uslar, M.; Rohjans, S.; Neureiter, C.; Pröstl Andrén, F.; Velasquez, J.; Steinbrink, C.; Efthymiou, V.; Migliavacca, G.; Horsmanheimo, S.; Brunner, H.; et al. Applying the Smart Grid Architecture Model for Designing and Validating System-of-Systems in the Power and Energy Domain: A European Perspective. *Energies* **2019**, *12*, 258. [CrossRef]
22. Fattahi, A.; Sijm, J.; Faaij, A. A systemic approach to analyze integrated energy system modeling tools: A review of national models. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110195. [CrossRef]
23. Mendes, G.; Ioakimidis, C.; Ferrão, P. On the planning and analysis of Integrated Community Energy Systems: A review and survey of available tools. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4836–4854. [CrossRef]
24. Liu, Y.; Yu, S.; Zhu, Y.; Wang, D.; Liu, J. Modeling, planning, application and management of energy systems for isolated areas: A review. *Renew. Sustain. Energy Rev.* **2018**, *82*, 460–470. [CrossRef]
25. Ibrahim, A.; Jiang, F. The electric vehicle energy management: An overview of the energy system and related modeling and simulation. *Renew. Sustain. Energy Rev.* **2021**, *144*, 111049. [CrossRef]
26. Weinand, J.M.; Scheller, F.; McKenna, R. Reviewing energy system modelling of decentralized energy autonomy. *Energy* **2020**, *203*, 117817. [CrossRef]
27. Lambert, T.; Gilman, P.; Lilienthal, P. Micropower System Modeling with HOMER. Available online: https://www.homerenergy.com/documents/MicropowerSystemModelingWithHOMER.pdf (accessed on 19 September 2023).
28. Fodstad, M.; Del Granado, P.C.; Hellemo, L.; Knudsen, B.R.; Pisciella, P.; Silvast, A.; Bordin, C.; Schmidt, S.; Straus, J. Next frontiers in energy system modelling: A review on challenges and the state of the art. *Renew. Sustain. Energy Rev.* **2022**, *160*, 112246. [CrossRef]
29. Ahmadi, S.; Saboohi, Y.; Vakili, A. Frameworks, quantitative indicators, characters, and modeling approaches to analysis of energy system resilience: A review. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110988. [CrossRef]
30. Kotzur, L.; Nolting, L.; Hoffmann, M.; Groß, T.; Smolenko, A.; Priesmann, J.; Büsing, H.; Beer, R.; Kullmann, F.; Singh, B.; et al. A modeler's guide to handle complexity in energy systems optimization. *Adv. Appl. Energy* **2021**, *4*, 100063. [CrossRef]
31. Bolwig, S.; Bazbauers, G.; Klitkou, A.; Lund, P.; Blumberga, A.; Gravelsins, A.; Blumberga, D. Review of modelling energy transitions pathways with application to energy system flexibility. *Renew. Sustain. Energy Rev.* **2019**, *101*, 440–452. [CrossRef]
32. Groissböck, M. Are open source energy system optimization tools mature enough for serious use? *Renew. Sustain. Energy Rev.* **2019**, *102*, 234–248. [CrossRef]
33. Palzer, A.; Henning, H.-M. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies—Part II: Results. *Renew. Sustain. Energy Rev.* **2014**, *30*, 1019–1034. [CrossRef]
34. Bhattacharyya, S.C.; Timilsina, G.R. A review of energy system models. *Int. J. Energy Sect. Manag.* **2010**, *4*, 494–518. [CrossRef]
35. McGookin, C.; Gallachóir, B.Ó.; Byrne, E. Participatory methods in energy system modelling and planning—A review. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111504. [CrossRef]
36. Vågerö, O.; Zeyringer, M. Can we optimise for justice? Reviewing the inclusion of energy justice in energy system optimisation models. *Energy Res. Soc. Sci.* **2023**, *95*, 102913. [CrossRef]
37. Huckebrink, D.; Bertsch, V. Integrating Behavioural Aspects in Energy System Modelling—A Review. *Energies* **2021**, *14*, 4579. [CrossRef]
38. Krumm, A.; Süsser, D.; Blechinger, P. Modelling social aspects of the energy transition: What is the current representation of social factors in energy models? *Energy* **2022**, *239*, 121706. [CrossRef]
39. Cuesta, M.A.; Castillo-Calzadilla, T.; Borges, C.E. A critical analysis on hybrid renewable energy modeling tools: An emerging opportunity to include social indicators to optimise systems in small communities. *Renew. Sustain. Energy Rev.* **2020**, *122*, 109691. [CrossRef]
40. Lund, H.; Thellufsen, J.Z.; Østergaard, P.A.; Sorknæs, P.; Skov, I.R.; Mathiesen, B.V. EnergyPLAN—Advanced analysis of smart energy systems. *Smart Energy* **2021**, *1*, 100007. [CrossRef]
41. Sarica, K.; Tyner, W.E. Analysis of US renewable fuels policies using a modified MARKAL model. *Renew. Energy* **2013**, *50*, 701–709. [CrossRef]
42. McPherson, M.; Karney, B. Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector. *Energy Policy* **2014**, *68*, 146–157. [CrossRef]
43. Energy Information Administration. *The National Energy Modeling System: An Overview 2009*; Energy Information Administration: Washington, DC, USA, 2009.
