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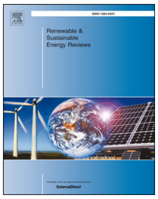

A review of modelling tools for energy and electricity systems with large shares of variable renewables

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ABSTRACT

This paper presents a thorough review of 75 modelling tools currently used for analysing energy and electricity systems. Increased activity within model development in recent years has led to several new models and modelling capabilities, partly motivated by the need to better represent the integration of variable renewables. The purpose of this paper is to give an updated overview of currently available modelling tools, their capabilities and to serve as an aid for modellers in their process of identifying and choosing an appropriate model. A broad spectrum of modelling tools, ranging from small-scale power system analysis tools to global long-term energy models, has been assessed. Key information regarding the general logic, spatiotemporal resolution as well as the technological and economic features of the models is presented in three comprehensive tables. This information has been validated and updated by model developers or affiliated contact persons, and is state-of-the-art as of the submission date. With the available suite of modelling tools, most challenges of today's electricity system can be assessed. For a future with an increasing share of variable renewables and increasing electrification of the energy system, there are some challenges such as how to represent short-term variability in long-term studies, incorporate the effect of climate change and ensure openness and transparency in modelling studies.

1. Introduction

Electricity generation from renewable energy sources (RES) is increasing in Europe, much of it driven by ambitious targets for emission reductions set by the European Commission. In the 2050 Low Carbon Economy roadmap, the EU set a goal of reducing emissions to 80% below the 1990 level [1]. The EU also states that all sectors have to contribute to this reduction, but the sector with the highest potential for cutting emissions is the power sector. Through increasing the share of zero-emitting RES in the electricity mix, the power sector can almost totally eliminate its emissions by 2050.

Most of the increased RES in the electricity mix has in the latest years been, and is projected to be, solar and wind technologies. Part of this increase is due to the large cost reductions experienced and also projected. According to the International Renewable Energy Agency (IRENA), the levelised cost of electricity (LCOE) of solar photovoltaics (PV) has halved between 2010 and 2014 [2]. Furthermore, in November 2016, the winning bid to build the Danish offshore wind farm Kriegers Flak was as low as 49.9 €/MW h [3].

However, solar and wind are variable renewable energy sources (VRES) whose outputs vary temporally on many scales. This is especially the case for wind, which ranges from local gusts of only seconds to large scale patterns evolving over several years. The solar radiation is to some extent more predictable, where the daily and seasonal cycles are well known components. However, on shorter timescales the solar radiation can be difficult to predict due to the rapid change in cloud cover. In an electricity grid that requires a balance between generation and consumption, larger shares of VRES leads to multiple challenges.

On a very short timescale, from sub-seconds to minutes, challenges of VRES integration are related to the operation and management of the grid. The main issues include the reduction of inertia of the power system, the increase of curtailment events, the rate of change of frequency as well as the system reactive power capability [4]. Grid support services such as frequency and voltage regulation, fault ride through, spinning reserve and system restoration are currently provided by conventional technologies (i.e. mostly fossil fuelled power plants and hydropower). However, if solar and wind technologies are to replace much of the fossil fuelled capacities, they or new system components like batteries must be able to provide the required grid support services in order to maintain a stable and reliable grid. With existing technology, both wind turbines and PV systems are capable of providing grid support services, but limited to some drive-train topologies for wind turbines and generally only for large utility-scale PV systems [5–7].

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Table 1

List of models included in the review, their full name, who they are developed/published by, availability (AV), necessary software and references. Abbreviations used in the availability column: C – Commercial, D – Free demo version, F – Free, OS – Open-Source, AC – Free academic version, UN – Unknown (/not yet decided), ED – Free for educational purposes, UR – Upon Request.

Model	#	Full-name	Published/Developed by	AV	Software	Refs.
AURORAxmp	1	–	EPIS	C (D, A)	Stand-alone	[27,28]
BALMOREL	2	–	Hans Ravn	OS	GAMS + Solver	[29–31]
Calliope	3	–	ETH Zürich - Stefan Pfenninger	OS	Python	[32–34]
CASPOC	4	–	Simulation Research Netherlands	C (D)	Stand-alone	[35,36]
COMPETES	5	COmprehensive Market Power in Electricity Transmission and Energy Simulator	Energy Research Centre of the Netherlands	A[a]	AIMMS/GUROBI	[37,38]
COMPOSE	6	Compare Options for Sustainable Energy	Morten Blarke, ENERGIANALYSE.DK	A, C	Stand-alone[b]	[39–41]
CYME	7	–	CYME International	C (T)	Stand-alone	[42,43]
DER-CAM	8	Distributed Energy Resources Customer Adoption Model	Lawrence Berkeley National Laboratory	F	Online – None, Licensed – GAMS	[44–46]
DESSTinEE	9	Demand for Energy Services, Supply and Transmission in Europe	Imperial College London - Iain Staffell, Richard Green	OS	Excel/VBA	[47,48]
DIETER*	10	Dispatch and Investment Evaluation Tool with Endogenous Renewables	DIW Berlin - Alexander Zerrahn & Wolf-Peter Schill	OS	GAMS + Solver	[49,50]
DIgSILENT/PowerFactory	11	DIgital SImuLation of Electrical NeTworks - Power Factory	DigSilent GmbH	C	Stand-Alone	[51–53]
EMLab- Generation	12	Energy Modelling Laboratory - Generation	TU Delft - Richstein, Chappin, Bhagwat & de Vries	OS	JAVA & Maven	[54,55]
EMMA	13	The European Electricity Market Model	Neon Neue Energieökonomik GmbH - Lion Hirth	OS	GAMS/CPLEX	[56–58]
EMPIRE	14	European Model for Power system Investment with Renewable Energy	NTNU – Christian Skar et al.	UN	Xpress-Mosel	[59]
EMPS	15	EFI's Multi-Area Powermarket Simulator	SINTEF Energy Research	C	Stand-alone	[60–62]
EnergyPlan	16	–	Sustainable Energy Planning Research Group - Aalborg University	F	Stand-alone	[63–65]
energyPro	17	–	EMD International A/S	C	Stand-alone	[66–69]
Enertile[c]	18	–	Fraunhofer ISI	NA	Solver (CPLEX)	[70–72]
ENTIGRIS[d]	19	–	Fraunhofer ISE – Christoph Kost	NA	GAMS	[73,74]
ETM (1)	20	EUROfusion Times Model	EUROfusion	UN	GAMS/CPLEX, VEDA-FE & VEDA-BE	[75,76]
ETM (2)	21	Energy Transition Model	Quintel Intelligence	OS	Online tool	[77,78]
ETSAP-TIAM	22	The TIMES Integrated Assessment Model	ETSAP-IEA	F[e]	GAMS/CPLEX, Excel, VEDA-FE & VEDA-BE	[23,79]
EUCAD	23	European Unit Commitment and Dispatch	Univ. Grenoble Alpes – Jacques Després	NA	GAMS/CPLEX	[80,81]
EUPower-Dispatch	24	–	Carlo Brancucci Martinez-Anido (European Commission, JRC)	UN	GAMS/CPLEX (MATLAB)	[82–84]
ficus	25	–	TUM EI EWK – Dennis Atabay	OS	Python	[85–87]
GCAM	26	Global Change Assessment Model	PNNL	OS	BOOST, XERCES, JAVA, HECTOR	[88,89]
GEM-E3	27	General Equilibrium Model for Economy-Energy-Environment	European Commission Funded Multinational Collaboration	NA	GAMS (Solved with PATH)	[90–92]
GENESYS	28	Genetic Optimisation of a European Energy Supply System	RWTH-Aachen University – Alvarez, Bussar, Cai, Chen, Moraes Jr., Stöcker, Thien +	OS	Stand-alone	[93,94]
GridLAB-D	29	–	U.S Department of Energy	OS	Stand-alone	[95,96]
HOMER	30	Hybrid Optimisation of Multiple Energy Resources	NREL – Peter Lilienthal	C (T)	Stand-alone	[97–99]
HYPERSIM	31	–	Opal-RT	C	Stand-alone	[100–102]
iHOGA	32	Improved Hybrid Optimisation by Genetic Algorithms	Dr. Rodolfo Dufo-López - University of Zaragoza	ED (C) (pro +)	Stand-alone	[103,104]
IMAKUS	33	Iteratives Modell zur Ausbauplanung von Kraftwerken und Speichern	Technische Universität München - Philipp Kuhn	UN	MATLAB/CPLEX MATLAB/GUROBI	[105,106]
INVERT/EE-Lab	34	–	EEG - Vienna University of Technology	NA	Python	[107–109]
IPSA 2	35	Interactive Power System Analysis	IPSA Power	C	Stand-alone	[110,111]
IRiE	36	Integrated Regulating power market in Europe	NTNU (within a SINTEF project)	UR	AMPL - CPLEX/GUROBI & EMPS	[112–114]
LEAP	37	Long-range Energy Alternatives Planning	Stockholm Environment Institute	[f]	SA	[115,116]
LIBEMOD	38	LIBEralization MODel for the European Energy Markets	Frisch Centre & the Research Department at Statistics Norway	NA	GAMS	[117–119]
LIMES-EU	39	Long-term Investment Model for the Electricity Sector	Potsdam Institute for Climate Research - Paul Nahmmacher	UN	GAMS/CPLEX	[120–122]
LOADMATCH*	40	LOADMATCH Grid Integration Model	M. Z. Jacobson et al.	UN	UN	[123]
LUSYM	41	Leuven University System Modelling	K. Van den Bergh et al.	UR	GAMS (MATLAB)	[124]
MARKAL	42	MARKet ALlocation model	IEA-ETSAP	C (D)	GAMS + Solver (VEDA)	[125–127]

