Energy Conversion and Management 266 (2022) 115863

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Review

A critical survey of integrated energy system: Summaries, methodologies and analysis

Dongran Song [a], Weiqi Meng [a], Mi Dong [a,*], Jian Yang [a], Junlei Wang [b], Xiaojiao Chen [c], Liansheng Huang [c,d]

[a] School of Automation, Central South University, Changsha, China
[b] School of Mechanical and Power Engineering, Zhengzhou University, Zhengzhou, China
[c] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
[d] University of Science and Technology of China, Hefei, China

ARTICLE INFO

Keywords:
Integrated Energy System (IES)
IES Model Methods
Operation Optimization
Model Tools
CiteSpace

ABSTRACT

With a rapid growth of Integrated Energy System (IES) in various scenarios, researches on IES have attracted extensive attention in the last few decades. Inspired by the ever-increasing studies about the IES, which focus on various energy scenarios but lack a systematic summarization, this paper aims to undertake a comprehensive review of the IES models, operation optimization methods, and model tools. Firstly, CiteSpace is used to visually analyze the cooperation and co-occurrence network of related articles in recent two decades, among which 1998 papers from WOS are selected for analyzing. Note that 243 papers highly related to IES are further investigated to systematically analyze and integrate the relevant work. On this basis, different definitions of IES around the world and 12 related research hotspots are summarized. Then, the IES modeling methods are creatively classified from eight aspects. Furthermore, from the perspective of operation optimization methods, three mainly optimal problems, including Economic Dispatch, Unit Commitment and Optimal Power Flow, are comprehensively analyzed. Besides, 22 energy model tools are discussed from the levels of National, Regional, and Users. Finally, seven advantages and three challenges are summarized, four key points are concluded, and six perspectives/recommendations are proposed for future research. In general, this paper is intended to offer an insightful guidance to prompt related researchers/engineers to broaden the horizons of their researches.

1. Introduction

Energy has a bearing on the national economy, national security, as well as the survival and development of mankind, which is vital to promoting social development. Energy plays a fundamental role in the economic system and has played a key role in the previous three technological revolutions. Under the "carbon peak" and "carbon neutral" goals, the new energy industry will usher in a high-quality and leap-forward development. And the proportion of clean power installed capacity will significantly increase, such as PV and Wind power [1,2]. Under the background of Covid-19 pandemic, renewable energy has a record of new power generation capacity in 2020 and is the only source with a net increase in total power generation capacity [3,4]. It is widely known that renewable energy owns various advantages, such as lower

Abbreviations: CCHP, Combination of Cooling, Heating and Power; CloudPSS, Cloud Based Integrated Energy Planning Studio; COMPOSE, Compare Options for Sustainable Energy; DE, Differential Evolution; DER-CAM, Distributed Energy Resources Customer Adoption Model; DRO, Distributed Robust Optimization; EC, Evolutionary Computation; ED, Economic Dispatch; EH, Energy Hub; EI, Energy Internet; ESME, Energy System Modeling Environment; GA, Genetic Algorithm; GEM-E3, General Equilibrium Model for Economy-Energy-Environment; HOMER, Hybrid Optimization of Multiple Energy Resources; iHOGA, Hybrid Optimization by Genetic Algorithm; IES, Integrated Eenergy System; LEAP, Long-range Energy Alternatives Planning System; MARKAL, Market Alocation model; MIP, Mixed Integer Programming; MILP, Mixed Integer Linear Programming; MINLP, Mixed Integer Nonlinear Programming; NEMS, National Energy Modeling System; OPF, Optimum Power Flow; P2G, Power-to-Gas; POLES, Prospective Outlook on Long-term Energy Systems; PRIMES, Price Induced Market Equity System; PV, Photovoltaics; RE, Renewable Energy; Renpass, Renewable Energy Pathways Simulation System; RES, Renewable Energy Source; RO, Robust Optimization; SI, Swarm Intelligence; SWITCH, Solar, Wind, Transmission, Conventional generation and Hydroelectricity; Temoa, Tools for Energy Model Optimization and Analysis; TIMES, The Integrated MARKAL-EFOM System; TRNSYS, Transient System Simulation; UC, Unit Commitment; WOS, Web of Science.

* Corresponding author at: School of Automation, Central South University, Changsha, China.
E-mail address: mi.dong@csu.edu.cn (M. Dong).

https://doi.org/10.1016/j.enconman.2022.115863
Received 20 March 2022; Received in revised form 21 May 2022; Accepted 4 June 2022
0196-8904/

energy costs, better air conditioning and public health, and promoting economic growth [5]. However, what people talking about related to renewable energy, actually is low carbon energy but not zero carbon energy. “How to reflect carbon neutrality in an economic way?”, Meanwhile, “What kind of electricity (Coal or Gas or Nuclear power) can balance the consumption of renewable electricity?”.

At present, renewable energy and efficiency are key points to low carbon emission, and the realization of the core objectives of the Paris Agreement requires a large-scale reform of the energy system. In order to achieve the goal of decarbonization and ensure the safety, stability, and efficiency of the power grid operation, it must accelerate the integration of “Source-Network-Load-Storage” and the development of multiple energies complementarity, and build a comprehensive energy system with multiple energies complementarity. Therefore, the network of centralized and distributed renewable energy power stations from different sources - “Integrated Energy System (IES)” - will become the pillar of the power industry in the future [6,7].

The technologies related to IES have always been valued by countries all over the world. Different countries often formulate their own comprehensive energy development strategies according to their own needs and characteristics [1,8]. The vision of President Obama’s smart grid national strategy is to build an efficient, low investment, safe, reliable, intelligent and flexible integrated energy network, in which the intelligent power network plays a core pivotal role [9]. Europe, Canada, Japan, and other countries have also carried out researches on IES. Through the 863 plan project, the National Natural Science Foundation and other research programs [1], China has launched many scientific and technological projects related to IES and has carried out international cooperation with Singapore, Germany, the United Kingdom and other countries. China is aiming to reach a peak of CO_2 emissions before 2030 and carbon neutrality before 2060 [4]. In response to the increasingly critical global environmental problems, the United Nations successively adopted two historic agreements in 2015: the Paris Agreement [10] and the 2030 agenda for sustainable development [11]. Obviously, The IES will stimulate energy innovation, exchange and explore practical solutions to make positive contributions to energy security and climate change. It could truly realize “electrify the energy demand, decarbonize the electricity supply”.

In conclusion, the significance of IES lies in:

- Innovative management system. Realize the overall management and coordinate planning of multiple energy subsystems.
- Innovative technology. By studying the physical characteristics of heterogeneous energy, the complementarity and substitutability of various energy sources are clarified. Develop new technologies for conversion and storage to improve the efficiency of energy development and utilization.
- Innovative market model. Establish a unified market value measurement standard and value conversion medium. Make energy conversion and complementarity reflect economic and social values.

1.1. The definition of IES

At the beginning of the review, the definition of IES should be made. When considering IES, there are arguably many alternative definitions [6,7,12-23]. Several key definitions are shown in Table 1. As it is, although the concept of IES has appeared for decades and preliminary studies have been carried out, there is still a lack of unified definition. Even in the world-famous Wikipedia database [24], the relevant entries cannot be found at present.

Based on the existing literature review, the IES is defined as: “IES adopts advanced information technology and management mode to integrate various energy sources such as coal, oil, natural gas, electric energy, and thermal energy in the region, so as to realize the coordinated planning, optimal operation, collaborative management, interactive response and complementary mutual aid among various heterogeneous energy subsystems. It is a new energy system that can increase energy efficiency and foster renewable energy development”.

Table 1
Definition of IES.

Author	Definition	Refs.
Ming Zeng	IES refers to the energy system in a region. It uses advanced technology and management mode to integrate a variety of energy resources and realize coordinated planning, optimized operation, collaborative management, interactive response and mutual assistance among multiple heterogeneous energy subsystems.	[21,22]
Hongjie Jia	IES refers to a comprehensive social energy production, supply and consumption system formed under the coordination and optimization of various energy production, transmission, distribution, conversion, storage, consumption and other links in the process of planning, design, construction and operation.	[17]
Haozhong Cheng	IES is the actual carrier of EI (Energy Internet)	[18]
Bragg-Sitton	IES are cooperatively-controlled systems. They are composed of several subsystems with different time and space scales, such as nuclear heat source, turbine that converts heat energy into electric energy, new energy, and one or more industrial processes that produce heat or power from energy.	[6]
M. S. Greenwood, et al.	IES focuses on creating financial and technically synergistic partnerships among various energy producers and consumers	[16]
M. Liserre, et al.	IES is a conception of hybrid-energy-system. By using existing resources to meet a variety of energy needs, IES is an effective way to achieve clean energy supply and promote the development of renewable energy. It can reduce environmental pollution emissions and improve production efficiency.	[12]

The Basic Structure of IES

Traditionally, there are relatively few connections between energy systems of different carriers (electricity, natural gas, district heating/cooling and hydrogen). Single energy carrier generally adopts independent design and operation scheme, which leads to low energy operation efficiency. However, at present, the coordination and optimization between energy networks (power, natural gas energy storage and thermal energy storage that provide demand response) and the implementation of such projects are increasingly favored by scholars. Different energy carriers realize unified management through energy conversion and energy storage devices to achieve overall optimization. Fig. 1 shows the typical IES and the interconnection between energy systems of different carriers.

1.2. Annual publishing trends

Numerous researches on IES have been launched and have generated a great interest. A state-of-the-art systematic review has been undertaken on published electronic resources for the study of the IES. Then, a preliminary study has been conducted to gather an overview of the topics related to model methods in IES. The identified main topics are: IES, energy models, and operation optimization. These topics (Table 2) are used to identify relevant keywords. The keywords are then utilized to search relevant publications on optimal methods of IES from well-established electronic databases: Google Scholar, ScienceDirect and WOS, which cover a wide range of scientific literature.

The criteria for retention include:

- Studies covering energy model and/or optimal methods
- Key articles from established authors/institutions in the area of IES
- Studies with significant contribution to CO_2 emissions

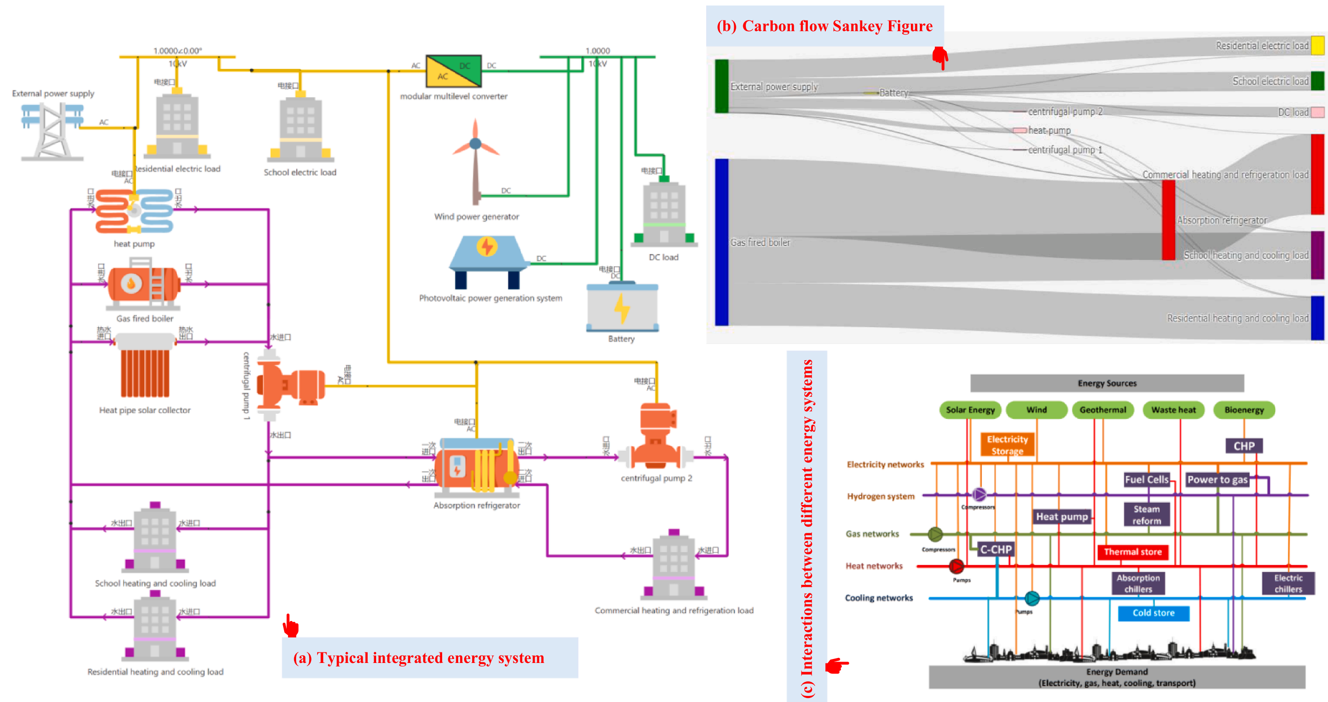

Fig. 1. Typical IES and interactions (Source (c): [25]).

Table 2
Searched keywords and associated groups*.

Database	Language	Objective	Time frame
WOS	English	"Title: Integrated Energy System" AND "Areas: Engineering" AND "Core Collection"	2000–2022
Google Scholar	English	"Title: Integrated Energy System"	
ScienceDirect	English	"Title: Integrated Energy System" AND "Areas: Energy"	
IEEE	English	"Document Title": Integrated energy system AND "Journals" or "Conferences"	

* Data retrieved in February 2022.

Fig. 2 shows the statistical data of relevant studies in the past decades (2000 to February 2022). While a large number of articles have been published under the current IES research direction, this paper tends to comprehensively summarize the research status, which is classified into three categories, i.e., Model methods, Operation optimization, and Model tools.

So far, the research on IES mainly includes the following twelve categories (Table 3): Multi-carrier energy systems and Energy Hubs [26-31], Operation (ED, UC, OPF etc.) [14,32-37], Evaluation Method of IES [22,38-45], Energy Internet (EI) [46-49], Policies, Challenges and Prospects of IES [50-57], Planning issues of IES [35,58-62], Application of Artificial Intelligence in IES [41,63-67], Energy system resilience [68-71], IES model and its application status [72-87], District-scale energy systems [88-92], Uncertainty modeling techniques [93-95], Energy Storage [96-101].

1.3. Scope and objective of this paper

The limitations of previous literature and the goals of this paper are shown in Fig. 3. The innovations of this research are summarized as two points:

(1) First, the knowledge base and research hotspots of IES in different stages are sorted out by bibliometrics and visual analysis (CiteSpace, 2000–2022).
(2) Second, the IES is comprehensively analyzed from the aspects of modeling method, operation optimization, and model tools. On this basis, it makes up for the shortcomings of the existing articles, summarizes the latest frontier issues of IES in detail, and puts forward improvement suggestions.

This paper will provide a preliminary guide for practitioners and scholars interested in IES, and present a useful reference for future IES development.

The structure of this paper is as follows (Fig. 4): Section 1 introduces the basic knowledge of IES. Section 2 analyzes the research status of IES based on CiteSpace. Section 3 presents the analysis of the methodology, including Modeling methods, Operation optimization and Model tools. Finally, the advantages, challenges, and prospects of IES are analyzed.

2. Visualized analysis

The CiteSpace is used to conduct quantitative statistics and visualization research on the literature related to IES in the core collection database of WOS. For examining and displaying the dataset retrieved from WOS, CiteSpace software V5.8.R3. with Java version 8 is used as a visualization and analytical research tool. The software is invented by Chaomei Chen, which is freely available online [102]. It is a tool to provide "hands-on analysis" for anyone who pays attention to the frontier of relevant scientific knowledge based on the map of scientific knowledge, because there may be no excellent review articles in relevant fields [103,104]. The software uses the references of experts in the academic field as the basis for the identification of academic research potential, sorts out the citations from relevant papers, obtains the vital information, and summarizes the existing research and forecast the future [105-107]. The philosophical basis and design inspiration of software come from the structure of Thomas Kuhn's scientific revolution [108,109],and Ronald Burt's structural hole theory [110,111].