44. Wiese, F.; Bramstoft, R.; Koduvere, H.; Pizarro, A.; Balyk, O.; Kirkerud, J.G.; Tveten, Å.G.; Bolkesjø, T.F.; Münster, M.; Ravn, H. Balmorel open source energy system model. *Energy Strategy Rev.* **2018**, *20*, 26–34. [CrossRef]
45. Stadler, M.; Groissböck, M.; Cardoso, G.; Marnay, C. Optimizing Distributed Energy Resources and Building Retrofits with the Strategic DER- CAModel. 2014. Available online: https://www.osti.gov/servlets/purl/1163652. (accessed on 19 September 2023).
46. Messner, S.; Strubegger, M. User's Guide for MESSAGE III. 1995. Available online: https://pure.iiasa.ac.at/id/eprint/4527/1/wp-95-069.pdf. (accessed on 19 September 2023).
47. Krien, U.; Schönfeldt, P.; Launer, J.; Hilpert, S.; Kaldemeyer, C.; Pleßmann, G. Oemof.solph—A model generator for linear and mixed-integer linear optimisation of energy systems. *Softw. Impacts* **2020**, *6*, 100028. [CrossRef]

48. Löffler, K.; Hainsch, K.; Burandt, T.; Oei, P.-Y.; Kemfert, C.; von Hirschhausen, C. Designing a Model for the Global Energy System—GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS). *Energies* **2017**, *10*, 1468. [CrossRef]
49. Fragkos, P.; Tasios, N.; Paroussos, L.; Capros, P.; Tsani, S. Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. *Energy Policy* **2017**, *100*, 216–226. [CrossRef]
50. Loulou, R.; Lehtilä, A.; Kanudia, A.; Remme, U.; Gary Goldstein, G. Documentation for the Times Model Part ii. 2005. Available online: https://iea-etsap.org/docs/documentation_for_the_times_model-partii.pdf. (accessed on 19 September 2023).
51. Klein, S.A. TRNSYS 18: A Transient System Simulation Program. Available online: http://sel.me.wisc.edu/trnsys (accessed on 19 September 2023).
52. Turnheim, B.; Berkhout, F.; Geels, F.W.; Hof, A.; McMeekin, A.; Nykvist, B.; van Vuuren, D. Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Glob. Environ. Chang.* **2015**, *35*, 239–253. [CrossRef]
53. Trutnevyte, E.; Hirt, L.; Bauer, N.; Cherp, A.; Hawkes, A.; Edelenbosch, O.; Pedde, S.; van Vuuren, D.P. Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. *One Earth* **2019**, *1*, 423–433. [CrossRef]
54. Trutnevyte, E.; Barton, J.; O'Grady, Á.; Ogunkunle, D.; Pudjianto, D.; Robertson, E. Linking a storyline with multiple models: A cross-scale study of the UK power system transition. *Technol. Forecast. Soc. Chang.* **2014**, *89*, 26–42. [CrossRef]
55. Li, F.G.; Trutnevyte, E.; Strachan, N. A review of socio-technical energy transition (STET) models. *Technol. Forecast. Soc. Chang.* **2015**, *100*, 290–305. [CrossRef]