(*continued on next page*)

Table 1 (*continued*)

Model	#	Full-name	Published/Developed by	AV	Software	Refs.
MESSAGE	43	Model for Energy Supply Strategy Alternatives and their General Environmental Impact	IIASA	UR	GAMS & ORACLE	[128–130]
NEMO	44	National Electricity Market Optimiser	UNSW - Ben Elliston	OS	Python	[131,132]
NEMS	45	National Energy Modelling System	U.S. Energy Information Administration (EIA)	F[g]	[h]	[133,134]
Oemof (SOLPH)	46	Open Energy Modelling Framework	Oemof developing group (Reiner Lemoine Institut/ZNES Flensburg/OVGU)	OS	Python + Solver	[26,135]
OpenDSS	47	Open Distribution System Simulator	Electric Power Research Institute	OS	Stand-alone	[136–138]
OSeMOSYS	48	The Open Source Energy Modelling System	KTH - Howells et al.	OS	GNU MathProg	[139–142]
PLEXOS	49	PLEXOS Integrated Energy Model	Energy Exemplar - Glenn Drayton	C (A)	Stand-alone	[143–145]
POLES	50	Prospective Outlook on Long-term Energy Systems	CNRS (GAEL Energy), Enerdata, JRC-IPTS	NA	N.A.	[146–148]
PowerGAMA	51	Power Grid and Market Analysis	SINTEF Energy Research - Harald G. Svendsen	OS	Python	[149–151]
PRIMES*	52	Price-Induced Market Equilibrium System	E3MLab/ICCS at the Technical University of Athens	NA	–	[152–154]
ProdRisk	53	–	SINTEF Energy Research	NA	Fortran + COIN-CLP/CPLEX	[155–158]
PyPSA	54	Python for Power System Analysis	FIAS - Tom Brown et al.	OS	Python	[159–161]
RAPSim	55	Renewable Alternative Powersystems Simulation	NES, AUU - Pöchacker, Khatib, Elmenreich et al.	OS	Stand-alone	[162,163]
ReEDS	56	Regional Energy Deployment System	NREL	NA	GAMS (Excel & R)	[164–166]
ReMIND	57	Regional Model of Investments and Development	Potsdam Institute for Climate Impact Research	NA	GAMS/CONOPT	[167–169]
REMix	58	Renewable Energy Mix	DLR	NA	GAMS	[170,171]
renpass	59	Renewable Energy Pathways Simulation System	Frauke Wiese & Gesine Bökenkamp	OS	MySQL, R, RMySQL	[172,173]
RETScreen	60	The RETSCreen Clean Energy Project Analysis Software	Natural Resources Canada	F	Windows with .NET	[174,175]
SAM	61	System Advisor Model	U.S. Department of Energy and NREL	F	Stand-alone	[176–178]
SIMPOW	62	Simulation of Power Systems	Solvina	C (D)	Stand-alone	[179,180]
SIREN	63	"Sustainable Energy Now" Integrated Renewable Energy Network	Sustainable Energy Now Inc. - Angus King	OS	Stand-alone	[181,182]
SNOW[i]	64	Statistics Norway's World model	Statistics Norway	F	GAMS & MPSGE	[183–185]
stELMOD	65	Stochastic Electricity Market Model	Jan Abrell (ETH Zürich) & Friedrich Kunz (DIW Berlin)	OS	GAMS/CPLEX	[186–188]
SWITCH	66	Solar, Wind, Transmission, Conventional generation and Hydroelectricity	Fripp, Johnston & Maluenda	OS	Python	[189–191]
Temoa	67	Tools for Energy Model Optimisation and Analysis	NC State University - K. Hunter et al.	OS	Python + Solver	[192–194]
TIMES	68	The Integrated MARKAL-EFOM System	IEA-ETSAP	C (D)	GAMS + Solver (VEDA)	[195–197]
TIMES-Norway	69	As TIMES	IFE/NVE	[j]	GAMS, CPLEX/XPRESS	[24,198,199]
TIMES-Oslo	70	As TIMES	IFE	[k]	GAMS, CPLEX/XPRESS	[25]
TRNSYS18	71	TRaNsient SYstem Simulation	TESS, SEL, UW, CSTB, TRANSSOLAR	C (D)	Stand-alone	[200–203]
urbs	7372	–	TUM (Hamacher, Huber & Dorfner)	OS	Python (Solver)	[204,205]
WEM*	73	World Energy Model	International Energy Agency	NA	Vensim + others	[206–208]
WeSIM	74	Whole-electricity System Investment Model	Imperial College of London	NA	Unknown	[209,210]
WITCH	75	World Induced Technical Change Hybrid model	FEEM	UR	GAMS	[211–213]

[a] Own tool of ECN used for quantitative analysis for EU or national projects (it could also be freely used for research by academia with whom ECN cooperates).

[b] Good performance open-source MILP solver included (COINMP), commercial solver license recommended (e.g. CPLEX or GUROBI).

[c] Previously called PowerACE.

[d] Previously RESlion.

[e] Free of charge for Institutes appointed by one of the Contracting Partners of ETSAP.

[f] Free for students. Free for country government, NGO or academics in developing countries. Commercial for Academic, non-consulting and consulting in OECD countries.

[g] Excluding IHS Global Insight macro sub-model.

[h] Intel Fortran, Eviews, IHS Global Insight model, OML & Xpress solver, GAMS & Xpress, AIMMS & CPLEX, R, MS Windows OS.

[i] There is both a global version and a Norwegian version of the model (SNOW-NO).

[j] Not available (Except for cooperation with Ph.D. or master students).

[k] Not available (Except for cooperation with Ph.D. or master students).

On an hourly timescale, both wind turbines and photovoltaic systems can shift from generating at nominal power to not generating anything at all [8]. With a large VRES penetration, this can lead to challenging ramping situations, periods of oversupply as well as periods where the renewable sources are not able to meet the demand. Future power systems with high shares of VRES may require increased system flexibility through e.g. flexible power plants, energy storage, demand response and transmission grid extensions [8].

On longer timescales, challenges related to VRES integration include identifying pathways to a renewable and emission free energy system, assessing different scenarios and testing the effect of various policies. For example by assessing the impact of a carbon tax, the future evolution of electricity and fuel prices or how much the demand of energy is going to increase due to population growth and increased standard of living. Due to the long investment cycles in the energy sector, such analyses usually cover a time span of several decades [9]. Technological possibilities for more geographically distributed energy production and better control systems suggest that the development of energy production, storage and distribution systems in the near future may depend more on consumer or prosumer preferences and multi-level governance in addition to planning and optimisation on a national level. Business opportunities arising from periodically low electricity prices can stimulate new technologies and reduce curtailment. It is suggested that such factors may be relevant to include in scenario modelling.

From short-term operation to long-term energy system planning, many different models have been developed to assess the numerous challenges related to energy and electricity systems. Jebaraj and Iniyan [10] reviewed a spectrum of energy models, including energy planning models, supply-demand models, forecasting models, renewable energy models, emission reduction, optimisation and even emerging modelling techniques based on neural networks or fuzzy logic. Connolly et al. [11] looked at 37 models specific for the integration of renewables in energy systems. Their review also considered a large variety of modelling types, and was based on communication with the model developers through surveys. Sinha and Chandel [12] had a specific focus on modelling of hybrid renewable energy systems, mainly focused on stand-alone systems in urban, rural and remote areas. Pfenninger et al. [13] looked at how energy models face the challenges seen in today's system; resolving time and space, balancing uncertainty and transparency, addressing growing complexity and integrating human behaviour and social risks and opportunities. Moreover, Hall and Buckley [14] reviewed and categorised 22 energy models that are used in the United Kingdom. There are also several other reviews worth mentioning; Després et al. (2015), Mahmud and Town (2016), Hedenus and Johansson (2013), Foley et al. (2010), Bhattacharyya and Timilsina (2010) and Van Beuzekom et al. (2015) [15–20]. In addition, The International Energy Agency has published an extensive report on the use of energy models, scenarios and their assumptions [21].

There has been a high level of activity on model development in recent years, with many new models and modelling features appearing in the literature. This has partly been motivated by the need to better address the challenges of VRES integration. Many previous reviews are restricted to parts of the modelling landscape, e.g. modelling of the transport sector or local energy systems [12,16]. This review seeks to cover a wide range of aspects, extending previous reviews, and providing an updated overview of state of art modelling tools by the time of submission. The aim of the paper is to present an assortment of models that are capable to assess challenges faced in today's energy system, useful for modellers to identify suitable models for their purposes.

2. Materials and methods

2.1. Included models

In order to include only the most recent and currently active models, a criterion was set that each model must have been used in a publication after 2012. The starting point for identifying models was in previous review papers [10–20], but many of the models in these reviews have not been active since 2012 and are therefore excluded. Some of the models were found through the Open Energy Modelling Initiative [22], while the majority of models were identified via manual web searches based on keywords and citations.

As models are continuously developed and updated, this exercise is basically shooting at a moving target. Therefore, to ensure that the information provided in this paper is state of the art at the time of submission, it has been validated and updated through personal communication with developers or contact persons affiliated with the models. Out of the 75 models included in the review, 71 are validated. Table 1 presents the models included in the study, their developers, availability and the necessary software to run them. Missing replies are marked by asterisked entries in the "model" column, and might be due to wrong contact information.