For an in-depth understanding of the principle of CiteSpace, see

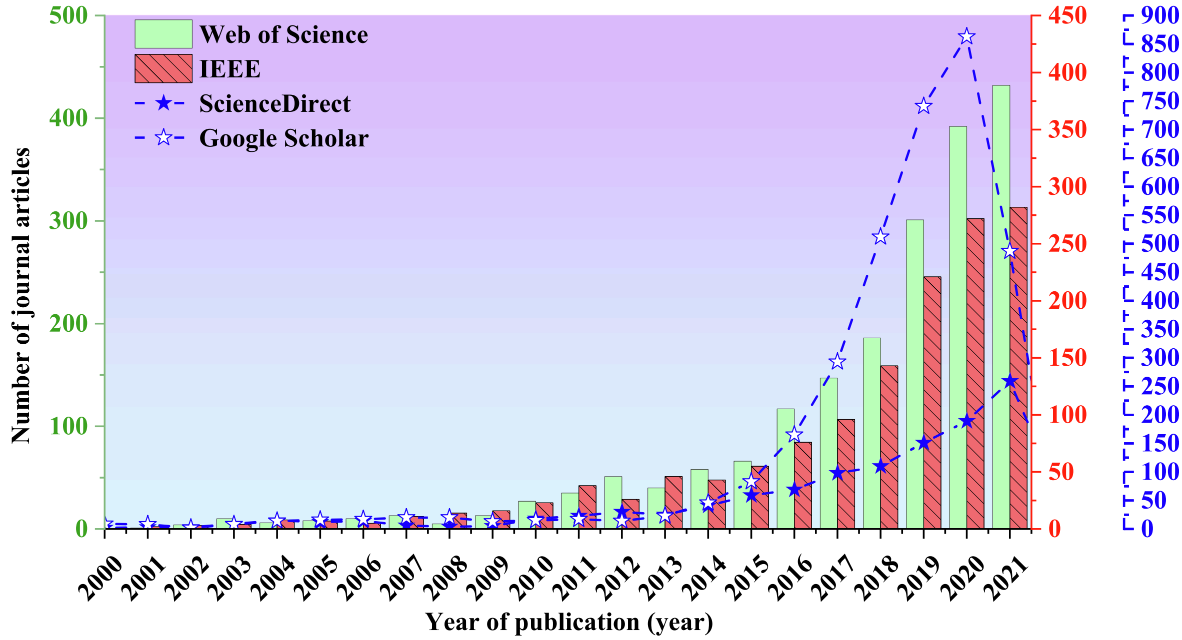

Fig. 2. Publication of IES related papers from 2000 to 2022 (as of the end of February 2022).

Table 3
Overview of the 84 review articles surveyed with their corresponding classification and review topic*.

Number	Focus topic	Refs.	Number	Focus topic	Refs.
1	Multi-carrier energy systems and Energy Hubs	[26-31]	7	Application of Artificial Intelligence in IES	[41,63-67]
2	Operation (ED, UC, OPF etc.)	[14,32-37]	8	Energy system resilience	[68-71]
3	Evaluation Method of IES	[22,38-45]	9	IES model and its application status	[72-87]
4	Energy Internet (EI)	[46-49]	10	District-scale energy systems	[88-92]
5	Policies, Challenges and Prospects of IES	[50-57]	11	Uncertainty modeling techniques	[93-95]
6	Planning issues of IES	[35,58-62]	12	Energy Storage	[96-101]

* The order of arrangement does not represent the degree of importance.

literature [103,104,112-115]. In this part, the research status, hotspots, and future development trends of the IES in the energy field will provide a reference for the following review.

Between February and March 2022, a systematic literature search was conducted to identify relevant publications that apply the models. Scientific publications (exclusion of news feed, non-scientific magazine, and newspapers), published from 2000 onward were selected, because model advancements may have changed the model design. After screening, 1998 articles in English were finally retained for analysis and interpretation.

The writing path of this section is from macro to micro, from intuitive to complex, from the whole to individual parts. The specific analysis includes: Institution analysis (macro) → Co-citation analysis (complex & whole) → Keyword analysis (micro & intuitive) → Typical cluster analysis (parts). The results of the visual analysis are shown in Table 4 and Fig. 5(For a clear vision, 10 graphs included in Fig. 5 are separately listed in Appendix A).

2.1. Analysis of macro knowledge flow

Using CiteSpace to analyze the author of the document, Fig. 5(a) is obtained. There are 682 nodes and 801 connections in the map, and the network density is 0.0034. Each node in Fig. 5(a) represents an author. The larger the radius of the node is, the more the documents are issued. The nodes connection represents the connection or cooperation relationship between authors. The thicker the connection, the closer the cooperation relationship between authors. The results show that at present, there are mainly three teams carrying out relevant research, namely: Ibrahim Dincer, Hongjie Jia and Wei Gu. At the same time, the author's cooperation network diagram, which is related to the specific research direction of each team, shows that the cooperation between different research teams is limited. The analysis of cooperative document issuing institutions shows that the links between research institutions and the inter-agency cooperation are relatively close (Fig. 5 (b)-(c)).

2.2. Carrier analysis of meso-research findings

Fig. 5(d) shows the results from a co-citation analysis of journals of IES-related literature. The co-citation analysis shows the research results of related journals cited in IES research, and demonstrates that the results of these journals are absorbed by IES research, and the knowledge contained in these journals flows into IES-related research. At the same time, through the co-citation frequency analysis of the core journals, the quality level of publications from a given journal can be effectively revealed. Betweenness centrality displays the significance of one node. It is displayed as a purple ring in Fig. 5(d). The thickness of the ring reflects the importance of the betweenness centrality. The greater the thickness, the higher the betweenness centrality of the node, and the higher the importance of the node. In Fig. 5(d), the purple ring corresponding to APPL ENERG is the thickest and is followed by ENERGY, with betweenness centrality values of 85 and 84, respectively.

Table 4 summarizes the visual analysis result of 1998 papers about the IES, which were retrieved from WOS and were published in recent 20 years, including the top 8 ranks of the Related-Author, Institution, Keywords, Hot articles, Hot journals, Cited-References and Country.

Table 4 shows that "APPL ENERG," "ENERGY" and "RENEW SUST ENERG REV" are the top three cited journals. In addition to "APPL

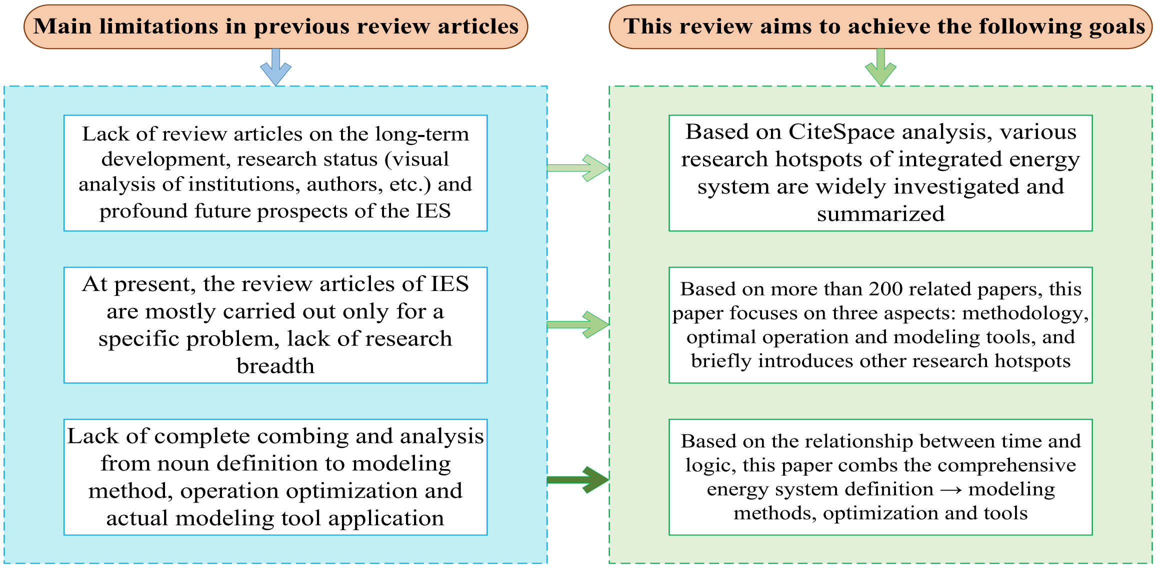

Fig. 3. Tackled problems of current reviews and the main goals of this paper.

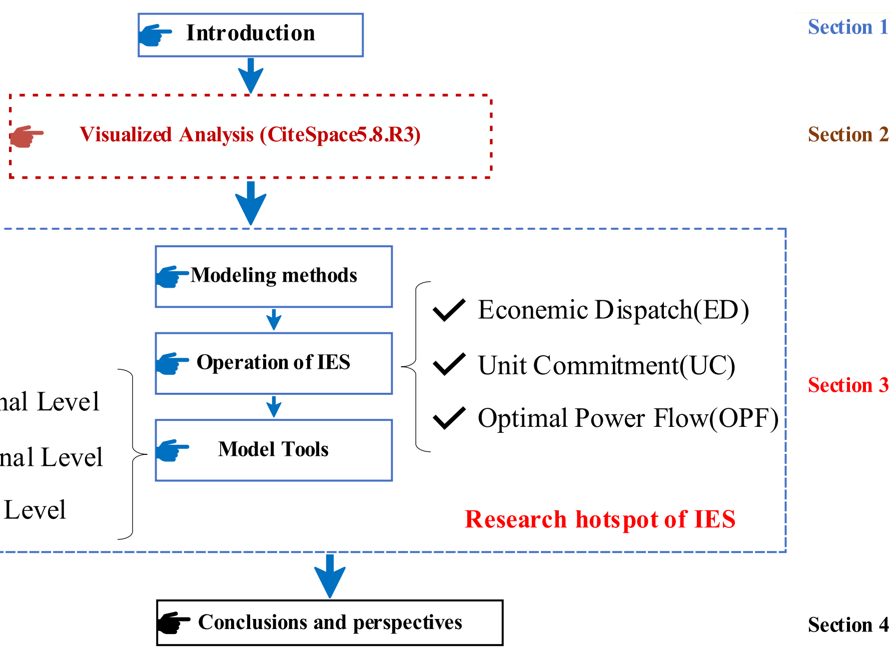

Fig. 4. The structure of this paper.

ENERG," it can be found that the cited frequency is not positively proportional to the betweenness centrality. Even if the cited frequency is high, it does not necessarily imply great influence of a journal. These results will hopefully guide researchers to quickly find suitable journals for publications related to IES.

2.3. Microcosmic research topic analysis

2.3.1. Keyword Co-occurrence network and burst detection analysis

The keywords represent the focus of the paper, which in turn reflects the disciplinary structure of the paper to some extent. Word frequency analysis is carried out on the literature in a certain field, and the research hotspots and development trends in the research field are expressed by extracting the distribution of the frequency of the keywords. By constructing the co-word network, the disciplinary structure in the data set is clearly displayed: each node represents a paper. The larger the node, the higher the word frequency of the keyword, and the greater the relevance to the topic of the paper. Fig. 5(e) shows that "Optimization," "Model," "Integrated Energy System," "Design" and "Performance" are the five most frequently used keywords in this field.

Based on keyword co-occurrence, the LLR algorithm is used to extract keyword tags and cluster the keywords. The visualization results are shown in Fig. 5(f). The IES research keyword clustering map includes 689 nodes and 4038 lines, forming 22 clustering tags. The clustering modularization q is 0.4135 ($Q > 0.3$), which shows that the community structure of the clustering network is significant, and the average contour value (s) is 0.7187. It indicates that the clustering results are valid. There are multiple clusters overlapping in the keyword clustering map, suggesting that this part of the clusters is closely related, that is, there are differences in the related research of optimization in IES, but the topics are concentrated. The keywords contained in the top 5 clustering modules are summarized in Table 5.

Table 4
IES visual analysis results.

Rank	Author	Institution	Keywords	Article	Journal	Cited-References	Country
1	IBRAHIM DINCER(59)	North China Elect Power Univ(114)	Optimization (380)	Santoyo-Castelazo and Azapagic, 2014 [116]	APPL ENERG (1260)	Liu XZ, 2016, APPL ENERG, 65, https://doi.org/10.1016/j.apenergy.2015.01.102	PEOPLES R CHINA.(827)
2	HONGJIE JIA (19)	Tianjin Univ(62)	Model(259)	Ghaffour et al., 2015 [117]	ENERGY(1182)	Li ZG, 2016, IEEE T SUSTAIN ENERG, 58, https://doi.org/10.1109/TSTE.2015.2467383	USA.(250)
3	WEI GU(17)	Southeast Univ (52)	Integrated energy system(247)	Brahman et al., 2015 [118]	RENEW SUST ENERG REV(901)	Gu W, 2017, APPL ENERG, 53, https://doi.org/10.1016/j.apenergy.2017.05.004	CANADA.(144)
4	YONGLI WANG(13)	Tsinghua Univ(50)	Design(220)	Ren and Gao, 2010 [119]	ENERG CONVERS MANAGE(900)	Bai LQ, 2016, APPL ENERG, 46, https://doi.org/10.1016/j.apenergy.2015.10.119	INDIA.(131)
5	SUYANG ZHOU(11)	Chinese Acad Sci (34)	Performance(217)	Bai et al., 2016 [120]	RENEW ENERG (724)	Li ZG, 2016, IEEE T SUSTAIN ENERG, 41, https://doi.org/10.1109/TSTE.2015.2500571	IRAN.(126)
6	PENG LI(11)	South China Univ Technol(33)	Power(177)	Gadalla et al., 2005 [121]	IEEE T POWER SYST(650)	Wu JZ, 2016, APPL ENERG, 39, https://doi.org/10.1016/j.apenergy.2016.02.075	ENGLAND.(111)
7	POURIA AHMADI(11)	Xi An Jiao Tong Univ(32)	Electricity(167)	Sechilariu et al., 2012 [122]	APPL THERM ENG(559)	Bahrami S, 2016, IEEE T SMART GRID, 37, https://doi.org/10.1109/TSG.2015.2464374	ITALY.(93)
8	QIUWEI WU (10)	Univ Ontario Inst Technol(32)	Generation(160)	Kanase-Patil et al., 2010 [123]	IEEE T SMART GRID(534)	Zhang XP, 2016, IEEE T POWER SYST, 34, https://doi.org/10.1109/TPWRS.2015.2390632	SOUTH KOREA.(69)

Keyword emergence refers to the significant increase of keyword frequency in a short time. Understanding the research with high attention during this period can judge the research hotspots and frontiers in the field [114, 116]. The keyword analysis in IES research literature in energy field is shown in Fig. 5(g). Keyword emergence analysis suggests that the optimization of mathematical model of IES may be the key research direction in this field in the future.

2.3.2. Brief conclusion

The analysis results show that: Ibrahim Dincer is the author of the most published papers, and his research directions include “energy and environmental policy and plan implementation technology, energy and exergy analysis of thermal systems and applications, energy conservation and emission reduction, and so on”. North China Electric Power University is the research institution with the largest number of publications, followed by Tianjin University and Southeast University. The publication institutions are mostly distributed in Chinese colleges and universities, State Grid, etc., and the cooperation between institutions is very close. The keywords for literature research mainly include: “Energy storage, optimal scheduling, optimal operation, mathematical modeling, multi-energy coupling” etc. Currently, researches in the field of IES are increasing year by year, and the research focus is that energy systems can be used as an important way to achieve key topics such as carbon neutrality and smart grids. Word emergence suggests that the analysis of IES optimization modeling may still be a major trend in future research.