It must be noted that this review does not explicitly distinguish between models and modelling tools. Some models are better regarded as tools or frameworks, where there is no data already in the model, but with equations and constraints from which a specific model can be built. Such tools are therefore usually highly flexible in the kind of systems they can model, where the user can define the spatiotemporal resolution, horizon, energy carriers, demand sectors etc. An example is the MARKAL/TIMES family of models, which have been applied to all from global to isolated island energy systems. In the tables these have been entered with their most typical characteristics. Specific examples of models developed by the TIMES modelling framework by adding ETSAP-TIAM, TIMES-Norway and TIMES-Oslo [23–25] are also included. OEMOF is another such framework [26]. It consists of a toolbox where several energy system modelling approaches can be integrated as single libraries. These libraries can then be used in so-called applications to build a computable model. In this review the application of a library called SOLPH has been used to illustrate OEMOF's capabilities.

2.2. Model features and properties

The model categorisation has been structured following the overarching typology presented by Després et al. [15]. This consists of the general logic, the spatiotemporal resolution as well as the technological and economic parameters of the models. Fig. 1 presents an overview of this categorisation, with a simplified flowchart that aims to aid prospective modellers in identifying an adequate modelling tool for their needs.

Starting with the problem statement at hand, the reader can find comprehensive information about the capabilities of the included models in Tables 1–3. Table 1 introduces the reviewed models alongside information about their availability, software requirements and developers. The general logic and spatiotemporal resolution is presented in Table 2, whereas Table 3 contains information about technological and economic parameters. By assessing the information stored in these tables, the reader should be able to identify and choose a model capable of giving insights to their specific question, model the involved processes with an adequate spatiotemporal resolution, and possess the necessary technological and economic properties.

The next paragraphs explain the various categories in further detail.

2.2.1. General logic

2.2.1.1. Purpose. Energy and electricity models are usually developed to solve a problem or to answer a given question. Four different purposes are identified. Models can fit into several of these categories:

Power System Analysis Tools – Tools developed to study power systems with a high degree of detail, usually dealing with power flows, fault level studies, dynamic stability etc. A typical application can be to study the power electronics in a wind turbine connected to the grid.

Operation Decision Support – Tools developed to optimise the

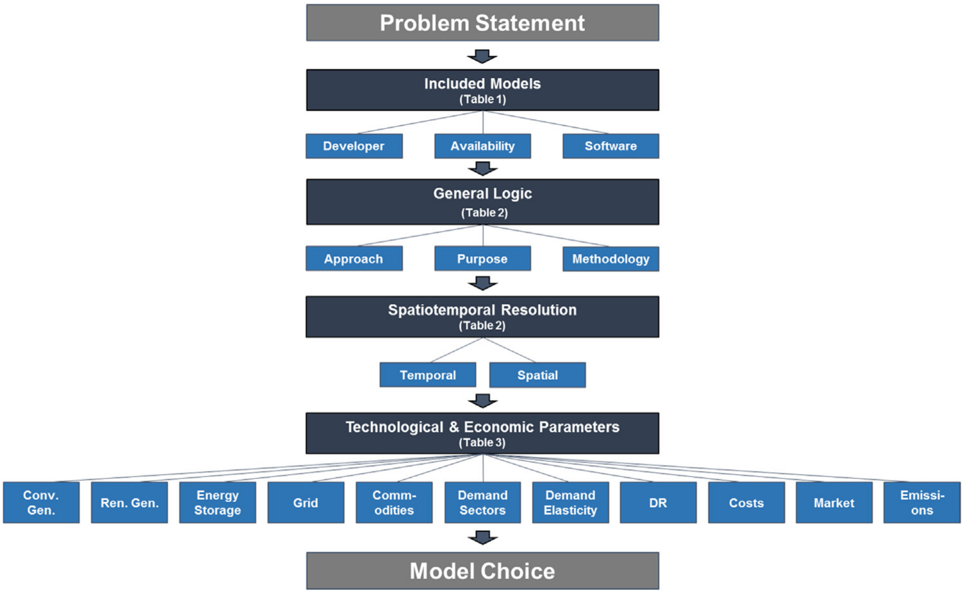

Fig. 1. Flowchart illustrating the model categorisation followed in this paper, where this information can be found, and how it can be applied in a process to identify a specific model for a given use. The abbreviations Conv. Gen. and Ren. Gen. refer to conventional and renewable generation technologies, and DR refers to demand response.

operation/dispatch of the energy/electricity system, considering for example unit commitment. Such models operate on short-term timescales, but on a larger scale than power system analysis tools e.g. on a national or European scale.

Investment Decision Support – Tools that optimise the investments in the energy/electricity system. Due to the long investment cycles in the energy sector, such models are usually long-term models. Investment modelling can be done either with a **myopic** or a **perfect foresight** approach. With a perfect foresight approach, the system is optimised for the whole study-period simultaneously, with complete knowledge of how market parameters will evolve across the planning horizon [196]. For the myopic approach, investments are made sequentially, only based on information from the current investment period.

Scenario – Such tools investigate future long-term scenarios in the energy/electricity sector. They can for example be used to evaluate the impact of various policies.

2.2.1.2. Approach. Energy models generally follow two approaches; either a **top-down** or a **bottom-up** approach. Often referred to as the engineering approach, bottom-up models are based on detailed technological descriptions of the energy system. On the other hand, top-down models follow the economic approach, considering macroeconomic relationships and long-term changes [21].

In many cases, particularly when assessing the integration of variable renewables, both long-term changes and technological properties are of high importance. To capture both, models can be combined in **hybrid** approaches [214].

2.2.1.3. Methodology. The methodologies of energy and electricity models are generally divided into three main categories; simulation, optimisation or equilibrium models.

Simulation models simulate an energy-system based on specified equations and characteristics. They are often bottom-up models, with a detailed technological description of the energy system. Simulation models allow the testing of various system topologies, as well as impacts and developments of various scenarios. **Agent-based simulation** is a specific case of models where actors participating in e.g. the electricity market are modelled explicitly as agents with distinct strategies and behaviour.

Optimisation models optimise a given quantity. When modelling energy and electricity systems this quantity is usually related to the system operation or investment, while some models have the capability of optimising several aspects simultaneously. The majority of optimisation models use a **linear programming** (LP) approach, with an objective function which is either maximised or minimised (e.g. minimising the total system cost), subject to a set of constraints (e.g. balancing the supply and demand in the grid). **Mixed-integer linear programming** (MILP) forces certain variables to be integral, which can be useful when for example optimising how many power plants or the number of wind turbines one should invest in. Optimisation models can also be **non-linear,** i.e. the objective function or constraints are non-linear. **Heuristic optimisation** models differ from traditional optimisation modelling as they do not necessarily find the optimum solution [215]. By simple and fast methods, such as the Covariance Matrix Adaption Evolution Strategy (CMA-ES) [216], the optimal solution can be approximated.

Equilibrium models take an economic approach, modelling the energy sector as a part of the whole economy and studies how it relates to the rest of the economy. Such models are therefore often used to evaluate the impact of various policies on the economy as a whole. General equilibrium models, or **computable general equilibrium models** (CGE), consider the whole economy. They determine the equilibrium across all markets, and determine important economic parameters such as the gross domestic product (GDP) endogenously. **Partial equilibrium models** (PE) focus on balancing one market, in this case the energy or electricity market, with the rest of the economy not modelled.

2.2.2. Spatiotemporal resolution

The spatiotemporal resolution of a model is particularly important, as it sets limitations to which processes can be appropriately modelled. This is especially important in systems with a large share of VRES, as the variability of the solar and wind resources must be captured. This is further discussed in Section 4.1.

Time-steps can vary from milliseconds in power system analysis tools to several decades in long term economic equilibrium models. In some models time-steps are fixed, while in others the time-step is given by the input data. Likewise, the geographical scope can vary from analysing single projects or individual buildings to modelling the energy system of the whole world.

2.2.3. Technological and economic properties

Measures such as grid development, energy storage and demand side management have been identified as some of the key contributors for successfully building an energy system containing large shares of

VRES. When modelling the impact of increased shares of VRES in the European energy system, some properties and features of a model are therefore crucial. Model components and properties are categorized as follows:

Conventional Generation – Modelling of conventional generation technologies such as thermal generation, nuclear and bioenergy can be done in various ways, for example by modelling each power plant individually or by aggregating all power plants of a technology within a region.

Renewable Generation – Whereas conventional generation is dispatchable, renewable generation (except geothermal & tidal) depends on meteorological conditions. These conditions, and thus the generation, can be modelled by meteorological data (e.g. wind speed data in combination with a power curve for wind production), by stochastic methods (e.g. stochastic inflow modelling for hydropower scheduling) or not modelled at all (e.g. by deriving capacity factors from historical data). The renewable generation technologies considered are: wind, PV, solar thermal, concentrated solar power, hydropower with reservoir, run-of-the-river hydropower, geothermal energy, wave power and tidal energy.

Energy Storage – Due to the fluctuating output from solar and wind that does not necessarily comply well with the demand, means of storing energy is important. Pumped hydropower storage (PHS) is the only large-scale energy storage technology widely available today, and amounts about 96% of the storage capacity in Europe [217]. Due to limited available locations for further PHS expansions and increasing need for energy storage, other solutions such as hydrogen, thermal energy storages, batteries, or compressed air energy-storage (CAES) may be increasingly important in the future.

Grid – Power system analysis tools apply detailed modelling of power systems, including power flows, short-circuit analyses, harmonics, stability and so on. In models which mainly are concerned with load flow between regions, three approaches with decreasing complexity are followed. These are AC (alternating current) flow, DC (direct current) flow or by net transfer capacities (NTC).