3. Methodologies

3.1. Model methods

At present, a large number of analysis models have been used for the analysis of IES, and there are many classifications for these models. For example, based on model technology, related models can be divided into optimization, econometrics, process, dynamics, game theory, and so on [124]; based on the optimization methods, the models are divided into Top-down, Bottom-up, mixed, etc. (Table 6) [125,126]; based on the geographical location, they are divided into National, Regional and Users [127].

In addition, Table 7 compares and analyzes different modeling methods. It is not difficult to find that the Top-down accounting model has strong flexibility and low technical requirements, but its weakness is that it is unable to strictly analyze the influence of price factors. The econometric model can neither fully analyze the new and traditional energy, nor the needs to be further improved in technology [129].

In order to meet more detailed classification requirements, it considers eight different categories to classify the modeling methods, including the purpose of building energy model, the analysis method of the model, the different methodologies used in model design, the mathematical method used, the spatial area covered by the model, the department targeted by the energy model, the time frame of model analysis and the required data type (Fig. 6). The above division benchmark, would enable researchers to compare various IES models in depth.

3.2. Operation optimization/scheduling

Expand the research problems in power system to IES, such as: Unit Commitment (UC), Optimal Power Flow (OPF), Economic Dispatch (ED) and so on [130-136].

3.2.1. Unit Commitment in IES

The “UC” problem in electrical power systems is to obtain the optimal start up and shut down schedule for electricity generation plant to satisfy the forecasted demand profile [137-139]. In the IES, it refers to controlling the optimal startup and shutdown of each unit to meet the needs of multiple energies system. Among them, energy storage is an important consideration of unit combination. To solve this optimization problem, scholars first put forward the UC framework of the concept of EH in 2009 [140]. EH is an improvement of the classical ED method of power system, and is widely used in IES.

3.2.2. Optimal power Flow in IES

The “OPF” is a large-scale, nonconvex, MINLP optimization problem, which belongs to NP-hard problem. The mathematical formula of OPF is detailed in Frank and Rebennack [141], so it will not be introduced here. The OPF in the power system is solved by combining ED calculation with a steady-state power flow equation. In the IES, the OPF is to meet the energy needs of a variety of energy and conversion devices under the constraints of the transmission system in the energy system. An actual case is shown in Fig. 7.

3.2.3. Economic Dispatch in IES

Traditionally, “ED” describes a broader set of optimization objectives

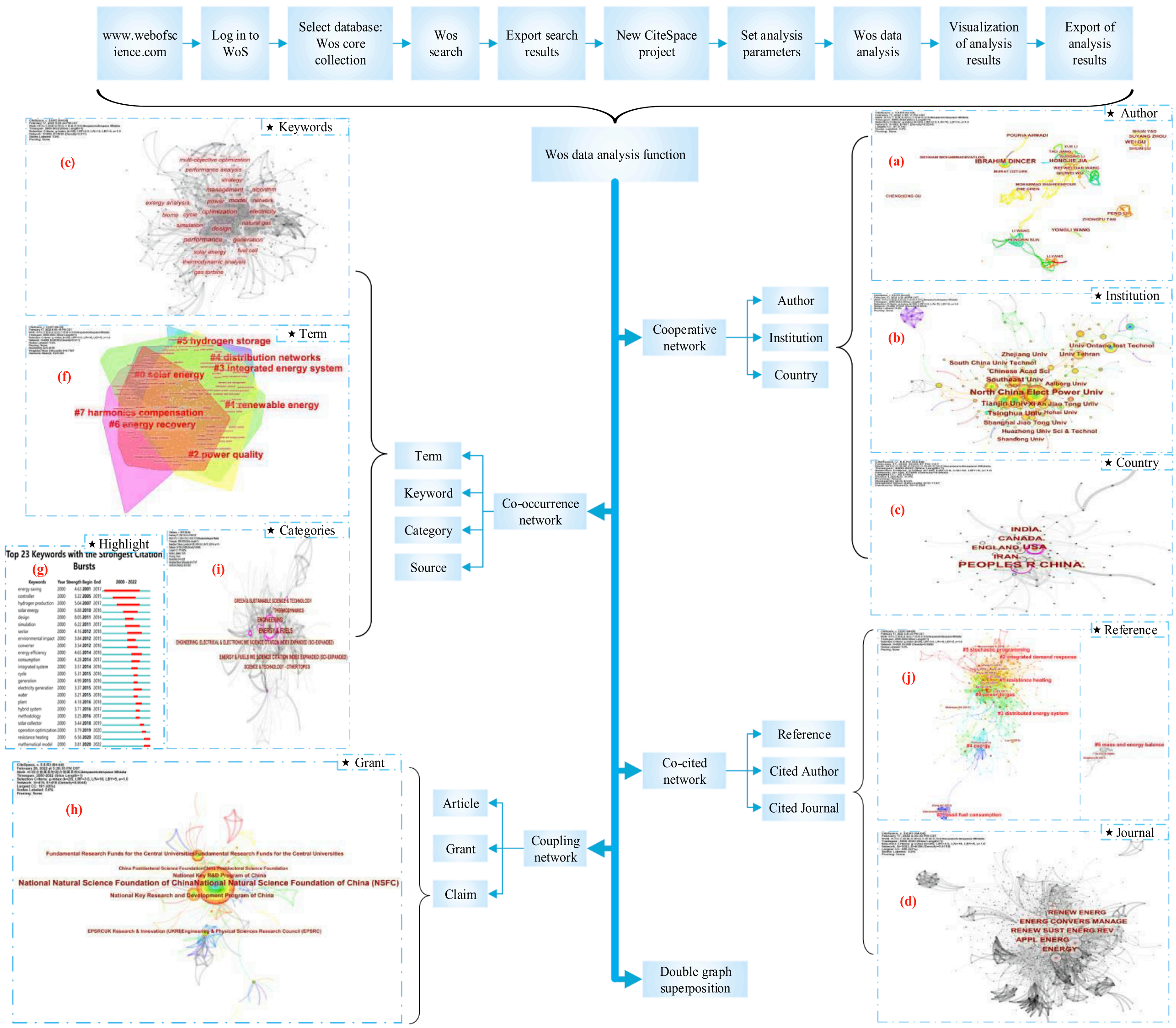

Fig. 5. CiteSpace analysis of research papers about IES (Appendix A).

Table 5
Keywords clustering of research papers of IES.

Cluster ID	Clusters name	Main keywords (LLR)
1	Solar energy	solar energy (92.96); exergy (81.51); efficiency (43.85); solid oxide fuel cell (40.43); organic rankine cycle (38.26)
2	Renewable energy	renewable energy (33.4); hybrid energy system (19); PV system (18.37); hybrid renewable energy system (18.37); smart grid (16.75)
3	Power quality	power quality (24.43); energy storage (22.97); robust optimization (19.11); battery (15.66); storage (13.95)
4	Integrated energy system	integrated energy system (56.41); natural gas (35.82); resistance heating (34.68); load modeling (31.99); energy hub (25.48)
5	Distribution networks	distribution networks (20.26); power markets (16.54); multi-objective optimization (15.83); power grids (15.09); solar energy (14.43)

that apply to the efficient operation of the power system bounded by a number of operational constraints [137].

Article [142] introduces a method of using EH to optimize power generation and energy conversion in IES (Fig. 8). This is the

Table 6
Classification of IES model methods*.

Paradigm	Space	Sector	Time	Examples
Top-down/ simulation	Global; national	Macro-economy, energy	Long-term	AIM, SGM2, I/O models
Bottom-up optimisation/ accounting	National, regional	Energy	Long-term	MARKAL, LEAP
Bottom-up accounting/ optimisation	National, regional, local	Energy	Medium-term, short-term	Sector models (power, coal)

* Source: [125].

transformation of ED from the traditional power system considering only electric energy to the comprehensive energy system. At present, this method has been widely used in the optimization operation of IES [143]. A complete summary of the research methods of ED is shown in Fig. 9. A detailed description of all complex parameters in Fig. 9 is added in Appendix B.

Table 7
Comparison of IES by modelling approaches*.

Criteria	Bottom-up, optimisation	Bottom-Up, accounting	Top-down, econometric	Hybrid	Electricity planning
Geographical coverage	Local to global, but mostly national	National but can be regional	National	National or global	National
Activity coverage	Energy system, environment, trading	Energy System and environment	Energy System, environment	Energy System, environment and energy trading	Electricity system and environment
Level of disaggregation	High	High	varied	High	Not applicable
Technology coverage	Extensive	Extensive but usually predefined	Variable but normally limited	Extensive but usually predefined	Extensive
Skill requirement	Very high	High	Very high	Very high	Very high
New technology addition	Possible	Possible	Difficult	Possible but often limited	Possible
Time horizon	Medium to long-term	Medium to long-term	Short, medium or long term	Medium to long-term	Medium to long term

* Source:[128].

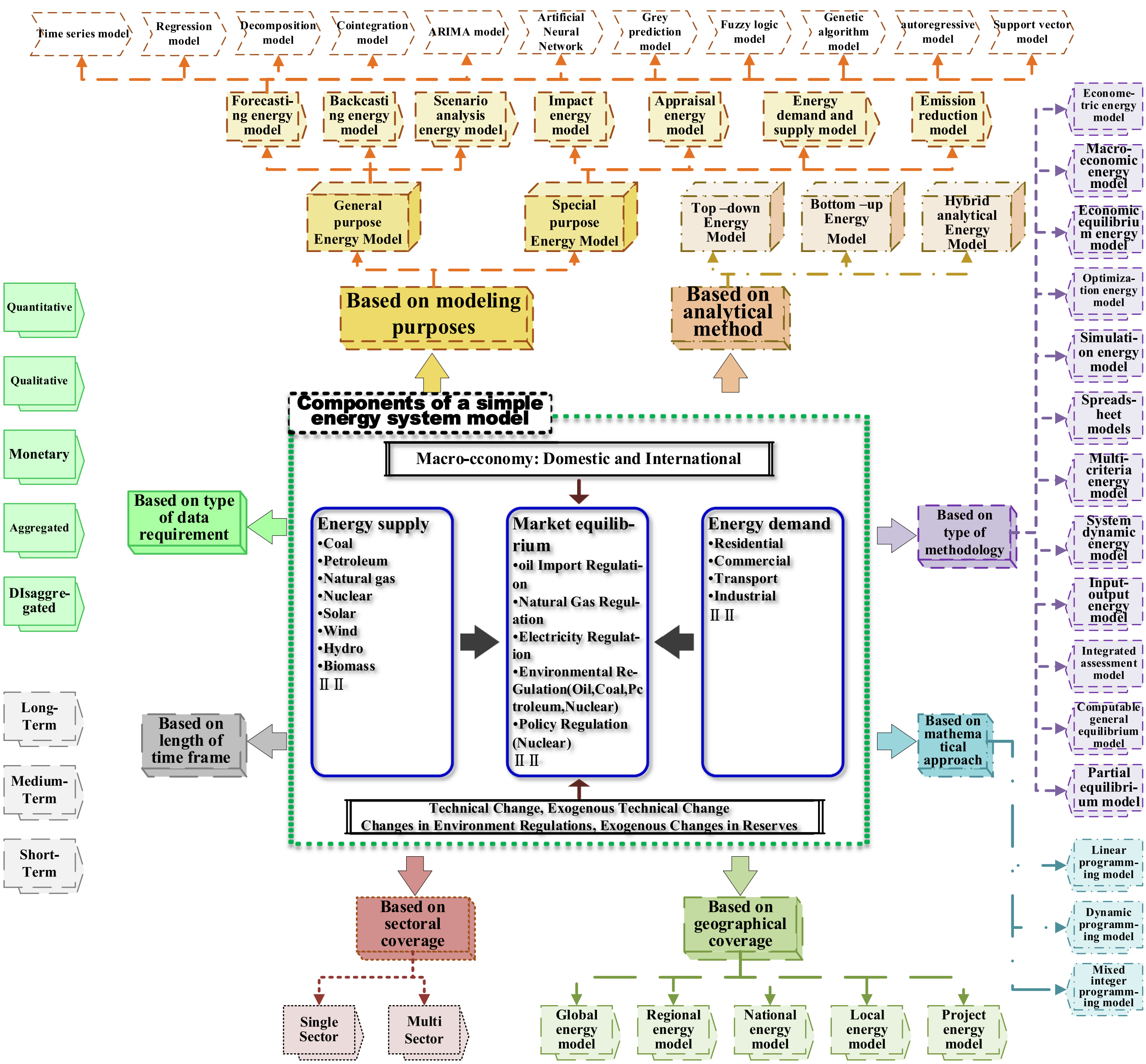

Fig. 6. Modeling methods and their classification.

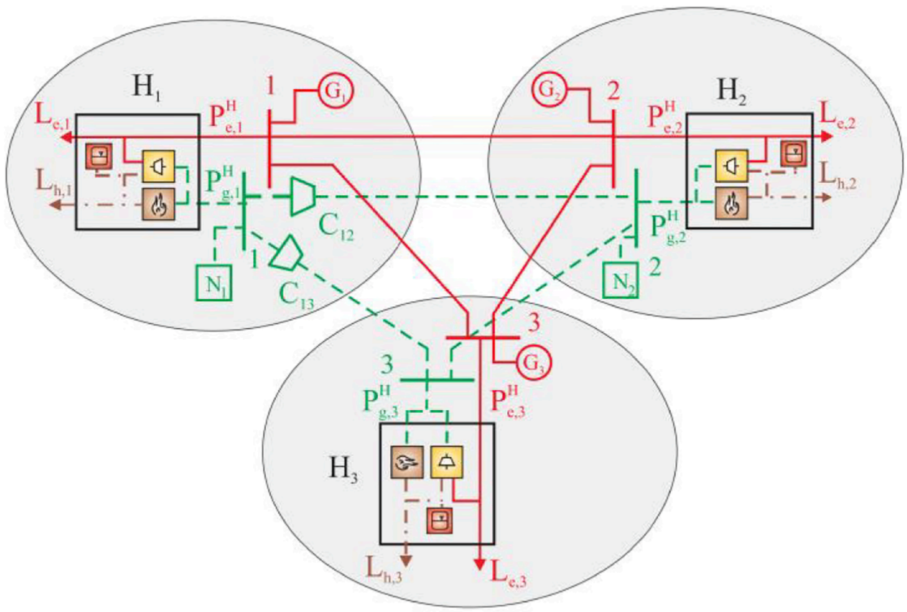

Fig. 7. System setup of three interconnected EHs.
Source: [25]

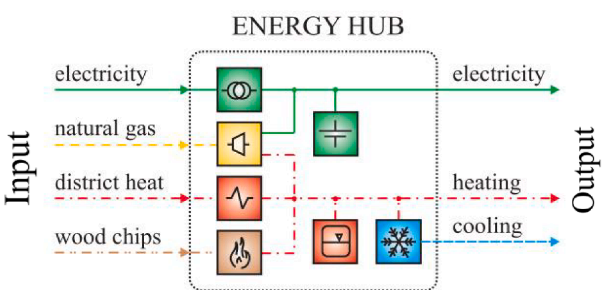

Fig. 8. Example of an EH.
Source: [155]

3.2.4. *Analysis*

Summarizing the three kinds of optimization problems mentioned above, optimization techniques are the key to solve them. Power related models often rely on optimization as the basic method. Hobbes determines that the main elements of its structure are as follows [144]: an objective function usually considers cost minimization, but financial and environmental objectives can also be used. A set of decision variables, which are determined by the modeler through the model; A set of constraints to ensure the feasible range of decision variables.

The IES optimization model is large-scale, nonlinear and with multi-stage mathematical submodule. The optimal IES operation has been extensively studied. Relevant review articles in Table 1 summarize the methods of optimizing operation. For example, according to the review article [95], the uncertainty optimization methods mainly include Probabilistic approach [145], Possibilistic approach [146], Robust optimization [147-150], Hybrid Possibilistic–Probabilistic approaches, Interval analysis [151], and Information gap decision theory [152]. At present, a number of survey appeared, focusing on the use of these methods on the individual tasks of optimization problems [153,154].