Modelling a grid with N nodes using AC power flow results in 2N non-linear equations that must be solved iteratively for each time step [218]. Understandably, this is computationally demanding, and therefore in many cases a simplified linearised power flow is preferred (often referred to as DC-modelling). Studies have shown that the error of using the DC simplification is only in the order of a few percent, except at very high loadings [219,220]. At high loadings the reactive power consumption increases by the power of two, thus making the DC simplification less accurate as it does not represent reactive power. However, Brown et al. [219] limited the loading of their modelled power lines due to n-1 security and to allow for extra reactive power flows, thus avoiding this issue in all but a few instances (they allowed some overloading in order to avoid unnecessary grid expansions).

The NTC approach considers transfer capacities, often interregional exchange capacities between countries. Studies have shown that the NTC approach shows small differences compared to the linearised load flow [9]. Due to its simplicity and overall high accuracy, modelling with the NTC approach is highly popular and used in many of the models.

Commodities – Whilst many models have a specific focus on the power sector alone, some models also include other commodities. This can be beneficial, as various forms of energy can be able to complement each other (see Section 4.2). The focus is on commodities which are believed to be the most important for a 100% renewable energy system, namely electricity, heat and hydrogen. In addition all commodities related to fossil fuels have been classified simply as fuels without specifying which specific fuels are modelled.

Demand sectors – End-use sectors have been split in the building, industry and transport sectors. This means that commercial and residential buildings are combined in the building sector, and likewise agriculture is included in the industrial sector. Many models concerns only the electricity systems and uses an aggregated demand/load based on the consumption of electricity in all of the sectors combined.

Demand Elasticity – A measure of how the demand changes due to price fluctuations. E.g. the demand of electricity might decrease if the prices become higher.

Demand Side Management – Demand side management (DSM) concerns measures taken on the consumers' side of the energy system, including improvements in energy efficiency, energy conservation and demand response (DR) [23].

Demand Response (DR) is the procedure of shifting certain loads from hours when the demand is higher than the supply to hours with surplus generation. This helps balancing the fluctuating output from variable renewables, and is a good complement to energy storage. It also reduces the highest load peaks for which the electrical grid is designed, thus reducing the need of expensive grid-development. As an example, the charging of electric vehicles can be shifted from the peak in demand usually experienced in the afternoon to the night when the consumption is much lower.

In terms of modelling, DR can be treated as a negative storage, by "storing" the demand rather than excess energy. It can also be modelled by shifting unmet flexible loads (e.g. charging EVs) to following timesteps. A third possibility is to model DR as a negative generating unit, with associated maximum capacities, costs etc.

Costs – Although very difficult to model accurately, costs are crucial for the modelling results. Investment, operation & maintenance, fuel, CO_2, taxes and balancing costs (start-up, shut-down and ramping costs) are included in the model categorisation.

Market – Most of the models assessed treat the market by simply balancing supply and demand under perfect market conditions. However, some models have no market modelling at all, whilst other models can treat the spot market (merit-order modelling), the reserve market or even the balancing market.

Emissions – Some models include modelling of various greenhouse gases and pollutants such as CO_2, NO_x, SO_x or CH_4, often as a side product of generation from various fuel types. In some models, any pollutant can be modelled as its own commodity whereas some models treat greenhouse gas emissions by CO_2 equivalents.

3. Results

Table 1 presented the 75 models included in this review, their availability, developers and software requirements. In this section, Tables 2, 3 extends this information by presenting the specific capabilities of each of the models.

The general logic and the spatiotemporal resolution of the models are presented in Table 2. Most of the models are bottom-up optimisation models with the purpose of giving investment and/or operation decision support. Such models work on several timescales and modelling horizons, and can analyse small scale energy systems as well as systems on the scale of the whole of Europe. Thirteen power system analysis tools are included in this review, all of which are bottom-up simulation models. There are also some hybrid models and one pure top-down model. These are mainly long-term and large-scale models focusing on scenario analysis.

Fig. 2 illustrates the relationship between the geographical coverage and the temporal resolution of the reviewed models. Panel a) presents models with pure bottom-up and top-down approaches, whereas panel b) presents hybrid models. Each model has been assigned a model ID

Table 2

General logic and spatiotemporal resolution. Abbreviations used in the table: **Purpose:** IDS – Investment Decision Support, ODS – Operation Decision Support, S – Scenario, PSAT – Power System Analysis Tool, A – Analysis; Approach: BU – Bottom-up, TD – Top-down, H – Hybrid; **Methodology:** S – Simulation, LP – Linear Programming, MIP – Mixed Integer Programming, PE – Partial Equilibrium, A- Accounting, ABS – Agent-based Simulation, MIQCP – Mixed Integer Quadratically Constrained Programming, CGE – Computable General Equilibrium, E – Equilibrium, CMA-ES – Covariance Matrix Adaptation Evolution Strategy, HO – Heuristic Optimisation, ECE – Economic Computable Equilibrium, SDDP – Stochastic Dual Dynamic Programming; **Temporal Resolution/Modelling Horizon/Geographical Coverage:** UD – user-defined, NL – No limitations.

Models	#	Purpose	Appr.	Methodology	Temporal resolution	Modelling horizon	Geographical coverage
AURORAxmp	1	I & ODS, S, PSAT	BU	S, LP, MIP, PE	UD (Hourly)	UD (50+ years)	Single project → Global
BALMOREL	2	I & ODS	H	PE/LP (MIP)	Hourly/Aggregate	50 years (UD)	Regional → International
Calliope	3	I & ODS	BU	LP (MIP under development)	UD	UD	UD
CASPOC	4	PSAT	BU	S	UD	µs to 1 year	Single-System/Local
COMPETES	5	I & ODS	BU	LP (In.), MIP (Op.)	Hourly	UD	National (Europe)
COMPOSE	6	ODS & S	BU	A (In.), MIP(Op.)	UD (Usually hourly)	UD	Single-Project/System
CYME	7	PSAT	BU	S	UD (Usually ms)	UD	Single-System → Regional
DER-CAM	8	I & ODS	BU	MIP	Hourly (In.) & Minutes (Op.)	Up to 20 years	Single-Project → Regional
DESSTinEE	9	S, I & ODS	BU	S	Hourly	2050	National (Europe)
DIETER*	10	I & ODS	BU	LP	Hourly	1 year	Calibrated to Germany
DIgSILENT/ PowerFactory	11	PSAT	BU	S	UD	UD	Power Systems
EMLab-Generation	12	IDS	H	ABS	Yearly	2050	Two Markets/Countries
EMMA	13	I & ODS	BU	LP	Hourly	Long-term economic equilibrium	National (Europe)
EMPIRE	14	IDS	H	LP (Multi-horizon stochastic)	5 y (In.), UD time-slices per year (Op.)	Typically 40–50 y	National (Europe)
EMPS	15	I & ODS	BU	LP[a]	Weekly[b]	25 years	Regional → Continental
EnergyPlan	16	S, IDS	BU	S	Hourly	1 year	Local → Continental
energyPro	17	I & ODS	BU	AO[c]	Minutes	Max 40 years	Local → Regional
Enertile	18	I & ODS	BU	LP	Hourly	Usually 2050	EUMENA (National)
ENTIGRIS	19	I & ODS	BU	LP	Hourly (Op.), 5 y (In.)	2050	Regional → International
ETM (1)	20	S	BU	PE & LP	Six time slices: three seasons (winter, summer and intermediate), & day/ night	2100	Global (17 regions)
ETM (2)	21	S	H	S	15-min (+ Hourly & Yearly)	2050	Community → International
ETSAP-TIAM	22	I & ODS, S	BU	LP, PE	Yearly (seasons & day-night hours)	2100	Global (15 regions)
EUCAD	23	ODS	BU	MIQCP	Hourly	Yearly	National (Europe)
EUPower-Dispatch	24	ODS	BU	MIP	Hourly	Yearly	National (Europe)
ficus	25	I & ODS	BU	MIP	Typically 15 min	1 year	Local → National
GCAM	26	S	H	PE	5 years	2100	Global (Regional)
GEM-E3	27	S	TD	CGE	5 years	2030 and 2050	Global (38 regions)
GENESYS	28	IDS	BU	CMA-ES & HO	Hourly	2050	EUMENA (National)
GridLAB-D	29	PSAT	BU	ABS	Sub-seconds – Years	3–5 Years	Local → National
HOMER	30	I & ODS	BU	S & O	Minutes	Multi-Year	Local
HYPERSIM	31	PSAT	BU	S	10 µs	UD	Single-System → Regional
iHOGA	32	I & ODS	BU	HO	Hourly	Yearly	Local
IMAKUS	33	I & ODS	BU	LP	Hourly	Several decades	Germany
INVERT/EE-Lab	34	S	BU	S	Y (In), Monthly (Op)	2030/2050/2080	Buildings
IPSA 2	35	PSAT	BU	S	[d]	[e]	Power Systems
IRiE	36	ODS	BU	MIP	15-min	Yearly	26 areas in Northern Europe
LEAP	37	S	H	S & LP	Yearly	Usually 20–50 years	Local → Global
LIBEMOD	38	S	H	ECE	Yearly (El split in summer and winter season; one day split into day and night)	1 → 20 years	National (Europe)
LIMES-EU	39	S, I & ODS	H	LP	5/10 y (6 rep. days per year, 8 time slices per day)	2050	National (Europe)
LOADMATCH*	40	S	BU	S	30 s	6 years (2050–2055)	CONUS (4° × 5° WWS data)
LUSYM	41	ODS	BU	MIP	15 min/Hourly & Daily (UC)/Weekly (Scheduling)	Daily/Weekly (UC) & Yearly (Scheduling)	National
MARKAL	42	S	BU	LP/MIP, PE	Multiple years (UD time-slices within a year)	Long-term (UD)	Local → Regional
MESSAGE	43	S, IDS	H	LP	UD (Multiple years)	Long-term (50–100+ years)	Global (11 Regions)
NEMO	44	I & ODS	BU	CMA-ES & S	Hourly	Typically 1 year	National
NEMS	45	S	H	S, O, PE	Yearly	2050	Regional/National (U.S.)
Oemof (SOLPH)	46	S, I & ODS	All	LP, MILP, PE	Seconds to years	UD	UD
OpenDSS	47	PSAT	BU	S	UD (1 s to 1 h)	UD	Distribution feeders/areas
OSeMOSYS	48	IDS	BU	LP	UD (intra-annual)	UD (10–100 y)	Community → Continental
PLEXOS	49	I & ODS, S, PSAT	BU	[f]	UD up to 1 min (Usually hourly)	UD (1 day to 50 + years)	Single project→ Global
POLES	50	S, I & ODS	H	PE/S	Yearly (Sectoral load shape for two typical days with two-hour resolution)	2050 (2100)	Global (66 regions)
PowerGAMA	51	S (IDS)	BU	S, LP	Usually hourly	Usually 1 year	Regional/National

(*continued on next page*)

Table 2 (*continued*)

Models	#	Purpose	Appr.	Methodology	Temporal resolution	Modelling horizon	Geographical coverage
PRIMES*	52	S, IDS	H	PE	Yearly	Long-term	National (Europe)
ProdRisk	53	ODS	BU	LP (SDDP)	Usually 5–25 weekly periods	Usually 3–10 years	Local → National
PyPSA	54	I & ODS, PSAT	BU	LP	Hourly	1 year	Local → Continental
RAPSim	55	PSAT	BU	S	Minutes	Multiple days	Local
ReEDS	56	S (& IDS)	BU	LP & PE	[g]	2050	[h]
ReMIND	57	S	H	NLP	[i]	2150	Global (11 regions)
REMix	58	I & ODS	H	LP	Hourly	Typically 1 year	Regional (Germany) → National (Europe)
renpass	59	ODS, S	BU	S (In) & O (Op)	Typically Hourly	1 year	Regional/National (Western Europe)
RETScreen	60	IDS, S	H	S	Monthly/Yearly/Daily	Max 100 years	Single-system → Global
SAM	61	IDS	BU	S	Sub-Hourly	1 year (/Lifetime for e.g. batteries + PV)	Single system
SIMPOW	62	PSAT	BU	S	Milliseconds	Seconds	Single-system → Local
SIREN	63	S	BU	S	Hourly	1 year	Regional/National
SNOW	64	S	H	CGE	Yearly	UD (1–100 years)	[j]
stELMOD	65	ODS	BU	MIP	Hourly	1 year	National (Europe)
SWITCH	66	I & ODS	BU	MIP	Hourly Dispatch/Decadal Investment Period	UD (2050)	Regional/National[k]
Temoa	67	S	BU	LP	Yearly (With UD time-slices)	UD	Regional (UD)
TIMES	68	I & ODS	H/BU	LP/MIP, PE	Multiple years - with UD time-slices within a year	Long-term (UD)	Local - Global
TIMES-Norway	69	S, IDS (& ODS)	BU	LP	Multiple years – 260 time-slices per year	2050	Norway (Sweden optional)
TIMES-Oslo	70	S, IDS (& ODS)	BU	LP	Multiple years – 260 time-slices per year	2050	Oslo (Norway optional)
TRNSYS18	71	PSAT	BU	S & L/NLP	0.01 s to 1 h	Multiple years	Single Project → Local
urbs	72	I & ODS	BU	LP	UD (Hourly)	UD (Yearly)	Local → National
WEM*	73	S	H	S	Yearly[l]	2040	Global (25 Regions)
WeSIM	74	I & ODS	H	LP	Hour or half-hourly	1 h – multi years	National → Continental
WITCH	75	S, IDS	H	NLP, E	5 years	150 years	Global (13 regions (UD))

[a] The model includes stochastic optimisation (Stochastic Dynamic Programming (SDP)), linear programming and simulation. In the strategy evaluation, SDP is used to calculate incremental water values and heuristics is used to treat the interaction between areas. In the simulation part of the model, total system costs are minimised in a linear problem formulation.

[b] In the strategy evaluation the resolution is weekly. In the simulation it can be weekly with a load-duration curve within the week or with hourly resolution.

[c] Analytical optimisation [69].

[d] 30 min (Load flow analysis), Usually Milliseconds (Fault Level & Transient Stability).

[e] About 1-year (Load flow), Fault levels (hundreds of milliseconds), Transient (seconds).

[f] Optimisation (Mixed-Integer, Linear and Non-Linear)/Partial Equilibrium (e.g. solving Nash-Cournot with integer problems uses Mixed Integer Quadratic Programming (MIQP)).

[g] Sequential 2-year periods, 17 seasonal/diurnal blocks of non-chronological aggregate hours.

[h] U.S. (+ Canada & Mexico) – (134 Supply/demand balancing areas (+ 20 CA/+ 49 ME) & 356 renewable resource regions (+ 47 CA/+ 49 ME).

[i] 5 years until 2060, 10 until 2110, 20 until 2150.

[j] Global version: Flexible, typically 2–10 regions, National version: Norway and rest of the world.

[k] Models typically have 1–50 load zones; models have been created for California, Western U.S., Hawaii, Chile, Nicaragua, China and other regions.

[l] A new feature in WEM 2016 is the inclusion of a more detailed power market module with hourly resolution.

and is represented by a rectangle spanning the range of typical resolutions the model can possess. The transparency of the rectangles is only added to improve visual representation, and the position of the boxes have been modified to ensure readability. The figure should therefore be regarded as an illustration of the modelling landscape rather than an exact representation.

The illustration shows that the geographical scope, the temporal resolution and the approach are all related. Hybrid and top-down models populate the upper right side of Fig. 2, whereas bottom-up models are spread over the whole range. Top-down and hybrid models generally have large geographical scales and long time-steps, with the long-term development of the energy system in focus. The operation and technical details are usually omitted and replaced by macro-economics, thus making such models top-down or hybrid.

The technological and economic features of the models are presented in Table 3. This includes features such as conventional and renewable generation, storage, grid, demand response, market modelling, emissions etc. The categories have been thoroughly explained in Section 2.2.3.

None of the models can tackle all challenges of today's energy system, but all challenges are covered by at least one of the models. There is generally a good coverage of the various technological and economic features, and modellers should be able to identify a model that can analyse most challenges related to VRES integration.

As previously mentioned, grid expansion, energy storage and demand side management are measures poised to be critical for the integration of VRES. Some earlier studies have assessed all these features, but most studies address the individual impact of one of the measures. From this review, one can identify several tools that may be used to study the effect of combining multiple measures.

Simple supply/demand modelling or spot (merit-order) of the energy/electricity market is the most common amongst the tools. However, a few of the models also have the capability to model the day-ahead market, reserve or balancing market.

Table 3
Technological and economic parameters. Abbreviations used in the table: Ren. Gen: HP – Hydropower, ROR – Run-of-river, SP – Solar Power, WP – Wind Power, ST – Solar Thermal, WaP – Wave Power, GT – Geothermal, CSP – Concentrated Solar Power, TP – Tidal Power; **Storage:** PHS - Pumped Hydro Storage, CAES – Compressed Air Energy Storage, B – Batteries, H – Hydrogen, TES – Thermal Energy Storage; **Grid:** NTC – Net Transfer Capacity; **Cost:** I – Investment, O&M – Operation & Maintenance, F – Fuel, CO2 – Carbon cost, T – Taxes, B – Balancing costs.

Models	#	Conv. Gen.	Ren. Gen.	Storage	Grid	Commodities	Demand sectors	Demand elasticity	DR	Costs	Market	Emissions
AURORAxmp	1	All	All	All (Generic)	Import/Export, NTC, DC Load Flow (SCUC/SCOPF)	Electricity, Heat	Electricity (with Heat), interface to gas models	Elastic	Yes	I, O&M, F, CO_2, B	All	Any Pollutant
BALMOREL	2	All	HP, ROR, SP, WP, ST, WaP	All	NTC	Electricity, Heat, Hydrogen & Fuels	Aggregated (Separate for Electricity and Heat)	Elastic	Yes	I, O&M, F, CO_2, T, B	Spot	CO_2, SO_2 and NO_x
Calliope	3	All	All	All	NTC	Electricity, Hydrogen, Heat & Fuels	Aggregated	Inelastic	Yes	I, O&M, F, CO_2	Supply/Demand	Any pollutant
CASPOC	4	All	All	All	Power Electronics & Circuit modelling	Electricity	Aggregated	Inelastic	No	NA	NA	No
COMPETES	5	All	HP, SP, WP, GT	PHS, CAES	NTC/DC Simplification	Electricity	Aggregated	Inelastic/ Elastic (short-term)	Yes	I, O&M, F, CO_2, B, T	Spot/Balancing (Short-term)	CO_2
COMPOSE	6	All	All	All	None (Constraints can be parametrised)	Electricity, Heat & Fuels	Buildings, Transport & Industry (User-defined)	Inelastic	No[a]	I, O&M, F, CO_2, T, B	Spot, Balancing Markets	CO_2
CYME	7	All	SP, WP (All)	B	Detailed Power Simulation	Electricity	Aggregated	NA	No	NA	NA	NA
DER-CAM	8	All (Except Nuclear)	All	All	Import/Export, Power Flow	Electricity & Heat	Aggregated, Electricity, Buildings	Elastic	Yes	I, O&M, F, CO_2, T	Supply/Demand, Spot, Balancing Markets	CO_2
DESSTinEE	9	All	All	PHS	NTC	Electricity	Buildings, Transport & Industry	Inelastic	No	I, O&M, F, CO_2	Spot (Merit-order)	CO_2
DIETER*	10	All (Except Nuclear & Lignite)	WP, SP	B, H, PHS, CAES	None	Electricity	Aggregated	Inelastic	Yes	I, O&M, F, CO_2, B	Spot	No
DIgSILENT/ PowerFactory	11	All	All	All (Generic)	Detailed Power Flow	Electricity	Aggregated	Inelastic	NA	NA	NA	No
EMLab-Generation	12	All	WP, SP (Generic)	All (Generic)	NTC	Electricity	Aggregated	Inelastic	No	I, O&M, F, CO_2	Spot + CO_2 market	CO_2
EMMA	13	All	WP, SP, HP, ROR	PHS	NTC	Electricity & Heat	Aggregated	Inelastic	Yes	I, O&M, F, CO_2, B	Spot	No
EMPIRE	14	All	All (Except Tidal)	All (Generic)	NTC	Electricity	Aggregated	Inelastic	Yes	I, O&M, F, CO_2	Supply/Demand	CO_2
EMPS	15	All	All	PHS	NTC (Full Load Flow possible)	Electricity	Aggregated	Elastic	Yes	I, O&M, F, CO_2, B	Spot	CO_2
EnergyPlan	16	All	All	All	Import/Export	Electricity, Heat, Hydrogen & Fuels	Buildings, Transport & Industry	Elastic	No	I, O&M, F, CO_2, T	Spot	CO_2
energyPro	17	All (Except nuclear)	All	PHS, CAES, B, TES	None	Electricity and Heat	Aggregated	Elastic	No	I, O&M, F, CO_2, B, T	Spot	CO_2, SO_2 & NO_x
Enertile	18	All	All	PHS, TES, B	NTC	Electricity & Heat	Buildings, Transport & Industry	Elastic for P2H, Inelastic otherwise	Yes	I, O&M, F, CO_2	Supply/demand	CO_2