Among them, the major solution methods can be divided into Mathematical optimization and Metaheuristic search type. The specific analysis is as follows:

a) Mathematical Optimization Methods

Mathematical methods mainly include programming methods, relaxation technology, Benders Decomposition, interior point methods, etc. It is found that mathematical optimization methods can be divided into two categories: the unified method and the decomposition coordination method [35].

3.2.5. *Unified method*

The Unified Method is to convert the original mathematical model into a mathematical problem that is easy to be solved by using approximate equivalence. The technologies involved mainly include relaxation technology and decomposition. The main principle is to convert non-convex problems into convex optimization problems.

3.2.6. *Decomposition coordination method*

The Decomposition Coordination Method decomposes the original optimization model into multiple subsystems for optimization, and the global optimal solution is found through information interaction between each system.

This mathematical problem can be solved by solvers like CPLEX and GUROBI. It has two key methods: the design of the decomposition scheme, and the ability to update information in real-time.

b) Meta-Heuristic Search Methods

Meta-Heuristic Search algorithms have formed an independent optimization method. Because of their flexibility and interpretation ability, systems based on artificial intelligence are developed and deployed in countless applications all over the world. Since the middle of the 20th century, there have been many doubts: for example, excessive dependence on biological characteristics, lack of innovation and lack of deep scientific explanation [162]. This part provides a brief overview of the most influential metaheuristic search methods.

3.2.7. *Swarm intelligence*

Swarm Intelligence (SI) is characterized by the interaction and selection of multi-agent, and the ability to find the overall optimal solution through local and global coordination. The typical representative of the SI method is the ant colony algorithm [163]. Its main advantages include: easiness to obtain the global optimal solution, fast calculation speed and feasible adjustment. The disadvantages are that the local optimal solution needs to be obtained and the local search ability is weak.

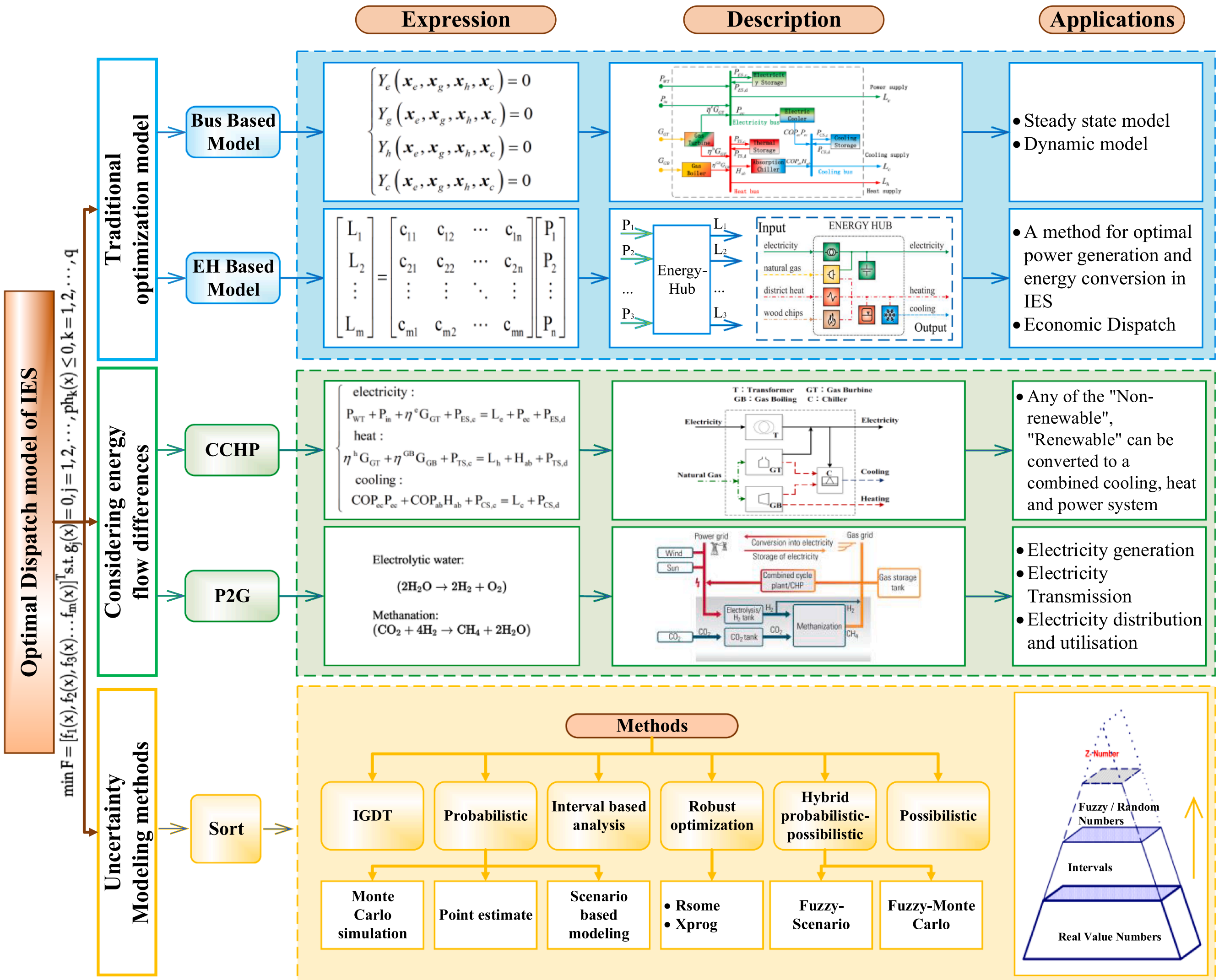

Fig. 9. ED model methods of IES.
Source: [25,95,156-161]

3.2.8. Evolutionary Computation

Evolutionary Computation (EC) belongs to a widely used subject. It mainly includes genetic algorithm (GA) [164] and Differential Evolution (DE) [165]. The main advantages are: limited information required, a simple fitness arrangement scheme and easy implementation of parallel computing. The disadvantages are that the design of objective function and adaptive individual selection are difficult, and the calculation pressure is high.

3.2.9. Machine learning algorithm

Traditional intelligent algorithms are slow in solving high-dimensional problems, and the selection of super parameters is also very difficult. To solve this kind of problem, machine learning is applied by relevant scholars, and its application in IES is becoming more and more prominent [63-65,166]. The advantages of machine learning are: strong generalization ability, solving nonconvex problems, and there are no problems such as super parameter selection. Disadvantages involve long offline training time.

The solution idea of the IES model is as follows: First, differentiate the differential equation into an algebraic equation, and then solve it by analytical method or artificial intelligence method. Fig. 10 summarizes the main benefits, limitations, and applications respectively.

In short, the limitations of *meta*-heuristic search methods include large amount of function calculation, no convergence proof for most problems, and optimal parameter selection of complex parameters, while the disadvantages of mathematical optimization methods involve poor performance in dealing with nonconvex optimization problems, incapability to deal with discrete variables, and difficulty in dealing with multi-objective problems.

3.3. Model tools

Modeling and simulation in the energy sector are one of the most active areas in the field of IES management. Effective development and utilization are important issues to improve energy efficiency and protect the environment under the background of sustainable development. The open-source IES optimization tools have been reviewed in [81]. According to review articles [72-87], various candidate energy tools were summarized. This includes over 100 tools, a handful of which are no longer available like EADER. To meet specific technical needs, this paper selects these tools by “Whether they are suitable for sustainable development?”, and takes 22 modeling tools for detailed analysis, including National level: EnergyPLAN, MARKAL, POLES, LEAP, ESME, PRIMES, DyneMo, E4cast, RETScreen; Regional level: GEM-E3, DER-CAM, NEMS, Renpass, TEMOA, SWITCH, CloudPSS; Users level: eTransport, TRNSYS, HOMER, COMPOSE, Calliope, iHOGA.

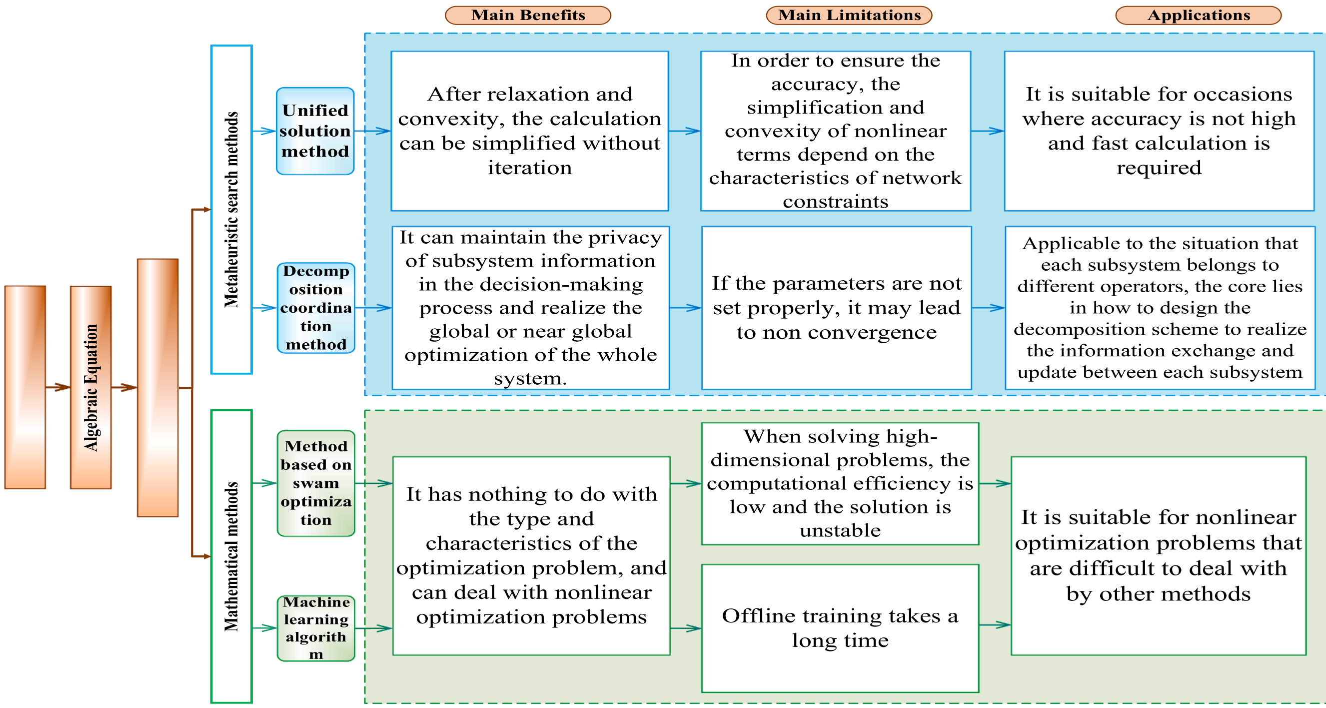

Fig. 10. Comparison of solution methods for IES.

In the actual energy planning process, the selected models can be divided into National Level IES (Table 9), Regional Level IES (Table 10) and User Level IES (Table 11) according to the geographical scope and energy generation/transmission/distribution/use characteristics. The characteristics of each simulation software in modeling type, programming language, time scale, optimization objective, practical application and user-friendliness are compared respectively. Finally, the characteristics of each model are briefly explained, and the benefits, limitations, and applications of 10 typical model tools are summarized.

3.3.1. National level

a) EnergyPLAN

EnergyPLAN was originally written in Excel spreadsheet in 1999. With later modification and development, the latest version was developed by Alborg University (Denmark) in September 2017 [167,168]. It is one of the most common tools in this choice and contains almost all relevant parameters of operation and planning analysis. The model adopts the “Bottom-up” method to optimize the energy system by running two different analysis methods. One is technical analysis, and the other is market economy calculation. In addition, the model supports recent energy storage technologies, such as hydrogen energy storage, superconducting energy storage and so on. The model has hourly time resolution and cannot fully balance power and network constraints. This platform has been used to simulate a 100% renewable energy system [169-173].

b) MARKAL

MARKAL (Market Alocation Model) has been developed as a mathematical model of the energy system of one or several regions, and it is a vertically integrated model of the entire energy system [174,175]. The model is an energy/economic/environmental model jointly developed in 1978 with the support of the energy technology system analysis program. It is a general model generator customized by data. It can model the whole energy system and simulate all thermal energy, renewable, storage and conversion and transportation technologies, but its training cycle takes several months. The model has been widely used in numerous studies, such as carbon capture, energy storage, nuclear fusion and so on [176]. Since the development of the original model, there have been a series of MARKAL models (Table 8). It has wide prospects in the future.

c) POLES

POLES (Prospective Outlook on Long-term Energy Systems) is a globally integrated simulation model developed by the United States, which is mainly used for long-term energy scenario analysis [180,181]. The model supports various modeling approaches, such as Bottom-up and Top-down. The specific features are as follows:

- The model can simulate all kinds of energy policies.
- The running time is in years, and the database is updated frequently, suitable for long-term scenarios.
- The add-on module covers all anthropogenic greenhouse gas emissions.

d) LEAP

LEAP (Long-range Energy Alternatives Planning System) is a comprehensive modeling tool developed by the Stockholm Institute of Environment in the United States for energy policy analysis and climate change assessment [182,183]. The model has been applied to hundreds of different organizations in more than 150 countries around the world and has been used to study the climate synergy of local air pollution reduction (especially in developing countries). The model also supports various modeling methods, such as Bottom-up and Top-down [183-186].

e) ESME

ESME (Energy System Modeling Environment) is a Bottom-up design tool developed by the Institute of energy technology (ETI) of University

Table 8
A family of MARKAL models.

Model	Method	Description	Refs.
MARKAL	LP	Standard version	[177]
TIMS	LP	Embodies the core of the MARKAL	[178]
MARKAL-MICRO	NLP	Integrated micro and energy system model	[174]
SAGE	NLP	A time-stepped version of MARKAL	[179]

College London [187]. The model is mainly used for long-term scenario analysis of comprehensive energy, but the details of its design are limited in technology. Monte Carlo analysis is introduced into the model based on the optimization principle, which is similar to TIMES/MARKAL. The specific features are as follows [188]:

- The model is designed to be policy-neutral and does not reflect the impact of various policies.
- The model can relate to other models developed by ETI and has good scalability. There is a research framework for realizing IES in cooperation with other technologies.
- The model lacks the connection with the general economic model.

f) PRIMES

PRIMES (Price Induced Market Equity System) is a large-scale applied energy system model developed by the Greek energy economy and Environment Laboratory (E3mlab) [189]. It provides detailed predictions of future energy supply and demand, price and investment, covering the whole energy system including emissions. The model runs for five years from 1990 to 2050. The specific features are as follows [190]:

- Combine behavioral modeling with engineering practice, covering all energy sectors and markets.
- It describes the policy impact and assessment related to the energy market and climate in detail.
- Include modular design and integration of the model, such as GEM-E3 macroeconomic model, the poles and the primes gas supply model.

g) DynEMo

DynEMo is a national-level dynamic energy simulation model developed by University College London [191]. The model includes electricity, oil, coal, natural gas and biomass, as well as the relationship between these energy carriers. The model adopts the Bottom-up modeling method, and the time step is from a few minutes to a few years. The specific features are as follows [192]:

- The model focuses on analyzing the behavior of the main elements in the energy system, so it is highly simplified.
- The model does not take energy storage technologies into account, such as hydrogen energy storage.

h) E4cast

E4cast is a partial equilibrium model originally developed by the Australian Bureau of Agriculture and Resource Economics (ABARE) in 2000 [193]. It is originally used to predict local energy consumption, production and trade, and has been updated so far. The specific features are as follows [194]:

- The model gives a detailed analysis of each energy sector, with special attention to renewable energy like wind.
- The model is mainly applied in Australia. It can also be used to assess the impact of policies on the environment and energy, as well as some private research.

i) RETScreen

RETScreen is a comprehensive clean energy management software platform originally developed by Natural Resources Canada in 1998 to analyze new energy and energy-saving technologies [195]. The specific features are as follows [196,197]:

- The model is based on Excel and has a high degree of visualization so that users can identify and evaluate the feasibility of energy efficiency, renewable energy and cogeneration projects intuitively.
- The model has been used as a research tool by more than 1400 academic institutions around the world, with a high international application rate and high citation rate.