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Table 3 (*continued*)

Models	#	Conv. Gen.	Ren. Gen.	Storage	Grid	Commodities	Demand sectors	Demand elasticity	DR	Costs	Market	Emissions
ENTIGRIS	19	All	HP, WP, SP, CSP	PHS, B, TES	NTC	Electricity	Aggregated	Inelastic	Yes	I, O&M, F, CO_2, B	Supply/Demand	CO_2
ETM (1)	20	All	All	TES	Import/Export	Electricity, Heat, Hydrogen & Fuels	Buildings, Transport & Industry	Elastic	No	I, O&M, F, CO_2, T	Supply/Demand	CO_2
ETM (2)	21	All	All (Except TP & WaP)	PHS, B, H, TES	Import/Export, NTC	Electricity, Heat, Hydrogen & Fuels	Buildings, Transport & Industry	Inelastic	Yes	I, O&M, F, CO_2, T	Supply/Demand, Spot, Balancing Markets	CO_2
ETSAP-TIAM	22	All	HP, ROR, WP, SP, ST, CSP,GT	PHS	Import/Export	Any commodity	Buildings, Transport, & Industry	Elastic	No	I, O&M, F, CO_2, T	Supply/Demand	CO_2, CH_4, NO_x, SO_x
EUCAD	23	All	All	PHS, CAES, B, H	NTC	Electricity & Hydrogen	Aggregated	Inelastic	Yes	O&M, F, B, T	Supply/Demand	None
EUPower-Dispatch	24	All	All	PHS	NTC	Electricity	Aggregated	Inelastic	Yes	O&M, F, CO_2	Supply/Demand	CO2
ficus	25	All	All	All (Generic)	Import/Export	Any commodity	Aggregated	Inelastic	No	I, O&M, F, CO_2	Supply/Demand	Any Pollutant
GCAM	26	All	HP, SP, CSP, WP, GT	PHS, H	None	Any	Buildings, Transport, Industry	Elastic	No	I, O&M, F, CO_2	Supply/Demand	CO_2 (Any)
GEM-E3	27	All	HP, WP, SP	None	Export/Import	Any Commodity	Buildings, Transport & Industry	Elastic	No	I, O&M, F, CO_2	Supply/Demand	Any Pollutant
GENESYS	28	None (Included in next version)	All	All	NTC	Electricity	Aggregated	Inelastic	No	I, O&M, F, CO_2	Supply/Demand	None (CO_2 in next version)
GridLAB-D	29	Diesel Generators	WP, SP	B	Detailed Power Flow	Electricity	Aggregated	Elastic	Yes	NA	Uniform Price Auction	NA
HOMER	30	All (Except nuclear)	All	CAES, B, H	Import/Export	Electricity & Heat	Aggregated	Inelastic	No[b]	I, O&M, F, CO_2	Supply/Demand	Any Pollutant
HYPERSIM	31	All	All	B	Detailed Power Flow	Electricity	Aggregated	NA	No	NA	NA	NA
iHOGA	32	Diesel/Petrol Generators	WP, HP, SP	H, B	Import/Export	Electricity & Hydrogen	Aggregated	Inelastic	No	I, O&M, F, CO_2	Supply/Demand	CO_2
IMAKUS	33	All	All (Exogenous)	All	Import/Export	Electricity & Hydrogen	Aggregated	Inelastic	Yes	I, O&M, F, CO_2	Supply/Demand	CO_2
INVERT/EE-Lab	34	Small-scale CHP	PV	None	None	Electricity & Heat	Buildings	Elastic	No	I, O&M, F	Supply/Demand	CO_2
IPSA 2	35	All	All	All	Detailed Power Flow	Electricity	Aggregated	Inelastic	Yes	NA	NA	NA
IRiE	36	All	HP, WP, SP	None	NTC	Electricity	Aggregated	Inelastic	No	O&M, F, CO_2, B	Reserve and Balancing market	None
LEAP	37	All	All	All	None	Electricity & Heat	Buildings, Transport & Industry	Elastic	No	I, O&M, F, CO_2	Supply/Demand	Any Pollutant
LIBEMOD	38	All	HP, ROR, WP, SP	PHS	NTC	Electricity, Heat & Fuels	Buildings, Transport & Industry	Elastic	No	I, O&M, F, CO_2, T, B	Supply/Demand, National Capacity Markets	CO_2
LIMES-EU	39	All	HP, WP, SP, CSP	All (Generic)	NTC	Electricity	Aggregated	Inelastic	No	I, O&M, F, CO_2	Supply/Demand	CO_2
LOADMATCH*	40	None	All	PHS, TES, H	None (Losses are taken into account)	Electricity, Heat & Hydrogen	Buildings, Transport & Industry	Inelastic	Yes	I, O&M, F, (+ Health and climate costs)	Supply/Demand	None
LUSYM	41	All	All	All (Generic)	Linearised DC Power Flow	Electricity	Aggregated	Inelastic	Yes	O&M, F, CO_2, B	Supply/Demand	CO_2

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Table 3 (*continued*)

Models	#	Conv. Gen.	Ren. Gen.	Storage	Grid	Commodities	Demand sectors	Demand elasticity	DR	Costs	Market	Emissions
MARKAL	42	All	HP, WP, SP, GT	PHS, (night-day storages)	NTC	Any commodity	Buildings, Transport & Industry	Elastic	Yes	I, O&M, F, CO_2, T	Supply/Demand (Competitive, perfect foresight)	Any
MESSAGE	43	All	All	All	Import/Export	Any commodity	Buildings, Transport & Industry	Elastic	Yes	I, O&M, F, CO_2, T	Supply/Demand	Any Pollutant
NEMO	44	OCGT, CCGT, Coal (CCS)	HP, WP, PV, CST, GT	PHS, B	None	Electricity	Aggregated	Inelastic	Yes	I, O&M, F, CO_2	Spot	CO_2
NEMS	45	All	All (except TP & WaP)	PHS, B, TES	Import/Export	Electricity & Heat (Partly Hydrogen in transport)	Buildings, Transport & Industry	Elastic	No	I, O&M, F, CO_2, T	Supply/Demand	CO_2, SO_2 and NO_x
Oemof (SOLPH)	46	All	All	All	Import/Export, NTC	Electricity, Heat, Hydrogen & Fuels	Buildings, Transport & Industry	Inelastic	Yes	I, O&M, F, CO_2, T, B	Supply/Demand	Any pollutant
OpenDSS	47	All (Generic)	SP (Others Generic)	All (Generic)	Full Multiphase AC Load Flow; Dynamics	Electricity	Aggregated (optionally disaggregated)	Inelastic	Yes	NA	NA	NA
OSeMOSYS	48	All	All	All	None	Electricity	Aggregated	Inelastic	Yes	I, O&M, F, CO_2, B	Supply/Demand	Any Pollutant
PLEXOS	49	All	All	All (Generic)	[c]	Electricity (with Heat), Gas and Water	Buildings, Transport & Industry	Elastic	Yes	I, O&M, F, CO_2, B	[d]	All (Generic)
POLES	50	All (25 explicit technologies)	All (16 explicit technologies)	PHS	None (Import/ Export)	Electricity, Fuels	Buildings, Transport & Industry	Elastic	No	I, O&M, F, CO_2, T	Supply/Demand (Carbon price)	GHG
PowerGAMA	51	All (Generic)	All (Generic)	All (Generic)	Linearised DC Power Flow	Electricity	Aggregated	Inelastic	No[e]	Marginal Costs	Supply/Demand (Perfect)	None
PRIMES*	52	All	All	All	DC linearised Optimal Power Flow	Electricity, Heat & Hydrogen	Buildings, Transport & Industry	Elastic	Yes	I, O&M, F, CO_2, T	Supply/Demand	CO_2
ProdRisk	53	Thermal Power Plants	HP, WP	PHES	None (Exists a prototype with detailed grid)	Electricity	Aggregated	Yes	No	No fixed price	Spot (Capacity Market under development)	None
PyPSA	54	All	All	All (Generic)	Non-linear/Linear Power Flow, NTC	Any commodity	Aggregated	Inelastic	Yes	Capital Cost & Marginal Cost	Supply/Demand	CO2
RAPSim	55	None (Under development)	WP, SP	None (Under development)	Detailed Power Flow	Electricity	Building	Inelastic	No	None	None	None
ReEDS	56	All	All (Except Tidal)	All (Except Hydrogen)	Linearised DC Power Flow	Electricity	Aggregated	Inelastic	Yes	I, O&M, F, CO_2, T	[f]	CO_2, SO_2, NO_x + Mercury
ReMIND	57	All (Coal, Oil, Gas, Uranium, Biomass)	HP, SP, WP, GT	All (Generic)	None	Electricity, Heat, Hydrogen & Fuels	Buildings, Transport & Industry	Elastic	Yes	I, O&M, F, CO_2	Supply/Demand (Pareto/Nash)	Any Pollutant
REMix	58	All	All	All	NTC, DC simplification	Electricity, Heat & Hydrogen	Aggregated	Inelastic	Yes	I, O&M, F, CO_2	Supply/Demand	CO_2
renpass	59	All	HP, WP, SP, GE, ROR	PHS, CAES, B	NTC	Electricity	Aggregated	Inelastic	No	I, O&M, F, CO_2	Spot	CO_2
RETScreen	60	All	All	B	Central/Isolated/ Off-Grid (Import/ Export)	Electricity & Heat	Buildings & Industry	Inelastic	No	I, O&M, F, CO_2, T	Supply/Demand	GHG
SAM	61	Conventional Thermal & Biomass	SP, ST, CSP, WP, GT	B, TES	None	Electricity	Aggregated	Inelastic	No	I, O&M, F, T	None (E.G. Power Purchase Agreement))	None