3.3.2. Regional level

a) GEM-E3

GEM-E3 (General Equilibrium Model for Economy-Energy-Environment) is a multi-regional, multi-sectoral and empirical large-scale dynamic equilibrium (CGE) model [198]. It provides a platform for the relationship between the economy, environment and energy system. The specific features are as follows [199]:

- With modular design, the model supports policy analysis.
- The model adds microeconomic mechanism and institutional characteristics to the macroeconomic framework, with strong technical details.
- The model supports a large number of modeling options, market institutions and closed rules.
- The model provides opinions on energy distribution under long-term structural adjustment.

b) DER-CAM

DER-CAM (Distributed Energy Resources Customer Adoption Model) is originally designed by Lawrence Berkeley National Laboratory [200,201]. Now, there are mainly two versions: investment planning and operation, which are still continuously updated. The specific features are as follows [202-204]:

- The model uses mathematical modeling technology to transform the optimal multi-energy optimization problem into mixed-integer linear programming (MILP), which can solve the global optimal solution.
- The model has a high degree of visualization and is applicable to various energy problems such as unit combination, planning and dispatching, which is widely used.

c) NEMS

NEMS (National Energy Modeling System) is a large-scale regional energy economy environment model developed by the U.S. Energy Information Administration (EIA) using a hybrid method [205,206]. The model is composed of four supply modules, two conversion modules, four end-use demand modules, one module simulating energy/economy interaction, one module simulating oil market and one integrated module providing market balance among all other modules. It can accurately predict the impact of energy policy and energy market on energy, economy, environment and security. The specific features are as follows [207,208]:

- NEMS is used for annual energy outlook analysis and environmental change analysis in the United States.
- The model adopts modular design and can flexibly simulate various market behaviors.

d) Renpass

Renpass (Renewable Energy Pathways Simulation System) is an open source simulation energy model developed and designed by znes Flensburg and others [209]. The model is completely open-source and can visually analyze 100% renewable energy system and current energy system with high time resolution and high regional coverage. The detailed introduction and description of Renpass model are further described in the doctoral thesis [210].

e) TEMOA

TEMOA (Tools for Energy Model Optimization and Analysis) is an open-source tool [211]. The model has become a key tool for technology assessment and policy analysis from local to global scale. The specific features are as follows [212]:

- The model transforms the energy planning problem into a linear programming problem, and there is an open-source software package based on Python.
- The model uses the modern control system to publicly archive the model source data.
- The model is a typical representative of energy system optimization model designed in high-performance computing environment.

f) SWITCH

SWITCH (Solar, Wind, Transmission, Conventional generation and Hydroelectricity) is a real-time energy system program model platform developed for California in United States, to realize the selection of the lowest cost scheme of the energy system under constraints [213]. The model can explore the performance of the energy system under different scenarios. So far, it has been adopted by many countries and regions, such as the western region of the United States, Chile, China, India and so on. It has been applied in various energy, customer and development institutions [214].

g) CloudPSS

CloudPSS (Cloud Based Integrated Energy Planning Studio) is a simulation platform for energy Internet Oriented Digital twin application in energy system, which is jointly developed by the Department of electrical engineering of Tsinghua University (research team for security control and efficient utilization of modern power energy system) and Tsinghua Sichuan energy Internet Research Institute (cloud simulation and intelligent Decision Research Center) [215]. The innovation of the model applies digital twin model and artificial intelligence aided decision-making to the actual energy system. CloudPSS includes the modeling, simulation and analysis functions of various energy networks. Specific module functions are as follows [216,217]:

- Simstudio: organize and manage the digital twin simulation model of energy and power system.
- Funcstudio: Digital twin technology of energy and power system.
- Appstudio: build a digital twin application scenario of energy and power system.

3.3.3. Users level

a) eTransport

The eTransport is an energy optimization model invested and developed by the Norwegian Research Council and 11 Norwegian energy companies since 2001 [218,219]. The model is mainly divided into two modules: the energy system model (operation model) and the investment model. The former adopts the combination of LP and MIP, while the latter carries out dynamic programming (DP) with the help of C + +. It includes a variety types of energy, energy conversion and energy transportation modes, supporting the modeling and simulation of electricity, heat, cold and gas [220]. Moreover, the category of spatial optimization was presented into this model, which is still expanding now.

b) TRNSYS

TRNSYS (Transient System Simulation) is a quasi-steady-state simulation model originally used for thermal system simulation. It has been widely used since 1975 [221,222]. At present, it is jointly maintained by relevant institutions in the United States, France and Germany. It is widely used in the solar system, HVAC systems, renewable energy systems, cogeneration, energy storage and other fields. The specific features are as follows [80,223-227]:

- The model adopts a modular design, which has the advantage of providing detailed dynamic operation simulation data, and it can simulate and analyze different systems.
- The module source code of the model is open; the system is convenient and flexible, and the compatibility is strong.
- TRNSYS does not provide optimization tools and requires the cooperation of other optimization tools.

c) HOMER

The first version of HOMER (Hybrid Optimization of Multiple Energy Resources) was released by the National Renewable Energy Agency (USA) in 1992 [228]. Its main functions are system optimization and sensitivity analysis [229,230]. It has been used in many off-grid energy system analyses. The specific features are as follows [231,232]:

- High degree of visualization: it has the drawing function of displaying the results in tabular form.
- Be able to conduct sensitivity analysis on hourly data sets.
- The computational complexity of the model makes it only suitable for the planning of microgrid scale, not for multi-objective optimization.

d) COMPOSE

COMPOSE (Compare Options for Sustainable Energy) is a new type of vertical IES optimization tool established at Auerbarg University in 2008 [233,234]. It takes the lowest cost as the objective function of optimization. Mixed integer linear programming (MILP) is used to realize economic optimization. The specific features are as follows [235,236]:

-Strong expansion ability: it has data transmission interfaces to connect other models, such as transmitting hourly energy distribution from EnergyPLAN and importing local climate data from RETScreen.

e) Calliope

Calliope is an energy system model framework that focuses on flexibility and high resolution. It realizes the separation of a framework (code) and model (data) [237]. Its main planning scope ranges from the urban area to the whole area. The model consists of a set of text files (YAML and CSV format), which fully define a system and describe the relevant technical features in detail. The specific features are as follows [238]:

- The model is attached with analysis and visualization tools, and its user-defined and editable abilities are outstanding.
- The model is open-source and available on GitHub.

f) iHOGA

iHOGA (Hybrid Optimization by Genetic Algorithm) is developed by the University of Zaragoza, Spain based on the improved genetic algorithm [239]. At present, it only supports Spanish. iHOGA has two versions. The educational version is free of charge but has some functional limitations. The professional version is a paid version without any functional restrictions. The specific features are as follows [240,241]:

- The model considers different types of power sales/purchase.
- The model supports data export. The model provides highly accurate modeling and uses genetic algorithm for multi-objective and single-objective optimization.

3.3.4. Analysis

In order to systematically and clearly summarize the characteristics of various modeling tools, Fig. 11 provides a comprehensive summary of the main benefits, limitations and applications of 10 typical modeling tools [172,240,242,243]. It includes: ①National Level: RETScreen, MRAKAL, LEAP, EnergyPLAN; ②Regional Level: DER-CAM, NEMS and CloudPSS; ③Users Level: HOMER, TRNSYS and iHOGA.

4. Discussions and conclusions

4.1. Discussions

This paper focuses on a systematic review of IES, which is mainly divided into Model methods, Operation optimization and Model tools. Table 1 summarizes the hot research directions related to IES, including 12 research directions: optimal operation, modeling tools, the EH,

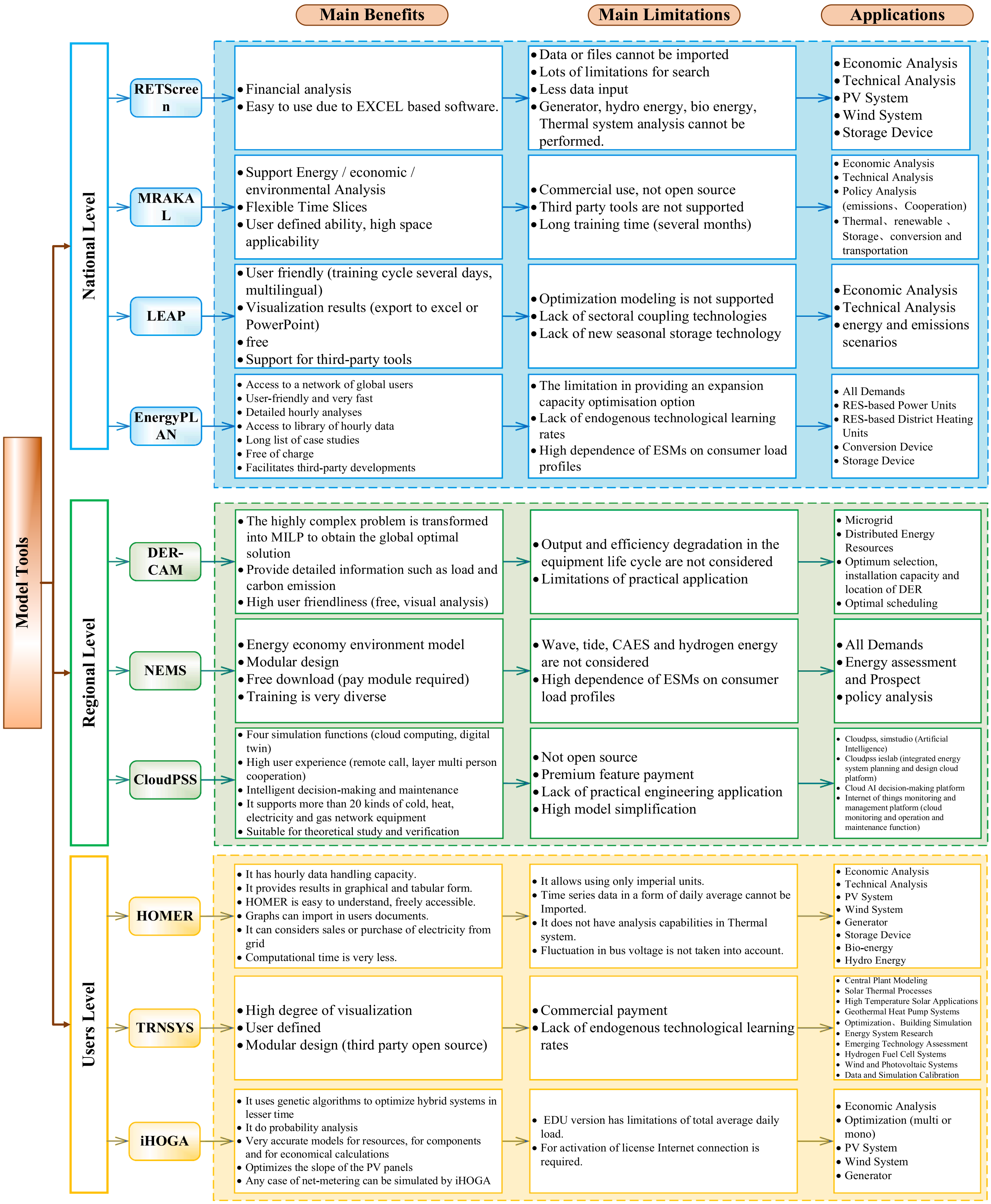

Fig. 11. Comparison and evaluation of 10 typical model tools.

energy storage, IES elasticity, IES uncertainty, the application of artificial intelligence in IES and so on. Table 4 presents the analysis on the research of IES in recent 20 years, including author, organization, key words, hot articles, hot journals, and cited articles. Based on these researches, the IES modeling methods are categorized into eight types and shown in Fig. 6, and model analysis on the typical optimization problem of optimal scheduling in IES are shown in Fig. 9. From Table 9 to Table 10, a total of 22 modeling tools are summarized comprehensively from the levels of National, Regional and Users. To sum up, Fig. 12 shows all the benefits and applications of IES.

Table 9
National level simulation tools*.

Model	Model Type (Methodology)	Programing language	Time Horizen	Objectives	Commodities	Main application	Availability	User friendliness
EnergyPLAN	S (Bottom-up)	Executable	1 year	Scenario / Investment Decision Support	Electricity, Heat and Hydrogen	Country models, city models. 100% renewable plans, assessment of technologies, Research projects	Free	★★★★★
MARKAL	LP/MIP, PE (Bottom-up)	GAMS/VEDA	Long-term (User-defined)	Scenario	All Commodity	Policy support, emissions, Global Energy and Climate Outlooks, evaluate, scenarios	Commercial (Demo-version available)	★★★★★
POLES	PE/S (Hybrid)	N.A.	2050 (2100)	Scenario, Investment & Operation Decision Support	Electricity, Oil, Gas, Coal, Biomass	Policy support, Research projects, Global Energy and Climate Outlooks, Climate change, mitigation scenarios	Not available	★★
LEAP	S & LP (Hybrid)	SA-C	Typically 20 to 50 years	Scenario	Electricity and heat	Energy Outlook, Policy support, Research projects, Climate Change	Free for students, developig countries. Commercial for OECD countries	★★★★
ESME	LP (Bottom-up)	ETI	Up to 2050	UK	Electricity, Heat and Hydrogen	Policy support, Research projects	Available for the ETI membership, academics	★★★
PRIMES	PE (Hybrid)	Others	Long-term	Scenario + Investment decision support	Electricity, Heat and Hydrogen	Impact assessment	Not available	★★
DynEMo	S (Spreadsheet)	VBA	Up to 2050	UK and France	Electricity and heat	capture the behaviour of all energy system scenarios	Limited Access	★★
E4cast	PE (Bottom-up)	GAMS	Up to 2050	Australia	Electricity and heat	energy consumption, production and trade	Commercial	★★
RETScreen	S (Hybrid)	Windows with.NET	Max 100 years	Investment Decision Support & Scenario	Electricity and Heat	low-carbon planning, implementation, monitoring and reporting	Free to use	★★★★

[*] Note: *S: Simulation, P:Optimization, LP:Linear Optimisation, MIP: Mixed Integer Programming, PE: Partial Equilibrium; VEDA:Solver, VBA: EXCEL.*

Table 10
Regional level simulation tools*.

Model	Model Type (Methodology)	Programing Language	Time Horizen	Objectives	Commodities	Application conditions	Availability	User friendliness
GEM-E3	CGE (Top-down)	GAMS	2030 and 2050	Scenario	All Commodity	Policy support, Research projects, scenarios	Not available	★★
DER-CAM	MILP (Bottom-up)	None(online version), GAMS (gets licensed)	Up to 20 years	Investment & Operation Decision Support	Electricity & Heat	Policy support, Research projects, Global Energy and Climate Outlooks, Climate change, mitigation scenarios	Free	★★★★
NEMS	S, P, PE (Hybrid)	Intel Fortran, Eviews, IHS Global Insight model, OML & Xpress solver, GAMS & Xpress, AIMMS & Cplex solver, R, MS Windows OS.	2050	Scenario	Electiricty and Heat (Hydrogen in transport can be accounted for)	Policy support, Research projects, scenarios	Free (Excluding IHS Global Insight macro submodel)	★★★
Renpass	S & P (Bottom-up)	MySQL, R, RMySQL	1 year	Operation Decision Support & Scenario	Electricity	100% renewable energy systems, Policy support, Research projects, scenarios	Open-source	★★★★
TEMOA	LP (Bottom-up)	Python + Linear solver	User-Defined	Scenario	Any commodity	Impact assessment	Open-source	★★★★
SWITCH	MILP (Bottom-up)	Python	2050 (user-selected)	Investment & Operation Decision Support	Electricity, Hydroelectric flows, Electric Vehicles	Policy support, Climate change, Climate change, scenarios	Open-source	★★★★
CloudPSS	S (Electricity-Planning)	None	Yearly / others	Scenario	All Commodity	Research projects, scenarios	Free	★★★★★

[*] Note: *S: Simulation, P:Optimization, LP:Linear Optimisation, CGE:* Computable General Equilibrium, *MIP: Mixed Integer Programming, MILP:* Mixed-Integer Linear Optimisation, *PE: Partial Equilibrium; VEDA:Solver, VBA: EXCEL.*

Number	Benefits of integrated energy systems(summary)	Applications of integrated energy systems(summary)
1	Carbon emissions reduction by increasing whole system energy efficiency	a) co-generation of electricity and heat b) optimising (in terms of carbon emission and/or costs) the operation of the overall energy system.
2	Increase of the generation and utilisation of renewable energy	a) Limiting the capacity of generation that can be connected b) Contracts that allow tripping/curtailment of the renewable plant in case of network congestion c) Charging any reinforcement costs of the network to the developer of renewable plant
3	Reduce capital expenditure by increasing asset utilisation and reduce/delay network reinforcements	a) Increasing existing asset utilization b) Reduce/delay network reinforcements
4	Cost effective provision of flexibility in the electrical power system	a) shifting electrical load between different energy systems b) providing access to a large pool of smaller sized quick response generation plant
5	Opportunities for business innovation	New business models and innovative processes can be introduced to take advantage of the emerging markets. This would potentially increase market competition across different energy sectors bringing value to the final consumer
6	Increased reliability of the electrical power system (e.g. security of supply)	Detailed modelling and analysis is required to identify the advantages and disadvantages of certain interconnections between networks.
7	Facilitation of low carbon sustainable districts and local governance of community projects	All countries are carrying out the development and research of "low-carbon sustainable areas and communities project"

Fig. 12. Benefits of IES.

Besides, referring to Table 1, the challenges of IES research are summarized as follows:

- Fragmentation between different institutions and markets. At present, the information interaction between policy and the market still needs to be improved, and the benefits brought by the model need to be shared in many aspects.
- High complexity of energy systems. The multi-energy carriers of the energy system lead to the complexity of optimization and operation. The analysis and optimization between different systems need more advanced tools to meet the needs of different scenarios.
- Interdisciplinary research needs of IES. The research content of energy systems involving multiple disciplines needs more cooperative relations and multi-party coordination.

4.2. Conclusions

This paper systematically reviews and analyses the research status of the IES in the field of energy. Among them, the visual analysis software (CiteSpace) is used for visual analysis, and three hot research issues including modeling methods, optimization problems and modeling tools are explained. Here, the following conclusions are summarized:

a) CiteSpace is used to visually analyze 1998 articles related to IES: cooperation network (author, institution, country/region), co-occurrence network (terminology, keyword, field), co-cited network (literature, Journal) and coupling analysis (article), which provide researchers with analysis basis.
b) For the current diversified modeling methods, eight different classification methods (purpose of modeling, analytical methods, type of methodology, mathematical approach, geographic coverage, sectoral coverage, length of time frame and type of data requirement) are summarily considered to meet the classification needs of more application scenarios, so as to facilitate the understanding of modeling methods.
c) Three kinds of traditional power system optimization problems (UC, OPF and ED) are introduced into the IES for re-analysis, and the optimization methods are divided into two categories: mathematical solution method and *meta*-heuristic algorithm.
d) Twenty-two modeling tools are systematically compared and analyzed in terms of type, modeling language, time scale, objective function, application scenario, user-friendliness and so on (Table 9, 10 and 11). Besides, the advantages, disadvantages and applications of 10 typical modeling tools are further analyzed (Fig. 11).

5. Perspectives

Under the goal of carbon peak and carbon neutralization, the energy and power industry are undergoing unprecedented changes. It is particularly noteworthy that carbon neutralization will accelerate the zero-carbonization process of power growth and develop a clean and circular economy. It also needs the coordinated development of strong large power grid and intelligent distribution system to gradually evolve into an IES. Besides, it also exists many opportunities. The specific prospects are as follows:

- Develop IES simulation tools suitable for multiple scenarios. At present, there are many researches and modeling methods on IES, but the ability of relevant modeling methods and modeling tools still needs to be further improved. The modeling scales in different scenarios are different, and the corresponding optimization design, operation planning and related control algorithms are also different. In addition, the energy coupling and dynamic analysis under the respective characteristics of multi energy carriers still need further research.
- Develop standard models for case studies. Energy systems in different regions and different energy carriers need relevant authorities to develop standard network models to provide standards for comparing the actual effects of various research schemes.
- Develop standards to evaluate IES performance. Different energy systems have their own evaluation systems, and the evaluation varies greatly. Under multi energy coupling, it is necessary to establish standards to describe the overall performance of the energy system and quantify the mutual dependence and economy.
- Develop new opportunities to create business opportunities. Combined with the market potential under the demand side mechanism, explore new business models that give full play to the advantages between the demand side and the power market, natural gas market

Table 11
Users level simulation tools*.

Model	Model Type (Methodology)	Programing Language	Time Horizen	Objectives	Commodities	Application conditions	Availability	User friendliness
eTransport	PE/S (Hybrid)	N.A.	2050 (2100)	Scenario, Investment & Operation Decision Support	Electricity, Oil, Gas, Coal, Biomass	Policy support, Research projects, Global Energy, Climate Outlooks, Climate change, mitigation scenarios	Not available	★★
TRNSYS18	S & LP (Bottom-up)	Stand-alone	Multiple years	Power System Simulation Tool	Electricity, Hydrogen and Heat	Policy support, Research projects, Global Energy, Climate Outlooks, mitigation scenarios	Commercial (Demo-version available)	★★
HOMER	S & P (Bottom-up)	Stand-alone	Multi-Year	Scenario + Investment decision support	Electricity and Heat	Impact assessment	Commercial - Free trial version	★★
COMPOSE	MILP (Bottom-up)	Windows-based, open-source MILP solver, commercial solver license recommended	No limit	Operation Decision Support & Scenario	Electricity, Heat, Cooling, Fuels	Policy support, Research projects, Global Energy, Climate Outlooks, Climate change, scenarios	Free academic licensing, commercial licensing available	★★★★
Calliope	MILP (Bottom-up)	Python	No limit	Investment & Operation Decision Support	Electricity, Hydrogen, Heat and Fuels	Impact assessment	Open-Source	★★★★
iHOGA	Heuristic Optimisation (Bottom-up)	Stand-alone	Yearly	Investment & Operation Decision Support	Electricity and Hydrogen	Free Educational Version + Commercial PRO + version	Free Educational Version + Commercial PRO + version	★★★★

* Note: *S: Simulation, P:Optimization, LP:Linear Optimisation, CGE:* Computable General Equilibrium, *MIP: Mixed Integer Programming, MILP:* Mixed-Integer Linear Optimisation, *HP:* Heuristic Optimisation, *PE: Partial Equilibrium; VEDA:Solver, VBA: EXCEL.*

and carbon trading market, so as to achieve mutual benefit and win–win, low-carbon and high efficiency. Further investigate the market design that can give full play to the various advantages of IES, optimize the potential benefits to the greatest extent, and conduct quantitative analysis through the actual project.

- Develop smart energy systems that integrate multiple technologies. Introduce diversified modeling and Simulation of energy Internet; Flexible introduction of artificial intelligence, machine learning, digital twinning, blockchain and other technologies to give greater play to automation; Open interfaces of different tools are designed to promote later development.
- Develop IES with a high proportion of renewable energy to meet elastic demand. Introduce other low-carbon renewable energy (Energy Storage) into the infrastructure to meet the normal fluctuation and elastic demands of the system under various faults. The energy system of the old park shall be reconstructed as far as possible, and the energy supply and demand shall be reasonably regulated to meet the consumption of distributed energy.

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.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under Grant 52177204 and 51777217; the Natural Science Foundation of Hunan Province (No. 2020JJ4744); the Innovation-Driven Project of Central South University (No. 2020CX031); the Major Science and Technology Projects in Anhui Province under Grant 202003a05020019.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2022.115863.

References

[1] Murdock HE, Collier U, Adib R, Hawila D, Bianco E, Muller S, et al. Renewable energy policies in a time of transition. 2018.
[2] Liu Z, Deng Z, He G, Wang H, Zhang X, Lin J, et al. Challenges and opportunities for carbon neutrality in China. Nat Rev Earth Environ 2022;3:141–55.
[3] Murdock HE, Gibb D, André T, Sawin JL, Brown A, Appavou F, et al. Renewables 2020-Global status report. 2020.
[4] Murdock HE, Gibb D, Andre T, Sawin JL, Brown A, Ranalder L, et al. Renewables 2021-Global status report. 2021.
[5] Epa. Quantifying the Multiple Benefits of Energy Efficiency and Renewable Energy: A Guide for State and Local Governments. US Environmental Protection Agency Washington, DC, USA2018.
[6] Bragg-Sitton SM, Rabiti C, Boardman RD, O'Brien JE, Morton TJ, Yoon S, et al. Integrated Energy Systems: 2020 Roadmap. United States, 2020. p. Medium: ED; Size: 67 p.
[7] Ze-hui S, Chao-gang L. Overview of integrated energy systems. Chem Eng Des Commun 2019;45:209–10.
[8] Ranalder L, Busch H, Hansen T, Brommer M, Couture T, Gibb D, et al. Renewables in Cities 2021 Global Status Report. 2020.
[9] Chopra A, Kundra V. A POLICY FRAMEWORK FOR THE 21st CENT U RY GR ID: Enabling Our Secure Energy Future. (2011).
[10] United Nations Framework Covention on Climate Change, 2015. https://doi.org/FCCC/CP/2015/L.9/Rev.1.
[11] United Nations Sustainable Development Goals New York, 2013. http://www.un.org/sustainabledevelopment/sustainable-development-goals/.
[12] Liserre M, Sauter T, Hung JY. Future energy systems: integrating renewable energy sources into the smart power grid through industrial electronics. IEEE Ind Electron Mag 2010;4:18–37.
[13] Jaccard M. Sustainable fossil fuels: the unusual suspect in the quest for clean and enduring energy. Cambridge: Cambridge University Press; 2006.
[14] Memon SA, Patel RN. An overview of optimization techniques used for sizing of hybrid renewable energy systems. Renewable Energy Focus 2021;39:1–26.
[15] LeMar P. Integrated Energy Systems (IES) for Buildings: A Market Assessment. United States, 2002. p. Medium: ED; Size: 75 pages.
[16] Greenwood MS, Yigitoglu AG, Rader JD, Tharp W, Poore M, Belles R, et al. Integrated Energy System Investigation for the Eastman Chemical Company, Kingsport, TN Facility. United States, 2020. p. Medium: ED; Size: 110 p.
[17] Hongjie J, Yunfei M, Xiaodan Y. Thought about the integrated energy system in China. Electric Power Constr 2015;36:16–25.
[18] Haozhong C, Xiao H, Li W, Yuquan L, Qi Y. Review on research of regional integrated energy system planning. Autom Electric Power Syst 2019;43:2–13.
[19] Bo Y, Hengnan S. Planning design method of integrated energy system. Electric Power Constr 2016;37:78–84.
[20] Kaiqi M, Di W, Hao Z. A look at hybrid simulation technology for integrated energy system. Distrib Utiliz 2018;35:28–33.