(*continued on next page*)

Table 3 (*continued*)

Models	#	Conv. Gen.	Ren. Gen.	Storage	Grid	Commodities	Demand sectors	Demand elasticity	DR	Costs	Market	Emissions
SIMPOW	62	All	All	None	Detailed Power Flow	Electricity	Aggregated	Inelastic	NA	NA	NA	NA
SIREN	63	All	All	All (Generic)	NTC	Electricity	Aggregated	Inelastic	No	I, O&M, F	Supply/Demand	CO_2
SNOW	64	All	All	None	Import/Export	Any commodity	46 industries, households & public sector	Elastic	No	I, O&M, F, CO_2, T	Supply/Demand	Any Pollutant
stELMOD	65	All	HP, WP, ROR & SP	PHS	NTC, DC simplification	Electricity, Heat	Aggregated	Inelastic	No	O&M, F, CO_2, B	Spot, Intra-day, Reserve-Market	CO_2
SWITCH	66	All	All (Generic)	All	[g]	Electricity (Partly transport)	Aggregated	Elastic/ Inelastic	Yes	I, O&M, F	Supply/Demand	CO_2
Temoa	67	All	All	All	NTC	Any commodity	Buildings, Transport & Industry	Inelastic	No	I, O&M, F	Supply/Demand	Any Pollutant
TIMES	68	All	All	All	NTC	Any commodity	Buildings, Transport & Industry	Elastic	Yes	I, O&M, F, CO_2, T, B	[h]	Any
TIMES-Norway	69	All (Except Coal)	All (Except GT (for el), CSP, WaP & T)	B, TES	NTC	Any commodity	Buildings, Transport & Industry	Inelastic	No[i]	I, O&M, F, CO_2, T	[h]	CO_2
TIMES-Oslo	70	All (Except Coal & Nuclear)	All (Except GT (for el), CSP, WaP & T)	None	NTC	Any commodity	Buildings, Transport & Industry	Inelastic	No	I, O&M, F, CO_2, T	[h]	CO_2
TRNSYS17	71	All (Except Nuclear)	SP, WP, ST, CSP, GT	B, H, TES	[j]	Electricity, Heat, Hydrogen & Fuels	Building and Industry	Inelastic	NA	NA	NA	NA
urbs	72	All	All	All (Generic)	NTC (+ Linearised Load Flow)	Any Commodity	Aggregated	Inelastic	Yes	I, O&M, F, CO_2, B	None	Any Pollutant
WEM*	73	All	All	All	None	Electricity, Heat, Hydrogen & Fuels	Building, Transport & Industry	Elastic	Yes	I, O&M, F, CO_2, B	Supply/Demand (+ Spot)	CO_2
WeSIM	74	All	All	All	NTC	Electricity, Heat & Gas	Aggregated	Inelastic	Yes	I, O&M, F, CO_2, B	Supply/Demand	CO_2
WITCH	75	All	HP, WP, SP, CSP	TES, B	NTC	Any commodity	Aggregated	Elastic	Yes	I, O&M, F, CO_2, B	Supply/Demand + CO_2-Market	Any Pollutant

[a] Can be parametrised.

[b] Can model controllable loads in a variety of ways.

[c] Import/Export, NTC, DC Load Flow, AC Load Flow (linearised approximation using Fixed or Variable Shift Factors - PTDFs), SCOPF and FBMC.

[d] Physical & Financial Forward Power Markets (Year-Ahead, Month Ahead, Spot, Intra-day) Balancing Market, All Reserve-Markets, Capacity Market, Gas Market, Water Market, Perfect Competition, Nash-Cournot market modelling or Bertrand pricing.

[e] A simplified model for flexible demand is included.

[f] Energy market (supply/demand balance), Capacity market (planning reserve margin requirement), Ancillary Service market (operating reserves), Renewable Energy Credit (REC) market (state Renewable Portfolio Standards).

[g] SWITCH uses a simplified transport model for investment planning, but can also use security-constrained AC power flow for production cost modelling.

[h] Supply-Demand (Competitive with perfect foresight or n-period myopic).

[i] Will be implemented In next version.

[j] Usually treats the grid as an infinite power source/sink, but has models for transmission losses and grid outages.

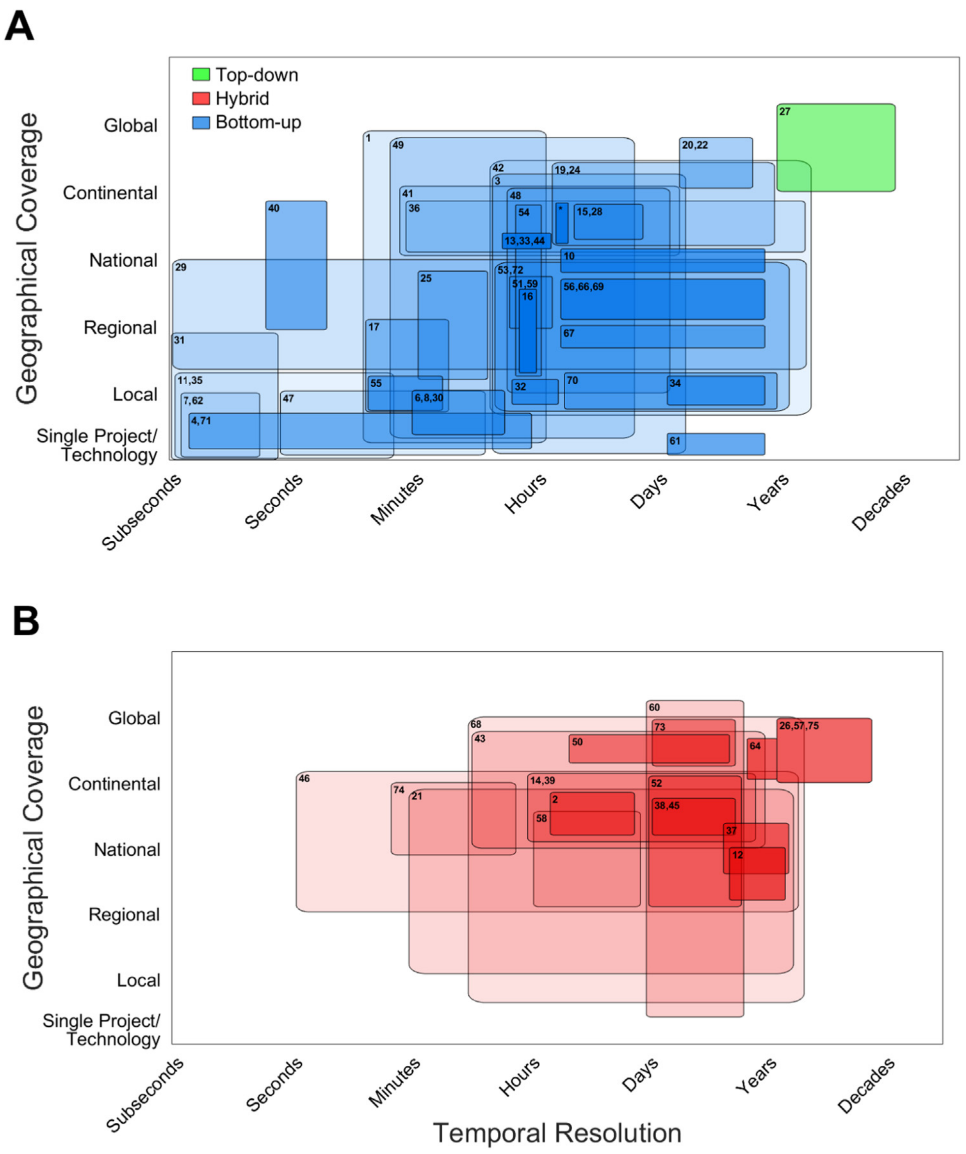

Fig. 2. Illustration of geographical coverage vs temporal resolution in the assessed models. The modelling approach is indicated by the colour of the rectangles, with transparency added for visual representation only. Panel A shows pure bottom-up and top-down models, and panel B shows hybrid models. For full interpretation of the figure, the reader is referred to the web version of this article. The rectangle marked with an asterisk (*), corresponds to models number 5, 9, 18, 23, 63 and 65.