[21] Ming Z, Dao-xin L, Na L, Da-peng D. Key economic issues in integrated energy system. East China Electric Power 2013;41:1403–8.
[22] Ming Z, Yingxin L, Mengxi H. Review and prospects of integrated energy system modeling and benefit evaluation. Power System Technol 2018;42:1697–708.
[23] Jianzhong W. Drivers and State of-the-art of Integrated Energy Systems in Europe. Autom Electric Power Syst 2016;40:1–7.
[24] Wikipedia. https://en.wikipedia.org/wiki/Main.
[25] Abeysekera M, Jenkins N, Wu J. Integrated energy systems: An overview of benefits, analysis, research gaps and opportunities. (2016).
[26] Wang JX, Zhong HW, Ma ZM, Xia Q, Kang CQ. Review and prospect of integrated demand response in the multi-energy system. Appl Energy 2017;202:772–82.
[27] Aljabery AAM, Mehrjerdi H, Mahdavi S, Hemmati R. Multi carrier energy systems and energy hubs: Comprehensive review, survey and recommendations. Int J Hydrogen Energy 2021;46:23795–814.
[28] Guelpa E, Bischi A, Verda V, Chertkov M, Lund H. Towards future infrastructures for sustainable multi-energy systems: a review. Energy 2019;184:2–21.
[29] Son YG, Oh BC, Acquah MA, Fan R, Kim DM, Kim SY. Multi energy system with an associated energy hub: a review. IEEE Access 2021;9:127753–66.
[30] Mohammadi M, Noorollahi Y, Mohammadi-ivatloo B, Yousefi H. Energy hub: From a model to a concept – A review. Renew Sustain Energy Rev 2017;80:1512–27.
[31] Lian J, Zhang Y, Ma C, Yang Y, Chaima E. A review on recent sizing methodologies of hybrid renewable energy systems. Energy Convers Manage 2019;199:112027.
[32] Hosseini SHR, Allahham A, Walker SL, Taylor P. Optimal planning and operation of multi-vector energy networks: a systematic review. Renew Sustain Energy Rev 2020;133.
[33] Fonseca JD, Commenge JM, Camargo M, Falk L, Gil ID. Sustainability analysis for the design of distributed energy systems: A multi-objective optimization approach. Appl Energy 2021;290.
[34] Ogunmodede O, Anderson K, Cutler D, Newman A. Optimizing design and dispatch of a renewable energy system. Appl Energy 2021;287.
[35] Jinghua L, Mengshu Z, Yuejiang L, Yujin H, Tong W. Review on optimal scheduling of integrated energy systems. Power Syst Technol 2021;45:2256–72.
[36] Bhowmik C, Bhowmik S, Ray A, Pandey KM. Optimal green energy planning for sustainable development: a review. Renew Sustain Energy Rev 2017;71:796–813.
[37] Wang Y, Wang J, Gao M, Zhang D, Liu Y, Tan Z, et al. Cost-based siting and sizing of energy stations and pipeline networks in integrated energy system. Energy Convers Manage 2021;235:113958.
[38] Gencer E, Torkamani S, Miller I, Wu TWZ, O'Sullivan F. Sustainable energy system analysis modeling environment: analyzing life cycle emissions of the energy transition. Appl Energy 2020;277.
[39] Koj JC, Wulf C, Zapp P. Environmental impacts of power-to-X systems - A review of technological and methodological choices in Life Cycle Assessments. Renew Sustain Energy Rev 2019;112:865–79.
[40] Berjawi AEH, Walker SL, Patsios C, Hosseini SHR. An evaluation framework for future integrated energy systems: a whole energy systems approach. Renew Sustain Energy Rev 2021;145.
[41] Tahir MF, Chen HY, Han GZ. A comprehensive review of 4E analysis of thermal power plants, intermittent renewable energy and integrated energy systems. Energy Rep 2021;7:3517–34.
[42] Shixiang Z, Shuaikang L. Evaluation method of park-level integrated energy system for microgrid. Power Syst Technol 2018;42:2431–9.
[43] Wang JJ, Jing YY, Zhang CF, Zhao JH. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew Sustain Energy Rev 2009;13:2263–78.
[44] Luo XJ, Oyedele LO, Owolabi HA, Bilal M, Ajayi AO, Akinade OO. Life cycle assessment approach for renewable multi-energy system: a comprehensive analysis. Energy Convers Manage 2020;224.
[45] Al Moussawi H, Fardoun F, Louahlia-Gualous H. Review of tri-generation technologies: design evaluation, optimization, decision-making, and selection approach. Energy Convers Manage 2016;120:157–96.
[46] Xiaodan Y, Xiandong X, Shuoyi C, Jianzhong W, Hongjie J. A brief review to integrated energy system and energy internet. Trans China Electrotechn Soc 2016;31:1–13.
[47] Weiliang W, Dan W, Hongjie J, Zhaoyu C, Bingqing G, Haiming Z. Review of steady-state analysis of typical regional integrated energy system under the background of energy internet. Proc CSEE 2016;36:3292–306.
[48] Coroama VC, Hilty LM. Assessing Internet energy intensity: a review of methods and results. Environ Impact Assess Rev 2014;45:63–8.
[49] Guo M, Xia M, Chen Q. A review of regional energy internet in smart city from the perspective of energy community. Energy Rep 2022;8:161–82.
[50] Krumm A, Susser D, Blechinger P. Modelling social aspects of the energy transition: what is the current representation of social factors in energy models? Energy 2022;239.
[51] Moustakas K, Loizidou M, Rehan M, Nizami AS. A review of recent developments in renewable and sustainable energy systems: key challenges and future perspective. Renew Sustain Energy Rev 2020;119.
[52] Munro FR, Cairney P. A systematic review of energy systems: the role of policymaking in sustainable transitions. Renew Sustain Energy Rev 2020;119.
[53] Dias RA, de Paula MR, Rizol PMSR, Matelli JA, de Mattos CR, Balestieri JAP. Energy education: reflections over the last fifteen years. Renew Sustain Energy Rev 2021;141.
[54] Lehtveer M, Goransson L, Heinisch V, Johnsson F, Karlsson I, Nyholm E, et al. Actuating the European energy system transition: indicators for translating energy systems modelling results into policy-making. Front Energy Res 2021;9.
[55] Koppl A, Schleicher SP. What will make energy systems sustainable? Sustainability 2018;10.
[56] Hongjie J, Dan W, Xiandong Y. Research on some key problems related to integrated energy systems. Auomat Eleeric Power Syst 2015;39:198–207.
[57] Ming Z, Dao-xin L, Na L. Key economic issues in integrated energy system. East China Electric Power 2013;41:1403–8.
[58] Fan H, Yu ZC, Xia SW, Li X. Review on coordinated planning of source-network-load-storage for integrated energy systems. Front Energy Res 2021;9.
[59] Mendes G, Ioakimidis C, Ferrao P. On the planning and analysis of Integrated Community Energy Systems: a review and survey of available tools. Renew Sustain Energy Rev 2011;15:4836–54.
[60] Mirakyan A, De Guio R. Integrated energy planning in cities and territories: a review of methods and tools. Renew Sustain Energy Rev 2013;22:289–97.
[61] Mirakyan A, De Guio R. Modelling and uncertainties in integrated energy planning. Renew Sustain Energy Rev 2015;46:62–9.
[62] Haozhong C, Li W. Review on research of regional integrated energy system planning. Automat Electric Power Syst 2019;43:2–13.
[63] Antonopoulos I, Robu V, Couraud B, Kirli D, Norbu S, Kiprakis A, et al. Artificial intelligence and machine learning approaches to energy demand-side response: a systematic review. Renew Sustain Energy Rev 2020;130.
[64] Zahraee SM, Assadi MK, Saidur R. Application of artificial intelligence methods for hybrid energy system optimization. Renew Sustain Energy Rev 2016;66:617–30.
[65] Perera ATD, Kamalaruban P. Applications of reinforcement learning in energy systems. Renew Sustain Energy Rev 2021;137.
[66] Wang H, Lei Z, Zhang X, Zhou B, Peng J. A review of deep learning for renewable energy forecasting. Energy Convers Manage 2019;198:111799.
[67] Al-Othman A, Tawalbeh M, Martis R, Dhou S, Orhan M, Qasim M, et al. Artificial intelligence and numerical models in hybrid renewable energy systems with fuel cells: advances and prospects. Energy Convers Manage 2022;253:115154.
[68] 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.
[69] Umunnakwe A, Huang H, Oikonomou K, Davis KR. Quantitative analysis of power systems resilience: standardization, categorizations, and challenges. Renew Sustain Energy Rev 2021;149.
[70] Jasiunas J, Lund PD, Mikkola J. Energy system resilience-A review. Renew Sustain Energy Rev 2021;150.
[71] Jesse BJ, Heinrichs HU, Kuckshinrichs W. Adapting the theory of resilience to energy systems: a review and outlook. Energy Sustain Soc 2019;9.
[72] Jebaraj S, Iniyan S. A review of energy models. Renew Sustain Energy Rev 2006;10:281–311.
[73] Keirstead J, Jennings M, Sivakumar A. A review of urban energy system models: approaches, challenges and opportunities. Renew Sustain Energy Rev 2012;16:3847–66.
[74] Krishna KS, Kumar KS. A review on hybrid renewable energy systems. Renew Sustain Energy Rev 2015;52:907–16.
[75] Groissbock M. Are open source energy system optimization tools mature enough for serious use? Renew Sustain Energy Rev 2019;102:234–48.
[76] Gao L, Hwang Y, Cao T. An overview of optimization technologies applied in combined cooling, heating and power systems. Renew Sustain Energy Rev 2019;114.
[77] 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.
[78] del Granado PC, van Nieuwkoop RH, Kardakos EG, Schaffner C. Modelling the energy transition: a nexus of energy system and economic models. Energy Strategy Rev 2018;20:229–35.
[79] Li J, Wang D, Jia H, Wu G, He W, Xiong H. Prospects of key technologies of integrated energy systems for rural electrification in China. Global Energy Interconnection 2021;4:3–17.
[80] Sinha S, Chandel SS. Review of software tools for hybrid renewable energy systems. Renew Sustain Energy Rev 2014;32:192–205.
[81] Chang M, Thellufsen JZ, Zakeri B, Pickering B, Pfenninger S, Lund H, et al. Trends in tools and approaches for modelling the energy transition. Appl Energy 2021;290.
[82] Ringkjob HK, Haugan PM, Solbrekke IM. A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renew Sustain Energy Rev 2018;96:440–59.
[83] Prina MG, Groppi D, Nastasi B, Garcia DA. Bottom-up energy system models applied to sustainable islands. Renew Sustain Energy Rev 2021;152.
[84] Zahraoui Y, Alhamrouni I, Mekhilef S, Khan MRB, Seyedmahmoudian M, Stojcevski A, et al. Energy management system in microgrids: a comprehensive review. Sustainability 2021;13.
[85] Martinez S, Michaux G, Salagnac P, Bouvier J-L. Micro-combined heat and power systems (micro-CHP) based on renewable energy sources. Energy Convers Manage 2017;154:262–85.
[86] Mahian O, Mirzaie MR, Kasaeian A, Mousavi SH. Exergy analysis in combined heat and power systems: a review. Energy Convers Manage 2020;226:113467.
[87] Bagherian MA, Mehranzamir K. A comprehensive review on renewable energy integration for combined heat and power production. Energy Convers Manage 2020;224:113454.
[88] 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;52:1391–404.

[89] 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.
[90] Atom M, Laurent L, Nikolai K, Igor K. Methodological Framework for the analysis and development of a sustainable, integrated, regional energy plan - A French region case study. EcoMod2009.
[91] Schweiger G, Heimrath R, Falay B, O'Donovan K, Nageler P, Pertschy R, et al. District energy systems: modelling paradigms and general-purpose tools. Energy 2018;164:1326–40.
[92] Zhang C, Peng K, Han Y, Wang L, Zeng SQ, Dong WJ. Key technologies and system development for regional integrated energy system. Energy Rep 2020;6: 374–9.
[93] Aien M, Hajebrahimi A, Fotuhi-Firuzabad M. A comprehensive review on uncertainty modeling techniques in power system studies. Renew Sustain Energy Rev 2016;57:1077–89.
[94] Yue XF, Pye S, DeCarolis J, Li FGN, Rogan F, Gallachoir BO. A review of approaches to uncertainty assessment in energy system optimization models. Energy Strategy Reviews 2018;21:204–17.
[95] Soroudi A, Amraee T. Decision making under uncertainty in energy systems: state of the art. Renew Sustain Energy Rev 2013;28:376–84.
[96] Yu HW, Duan JH, Du W, Xue S, Sun JH. China's energy storage industry: develop status, existing problems and countermeasures. Renew Sustain Energy Rev 2017; 71:767–84.
[97] Zhang C, Wei YL, Cao PF, Lin MC. Energy storage system: current studies on batteries and power condition system. Renew Sustain Energy Rev 2018;82: 3091–106.
[98] Rahman MM, Oni AO, Gemechu E, Kumar A. Assessment of energy storage technologies: a review. Energy Convers Manage 2020;223:113295.
[99] Capurso T, Stefanizzi M, Torresi M, Camporeale SM. Perspective of the role of hydrogen in the 21st century energy transition. Energy Convers Manage 2022; 251:114898.
[100] Abdalla AM, Hossain S, Nisfindy OB, Azad AT, Dawood M, Azad AK. Hydrogen production, storage, transportation and key challenges with applications: a review. Energy Convers Manage 2018;165:602–27.
[101] Amirante R, Cassone E, Distaso E, Tamburrano P. Overview on recent developments in energy storage: Mechanical, electrochemical and hydrogen technologies. Energy Convers Manage 2017;132:372–87.
[102] CiteSpace: Visualizing Patterns and Trends in Scientific Literature, 2006. https://citespace.podia.com/.
[103] Chen C. CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature. J Am Soc Inform Sci Technol 2006;57:359–77.
[104] Chen C. Searching for intellectual turning points: progressive knowledge domain visualization. Proc Natl Acad Sci 2004;101:5303–10.
[105] Garfield E. Citation indexes for science: a new dimension in documentation through association of ideas. Science 1955;122:108–11.
[106] Kessler MM. Bibliographic coupling between scientific papers. Am Documentation 1963;14:10–25.
[107] Small H. Co-citation in the scientific literature: a new measure of the relationship between two documents. J Am Soc Inf Sci 1973;24:265–9.
[108] Kuhn TS. The structure of scientific revolutions. Chicago University of Chicago Press; 1970.
[109] Shapere D. The structure of scientific revolutions. Philos Rev 1964;73:383–94.
[110] Burt RS. Structural holes and good ideas. Am J Sociol 2004;110:349–99.
[111] Lazega E. Structural holes: the social structure of competition. JSTOR1995.
[112] Chen CM. Science mapping: a systematic review of the literature. J Data Inf Sci 2017;2:1–40.
[113] Chen C. A Glimpse of the First Eight Months of the COVID-19 literature on Microsoft academic graph: themes, citation contexts, and uncertainties. Front Res Metrics Analyt 2020;5.
[114] Chen C, Song M. Visualizing a field of research: a methodology of systematic scientometric reviews. PLoS One 2019;14:e0223994.
[115] Document Co-Citation Analysis -DCA, 2015. https://blog.sciencenet.cn/blog-496649-920248.html.
[116] Santoyo-Castelazo E, Azapagic A. Sustainability assessment of energy systems: integrating environmental, economic and social aspects. J Cleaner Prod 2014;80: 119–38.
[117] Ghaffour N, Bundschuh J, Mahmoudi H, Goosen MF. Renewable energy-driven desalination technologies: a comprehensive review on challenges and potential applications of integrated systems. Desalination 2015;356:94–114.
[118] Brahman F, Honarmand M, Jadid S. Optimal electrical and thermal energy management of a residential energy hub, integrating demand response and energy storage system. Energy Build 2015;90:65–75.
[119] Ren H, Gao W. A MILP model for integrated plan and evaluation of distributed energy systems. Appl Energy 2010;87:1001–14.
[120] Bai L, Li F, Cui H, Jiang T, Sun H, Zhu J. Interval optimization based operating strategy for gas-electricity integrated energy systems considering demand response and wind uncertainty. Appl Energy 2016;167:270–9.
[121] Gadalla MA, Olujic Z, Jansens PJ, Jobson M, Smith R. Reducing CO_2 emissions and energy consumption of heat-integrated distillation systems. Environ Sci Technol 2005;39:6860–70.
[122] Sechilariu M, Wang B, Locment F. Building integrated photovoltaic system with energy storage and smart grid communication. IEEE Trans Ind Electron 2012;60: 1607–18.
[123] Kanase-Patil A, Saini R, Sharma M. Integrated renewable energy systems for off grid rural electrification of remote area. Renewable Energy 2010;35:1342–9.
[124] Hoffman KC, Wood DO. Energy system modeling and forecasting. Ann Rev Energy 1976;1:423–53.
[125] Pandey R. Energy policy modelling: agenda for developing countries. Energy Policy 2002;30:97–106.
[126] Nakata T. Energy-economic models and the environment. Prog Energy Combust Sci 2004;30:417–75.
[127] Wang H, Nakata T. Analysis of the market penetration of clean coal technologies and its impacts in China's electricity sector. Energy Policy 2009;37:338–51.
[128] Timilsina GR, Bhattacharyya SC. Energy demand models for policy formulation : a comparative study of energy demand models. (2009).
[129] Bhattacharyya SC, Timilsina GR. A review of energy system models. Int J Energy Sect Manage 2010;4:494–518.
[130] Liu H, Geng Z, Gu Y, Mo Z, Yu Z, He X, et al. A regional integrated energy system with a coal-fired CHP plant, screw turbine and solar thermal utilization: scenarios for China. Energy Convers Manage 2020;212:112812.
[131] Wang M, Yu H, Jing R, Liu H, Chen P, Li C. Combined multi-objective optimization and robustness analysis framework for building integrated energy system under uncertainty. Energy Convers Manage 2020;208:112589.
[132] Safder U, Ifaei P, Yoo C. Multi-scale smart management of integrated energy systems, Part 2: weighted multi-objective optimization, multi-criteria decision making, and multi-scale management (3M) methodology. Energy Convers Manage 2019;198:111830.
[133] Ifaei P, Safder U, Yoo C. Multi-scale smart management of integrated energy systems, Part 1: energy, economic, environmental, exergy, risk (4ER) and water-exergy nexus analyses. Energy Convers Manage 2019;197:111851.
[134] He J, Wu Y, Wu M, Xu M, Liu F. Two-stage configuration optimization of a novel standalone renewable integrated energy system coupled with hydrogen refueling. Energy Convers Manage 2022;251:114953.
[135] Kim H, Jung Y, Oh J, Cho H, Heo J, Lee H. Development and evaluation of an integrated operation strategy for a poly-generation system with electrical and thermal storage systems. Energy Convers Manage 2022;256:115384.
[136] Zhou J, Wu Y, Wu C, Deng Z, Xu C, Hu Y. A hybrid fuzzy multi-criteria decision-making approach for performance analysis and evaluation of park-level integrated energy system. Energy Convers Manage 2019;201:112134.
[137] Shahidehpour M, Yamin H, Li Z. Market operations in electric power systems: forecasting, scheduling, and risk management. John Wiley & Sons; 2003.
[138] Ehsan A, Yang Q. Optimal integration and planning of renewable distributed generation in the power distribution networks: a review of analytical techniques. Appl Energy 2018;210:44–59.
[139] Wood AJ, Wollenberg BF, Sheblé GB. Power generation, operation, and control. John Wiley & Sons; 2013.
[140] Ramirez-Elizondo LM, Paap GC. Unit commitment in multiple energy carrier systems. 41st North American Power Symposium. IEEE2009. pp. 1-6.
[141] Frank S, Rebennack S. A primer on optimal power flow: Theory, formulation, and practical examples. Colorado School of Mines, Tech Rep. (2012).
[142] Geidl M, Andersson G. Optimal power dispatch and conversion in systems with multiple energy carriers. Proc 15th Power Systems Computation Conference (PSCC) 2005.
[143] Geidl M, Andersson G. Operational and structural optimization of multi-carrier energy systems. Eur Trans Electr Power 2006;16:463–77.
[144] Hobbs BF. Optimization methods for electric utility resource planning. Eur J Oper Res 1995;83:1–20.
[145] Dantzig GB. Linear programming under uncertainty. Manage Sci 1955;1:197–206.
[146] Zadeh LA. Fuzzy sets. Fuzzy sets, fuzzy logic, and fuzzy systems: selected papers by Lotfi A Zadeh. World Scientific 1996:394–432.
[147] Zhang Y, Shen S, Mathieu JL. Distributionally robust chance-constrained optimal power flow with uncertain renewables and uncertain reserves provided by loads. IEEE Trans Power Syst 2016;32:1378–88.
[148] Lubin M, Dvorkin Y, Backhaus S. A robust approach to chance constrained optimal power flow with renewable generation. IEEE Trans Power Syst 2015;31: 3840–9.
[149] Luo Z, Gu W, Wu Z, Wang Z, Tang Y. A robust optimization method for energy management of CCHP microgrid. J Mod Power Syst Clean Energy 2018;6:132–44.
[150] Ding T, Liu S, Yuan W, Bie Z, Zeng B. A two-stage robust reactive power optimization considering uncertain wind power integration in active distribution networks. IEEE Trans Sustainable Energy 2015;7:301–11.
[151] Moore RE. Interval analysis. Prentice-Hall Englewood Cliffs1966.
[152] Ben-Haim Y. Info-gap decision theory: decisions under severe uncertainty. Elsevier; 2006.
[153] Song D, Li Z, Wang L, Jin F, Huang C, Xia E, et al. Energy capture efficiency enhancement of wind turbines via stochastic model predictive yaw control based on intelligent scenarios generation. Appl Energy 2022;312:118773.
[154] Song D, Tu Y, Wang L, Jin F, Li Z, Huang C, et al. Coordinated optimization on energy capture and torque fluctuation of wind turbines via variable weight NMPC with fuzzy regulator. Appl Energy 2022;312:118821.
[155] Geidl M, Andersson G. Optimal power flow of multiple energy carriers. IEEE Trans Power Syst 2007;22:145–55.
[156] Yang H, Xiong T, Qiu J, Qiu D, Dong ZY. Optimal operation of DES/CCHP based regional multi-energy prosumer with demand response. Appl Energy 2016;167: 353–65.
[157] Arnold M, Negenborn RR, Andersson G, Schutter BD. Distributed predictive control for energy hub coordination in coupled electricity and gas networks. Intelligent Infrastructures Springer 2010.:235–73.
[158] Xprog: MATLAB Toolbox for Optimization under Uncertainty. http://xprog.weebly.com/.

[159] Chen Z, Sim M, Xiong P. Robust stochastic optimization made easy with RSOME. Manage Sci 2020;66:3329–39.
[160] Power. Progress for Germany's Power-to-Gas Drive. in: S. Patel, (Ed.).2012.
[161] Li J, Liu J, Yan P, Li X, Zhou G, Yu D. Operation optimization of integrated energy system under a renewable energy dominated future scene considering both independence and benefit: a review. Energies 2021;14:1103.
[162] Sörensen K. Metaheuristics—the metaphor exposed. Int Trans Operat Res 2015;22:3–18.
[163] Tisseur R, de Bosio F, Chicco G, Fantino M, Pastorelli M, Ieee. Optimal Scheduling of Distributed Energy Storage Systems by Means of ACO Algorithm. 2016 51ST INTERNATIONAL UNIVERSITIES POWER ENGINEERING CONFERENCE (UPEC) 2016.
[164] Askarzadeh A. A memory-based genetic algorithm for optimization of power generation in a microgrid. IEEE Trans Sustainable Energy 2018;9:1081–9.
[165] Pulluri H, Naresh R, Sharma V. An enhanced self-adaptive differential evolution based solution methodology for multiobjective optimal power flow. Appl Soft Comput 2017;54:229–45.
[166] Kumbhar A, Dhawale PG, Kumbhar S, Patil U, Magdum P. A comprehensive review: Machine learning and its application in integrated power system. Energy Rep 2021;7:5467–74.
[167] L. H. EnergyPLAN. Aalborg University, Denmark, 2017.
[168] EnegyPLAN, 1999. www.energyplan.eu.
[169] Lund H, Münster E. Modelling of energy systems with a high percentage of CHP and wind power. Renewable Energy 2003;28:2179–93.
[170] H.L. E. Münster. Report on the understanding of the character of the balancing problems and strategies for solving them (long-term). DESIRE project2007.
[171] Ostergaard PA, Lund H. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Appl Energy 2011;88:479–87.
[172] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy 2015;154:921–33.
[173] Prina MG, Fornaroli FC, Moser D, Manzolini G, Sparber W. Optimisation method to obtain marginal abatement cost-curve through EnergyPLAN software. Smart Energy 2021;1:100002.
[174] Seebregts AJ, Goldstein GA, Smekens K. Energy/Environmental Modeling with the MARKAL Family of Models. In: Chamoni P, Leisten R, Martin A, Minnemann J, Stadtler H, editors. Operations Research Proceedings 2001. Berlin Heidelberg, Berlin, Heidelberg: Springer; 2002. p. 75–82.
[175] Loulou R, Goldstein G, Noble K. Documentation for the MARKAL family of models. Energy Technol Syst Analysis Programme 2004:65–73.
[176] Goldstein GAT, G. C. Global Energy Systems and Common Analyses: Final Report of Annex X (2005-2008). in: G.G.a.G. Tosato, (Ed.). International Energy Agency2008.
[177] Loulou R, Goldstein G, Noble K. Documentation for the MARKAL Family of Models. 2004.
[178] Loulou R, Remne U, Kanudia A, Lehtila A, Goldstein G. Documentation for the TIMES Model, PART I. International Energy Agency2005.
[179] Loulou R, Goldstein G, Noble K. Documentation for the MARKAL Family of Models, SAGE. 2004.
[180] European C, Joint Research C, Keramidas K, Kitous A, Schade B, Després J, et al. POLES-JRC model documentation : 2018 update. Publications Office2018.
[181] POLES, 2018. https://joint-research-centre.ec.europa.eu/poles_en.
[182] Long-Range Energy Alternatives Planning System (LEAP) 2018. https://ndcpartnership.org/toolbox/long-range-energy-alternatives-planning-system-leap%C2%A0.
[183] O'Keefe P, Raskin P, Bernow S. Energy and Development in Kenya: Opportunities and constraints. Nordic Africa Institute 1984.
[184] Heaps C. An Introduction to LEAP. Stockholm Environment Institute 2008.
[185] Winkler H, Borchers M, Alison H, Visagie E, Heindrich G. Cape Town energy futures: policies and scenarios for sustainable city energy development. (2005).
[186] Giatrakos GP, Tsoutsos TD, Zografakis N. Sustainable power planning for the island of Crete. Energy Policy 2009;37:1222–38.
[187] Energy System Modelling Environment (ESME), 2015. http://www.eti.co.uk/project/esme/.
[188] C. Heaton. Modelling Low-Carbon Energy System Designs with the ETI ESME Model. Energy technologies institute. (2014).
[189] Price-Induced Market Equilibrium System(PRIMES). https://e3modelling.com/modelling-tools/primes/.
[190] E3MLab. PRIMES MODEL, VERSION 6. National Technical University of Athens2017.
[191] DynEMo. https://www.ucl.ac.uk/energy-models/models/dynemo.
[192] Barrett M, Spataru C. DynEMo: A Dynamic Energy Model for the Exploration of Energy, Society and Environment. 2015 17th UKSim-AMSS International Conference on Modelling and Simulation (UKSim)2015. pp. 255-60.
[193] E4Cast. https://www.energyplan.eu/othertools/national/e4cast/.
[194] Syed A. Australian Energy Projections to 2049-50. Bureau of Resources and Energy Economics. (2014).
[195] RETScreen, 1998. https://www.nrcan.gc.ca/maps-tools-and-publications/tools/modelling-tools/retscreen/7465.
[196] A.G.S.H.S.J.C.H.R.I.C.N.R.C. Monarque. RETScreen international : results and impacts 1996-2012. Natural Resources Canada, Ottawa, 2004.
[197] Bakos GC, Soursos M, Tsagas NF. Technoeconomic assessment of a building-integrated PV system for electrical energy saving in residential sector. Energy Build 2003;35:757–62.
[198] GEM-E3. https://e3modelling.com/modelling-tools/gem-e3/.
[199] C. Joint Research, S. Institute for Prospective Technological, D. Van Regemorter, P. Capros, L. Paroussos, P. Karkatsoulis. GEM-E3 model documentation. Publications Office2013.
[200] Distributed Energy Resources Customer Adoption Model (DER-CAM), 2000. https://gridintegration.lbl.gov/der-cam.
[201] Marnay C, Chard JS, Hamachi KS, Lipman TE, Moezzi M, Ouaglal B, et al. Modeling of customer adoption of distributed energy resources. Lawrence Berkeley National Laboratory. (2001).
[202] Mashayekh S, Stadler M, Cardoso G, Heleno M. A mixed integer linear programming approach for optimal DER portfolio, sizing, and placement in multi-energy microgrids. Appl Energy 2017;187:154–68.
[203] Stadler M, Groissböck M, Cardoso G, Marnay C. Optimizing Distributed Energy Resources and building retrofits with the strategic DER-CAModel. Appl Energy 2014;132:557–67.
[204] Cardoso G, Stadler M, Bozchalui MC, Sharma R, Marnay C, Barbosa-Povoa A, et al. Optimal investment and scheduling of distributed energy resources with uncertainty in electric vehicle driving schedules. Energy 2014;64:17–30.
[205] National Energy Modeling System (NEMS). https://www.eia.gov/analysis/pdfpages/0581(2009)index.php.
[206] The National Energy Modeling System: An Overview 2003, 2009. http://www.eia.doe.gov/oiaf/aeo/overview/index.html.
[207] Gabriel S, Kydes A. The National Energy Modeling System: A large-scale equilibrium model at the U.S. Department of Energy. Conference: 15 international symposium on mathematical programming, Ann Arbor, MI (United States), 15-19 Aug 1994; Other Information: PBD: 1994; Related Information: Is Part Of Mathematical programming: State of the art 1994; Birge, JR; Murty, KG [eds]; PB: 312 p. Univ. of Michigan, Ann Arbor, MI (United States), United States, 1994. p. Medium: X; Size: pp. 83.
[208] Wilkerson JT, Cullenward D, Davidian D, Weyant JP. End use technology choice in the National Energy Modeling System (NEMS): an analysis of the residential and commercial building sectors. Energy Econ 2013;40:773–84.
[209] Renewable Energy Pathways Simulation System (Renpass). https://wiki.openmod-initiative.org/wiki/Renpass.
[210] Wiese F. renpass Renewable Energy Pathways Simulation System - Open Source as an approach to meet challenges in energy modeling. Interdisciplinary Institute for Environmental, Social and Human Sciences, Department of Energy and Environmental Management 2015.
[211] Tools for Energy Model Optimization and Analysis (Temoa). https://temoacloud.com/.
[212] Hunter K, Sreepathi S, DeCarolis JF. Modeling for insight using Tools for Energy Model Optimization and Analysis (Temoa). Energy Econ 2013;40:339–49.
[213] Solar and wind energy inte-grated with trans-mis-sion and con-ven-tional sources (SWITCH). https://rael.berkeley.edu/project/switch/.
[214] Johnston J, Henriquez-Auba R, Maluenda B, Fripp M. Switch 2.0: a modern platform for planning high-renewable power systems. SoftwareX 2019;10:100251.
[215] CloudPss. https://cloudpss.net/index/.
[216] Song Y, Chen Y, Yu Z, Huang S, Shen C. CloudPSS: a high-performance power system simulator based on cloud computing. Energy Rep 2020;6:1611–8.
[217] Zhang G, Pu H. CloudPss-An Energy Internet Modeling and Simulation Tool in the Cloud. In: 2016 8th International Conference on Information Technology in Medicine and Education (ITME); 2016. p. 455–8.
[218] Bakken BH, Skjelbred HI, Wolfgang O. eTransport: Investment planning in energy supply systems with multiple energy carriers. Energy 2007;32:1676–89.
[219] eTransport. https://www.sintef.no/en/projects/2001/etransport/.
[220] Bakken BH, Mindeberg SK. Linear models for optimization of interconnected gas and electricity networks. In: 2009 IEEE Power & Energy Society General Meeting; 2009. p. 1–2.
[221] TRNSYS. http://www.trnsys.com/index.html.
[222] Kalogirou SA. Use of TRNSYS for modelling and simulation of a hybrid pv–thermal solar system for Cyprus. Renewable Energy 2001;23:247–60.
[223] Choi Y, Rayl J, Tammineedi C, Brownson JRS. PV Analyst: Coupling ArcGIS with TRNSYS to assess distributed photovoltaic potential in urban areas. Sol Energy 2011;85:2924–39.
[224] Datta G. Effect of fixed horizontal louver shading devices on thermal perfomance of building by TRNSYS simulation. Renewable Energy 2001;23:497–507.
[225] Gowreesunker BL, Tassou SA, Kolokotroni M. Coupled TRNSYS-CFD simulations evaluating the performance of PCM plate heat exchangers in an airport terminal building displacement conditioning system. Build Environ 2013;65:132–45.
[226] M. Ahmed Cherif. TRNSYS as an Education Tool to Predict Indoor Environment Temperature for Undergraduate Students. ASEE Conferences, Indianapolis, Indiana.
[227] Tozzi P, Jo JH. A comparative analysis of renewable energy simulation tools: performance simulation model vs. system optimization. Renew Sustain Energy Rev 2017;80:390–8.
[228] Hybrid Optimization of Multiple Energy Resources (HOMER). https://www.homerenergy.com/.
[229] Shaahid SM, El-Amin I. Techno-economic evaluation of off-grid hybrid photovoltaic–diesel–battery power systems for rural electrification in Saudi Arabia—A way forward for sustainable development. Renew Sustain Energy Rev 2009;13:625–33.
[230] Sen R, Bhattacharyya SC. Off-grid electricity generation with renewable energy technologies in India: an application of HOMER. Renewable Energy 2014;62:388–98.

[231] Beuzekom Iv, Gibescu M, Slootweg JG. A review of multi-energy system planning and optimization tools for sustainable urban development. 2015 IEEE Eindhoven PowerTech 2015. pp. 1-7.
[232] Gilman P, Lambert T, Lilienthal P. Chapter 15: Micropower System Modeling with Homer. Hoboken, NJ, United States: John Wiley & Sons Inc; 2006.
[233] Compare Options for Sustainable Energy (COMPOSE). https://www.energyplan.eu/othertools/local/compose/.
[234] Blarke MB. Techno-economic consequences of large-scale heat pumps in distributed generation in favour of a domestic integration strategy for sustainable energy. Sustainable Energy Planning Research Group Department of Planning 2008.
[235] Rudra S. Design and System Analysis of Quad-Generation Plant Based on Biomass Gasification Integrated with District Heating. 2013.
[236] Blarke MB, Lund H. The effectiveness of storage and relocation options in renewable energy systems. Renewable Energy 2008;33:1499–507.
[237] Calliope. https://calliope.readthedocs.io/en/stable/.
[238] S.P.a.B. Pickering. Calliope: a multi-scale energy systems modelling framework. J Open Source Softw (2018).
[239] iHOGA. https://ihoga.unizar.es/.
[240] Kumar AP. Analysis of Hybrid Systems: Software tools. 2016 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB)2016. pp. 327-30.
[241] Saiprasad N, Kalam A, Zayegh A. Comparative study of optimization of HRES using HOMER and iHOGA Software. J Sci Ind Res 2018;77:677–83.
[242] EnergyPLAN. Other Energy System Analysis Models.
[243] Stadler M, Cardoso G, Mashayekh S, Forget T, DeForest N, Agarwal A, et al. Value streams in microgrids: a literature review. Appl Energy 2016;162:980–9.