4. Discussion and conclusions

This review has shown that there are numerous energy modelling tools currently available, capable of serving most needs from modelling of small-scale power systems to the global energy system. Grid expansion, energy storage and demand side management were earlier mentioned as key technologies and measures for a successful integration of VRES in the grid. Among the reviewed models, these measures are well represented. There are, however, some challenges faced by current modelling tools as well as future modelling needs.

4.1. Representation of variability

Many studies have looked into the effect and possibility of integrating wind and solar into the existing, fossil fuel dominated energy system. They all represent the geophysical data in distinct ways: Timescales ranging from seconds to several years, spatial resolutions ranging from a few kilometres to several latitudes, as well as the use of statistical representations [221–225]. The coarsest representation of variability is found in computable general equilibrium or partial equilibrium models, often with yearly aggregated data.

In long-term energy models, which are usually used to define the composition of and pathways to a future energy system, the temporal variability is often underrepresented [226]. A too coarse time-step can give poor estimation of the operation of the system, leading to unfavourable investments, overestimation of the share of VRES and an underestimation of the costs.

Welsch et al. used OSeMOSYS and a combined TIMES-PLEXOS model to study the Irish electricity system [142]. The medium to long-term energy model OSeMOSYS was first set up using 12 time periods each year, and was compared to a soft-linked combination of TIMES-PLEXOS using 8784 time periods over one year. Analysis of 2020 showed that the OSeMOSYS model allocated 21.4% of the dispatch to wrong generation capacities, by for example overestimating the use of wind energy. However, Welsch et al. further shows that by adding operational constraints in an enhanced OSeMOSYS model, without increasing the temporal resolution, the results from the TIMES-PLEXOS model were reproducible. They also extended the analysis to 2050, showing that the simple OSeMOSYS model, whose results are representative of conventional long-term energy models, invested in

14.1% less capacity and led to 14.5% lower investments than the enhanced model. They did not, however, extend the use of TIMES-PLEXOS to 2050, as computational costs become too high over such a long time-horizon with a high resolution and operational detail.

Similarly, Poncelet et al. used TIMES to evaluate the impact of utilising long-term energy models with a low temporal resolution [227]. Their version of the TIMES model was calibrated to Belgium and used 12 representative time-slices per year. It was compared to a unit-commitment (UC) model (mixed-integer linear formulation based on Van den Bergh et al. [228], later named LUSYM [124]) with an hourly resolution. They showed that the TIMES model invested in less VRES capacity than the UC model towards 2050, but their electricity generation shares were equal; showing once again that a low temporal resolution leads to an overestimation of VRES penetration and thus and underestimation of the necessary investment.

LEAP, MARKAL/TIMES and EnergyPLAN were used by Haydt et al. [229] to study the island of Flores (Azores) in the Atlantic Ocean through three different balancing methods (integral with load-curve of 9 time slices, semi-dynamic with 288 time periods and a dynamic approach with hourly modelling). Haydt et al. found that the models which did not consider the variability well enough overestimated the generation of VRES, therefore underestimating the necessary installed capacity as well as CO_2 emissions.

Tackling both the operational and planning issues of energy systems can, as has been shown above, be done by either linking models with different features or by adding capabilities within a model itself. As an example of the latter, Seljom et al. [230] developed a stochastic TIMES model, that dealt with the short-term uncertainty experienced in electricity generation and heat demand in buildings. Similarly, the EMPIRE model is a stochastic optimisation model, which simultaneously deals with the long-term evolution of the European electricity system as well as its operation [59]. Després [81] combined two models, EUCAD and POLES, respectively a power system optimisation model and a long-term energy model. EUCAD optimises the operation of the European power system every 24 h, taking into account the power system balance, international exchanges and system constraints such as operating points, on- and off-time, ramping and frequency reserves. This detailed representation of the power system was then combined with POLES, which covers the long-term evolution of demand, costs, and technological evolution and makes investment decisions for generation, storage and grid capacities. In addition, Jaehnert et al. has coupled the day-ahead market model EMPS with IRIE, a model that concerns reserve procurement and system balancing [231].

It is evident that considerations regarding VRES variability and operation are key aspects in present modelling, and represent challenges that become more and more important the larger the share of VRES in the energy mix becomes.

4.2. *Consumer participation, electrification and sector coupling*

Through distributed generation and demand side management, consumers are to an increasing extent becoming involved in the electricity system. More and more consumers are becoming prosumers, delivering power to the grid through distributed generation units as well as drawing power from the grid when local production is not sufficient. This affects both the distribution grids and the whole energy system on a larger scale. Consumers will also have to participate in demand response, which involves an intelligent management of their flexible loads. It will thus be important to capture consumer responses to changes in electricity and policies in energy modelling tools. Rai and Henry [232] modelled consumer energy choices using an agent-based simulation model. They show that such models can increase our understanding of consumer choices, knowledge that will be increasingly important as consumers become more involved in the energy system.

Decarbonisation of the electricity sector is a challenge that can, in theory, relatively easily be solved by replacing conventional fossil fuelled power generators with already mature and increasingly cost-competitive renewable technologies. The transport, heating and industrial sectors, however, are not that straight forward. One possible solution is to use different types of fuels, such as hydrogen or biofuels. Another possible solution is electrification, through for example switching to electric vehicles, electric water heaters, heat pumps, electric induction stoves, electrifying industrial equipment and so on. Switching from fossil fuelled vehicles to electric vehicles will not only enable decarbonisation of transport, but also lead to a lower primary energy demand as electric vehicles are much more efficient than their fossil fuelled counterparts [233]. This is also the case for other appliances, such as electric heat pumps for space and water heating with efficiencies of 200–300% [234]. The extent of future electrification is uncertain, but it can be hypothesized to lead to a significant increase in the electricity demand.

A more interconnected energy system, where the power, heat, industrial and transport sectors are closely linked, can help accommodate generation from variable renewables as well as abate emissions. Connolly et al. [235] recommends avoiding the traditional one-sided focus on how the power-sector alone can integrate VRES, and rather look into the synergies that can be achieved by merging the power, heating and transport sectors through a "Smart Energy Systems approach". They argue that measures such as battery electric vehicles, thermal storage, heat pumps and various types of fuel storage could provide increased flexibility for VRES, and thus enable higher penetration rates and even 100% renewable energy systems. A first step towards a 100% renewable-based Irish energy system was investigated by the use of EnergyPLAN [236], a modelling tool that can take into account the coupling between the electricity, heat and transport sectors [64]. Similarly, in a study combining the LOADMATCH grid integration model and the GATOR-GCMOM global climate/weather model, Jacobson et al. [225] assessed the energy system of the contiguous United States in 2050–2055 consisting of 100% renewable energy for all sectors (electricity, transportation, heating/cooling, and industry). They showed that the system is delivered at a low cost and is reliable with no load loss for the six simulated years. One of the main factors for the success of this system was the interplay between the various sectors, with hydrogen and heat as major contributors. Due to the importance of sector coupling in integrating large amounts of VRES, it is suggested that this is given more attention in future modelling studies.

4.3. *Impacts and links beyond the energy system*

Agenda 2030 [237], including its 17 Sustainable Development Goals and 169 targets, constitutes a global framework for sustainable development. In order to find a sustainable path forward, there is a need to address the interaction between different goals and solutions for energy supply, food production, protection of climate, the environment and ecosystem functions and many other aspects relevant to the livelihoods of people. This requires knowledge about the potential impacts and the links between them. Possible impacts of different energy systems are numerous and diverse including climate impacts due to CO_2 emissions, impacts on human health and the environment due to emissions of pollutants, impacts on changing land use e.g. for production of biofuels, local environmental impacts of hydropower dams, and impacts on availability of water and scarce resources [238,239].

Several studies have assessed external impacts of present and future energy systems through linking electricity or energy systems models with other types of models. Berrill et al. [240], Rauner and Budzinski [241], and Garcia-Gusano et al. [242] all couple some form of life cycle analysis modelling tool to their energy system models. E.g. Berrill et al. [240] coupled the energy model REMix with the integrated life cycle analysis modelling framework THEMIS to study different electricity scenarios for Europe towards 2050 and their impacts on climate change, freshwater ecotoxicity, particulate matter formation, mineral resource depletion and land occupation. They find that impacts of wind and solar energy do not significantly compromise the climate benefits of utilising these energy resources, but that VRES-based systems require more infrastructure leading to much larger mineral resource depletion impacts than fossil fuel systems, and greater land occupation impacts than systems based on natural gas.

Buonocore et al. [243] developed a linked electric dispatch and public health impact assessment model (EPSTEIN), in order to assess the public health benefits of displacing emissions from fossil-fuelled power plants through energy efficiency and renewable energy. Furthermore, Abel et al. [244] investigated future health impacts of power sector-related air pollution in the eastern United States, resulting from increased air conditioning usage in a warming climate. By using a comprehensive modelling system consisting of five linked models to assess the meteorology (WRF), building electricity demand (RBESS), power sector (MyPower), air quality (CMAQ), and health impacts (BenMAP), they estimated that increased air conditioning potentially can cause up to a thousand $PM_{2.5}$- and O_3-related deaths. Also looking at the United States, Wiser et al. [245] used ReEDS to estimate the benefits of increased penetration of solar energy in the United States on greenhouse gas emissions, air pollutants and water usage.

While it may not be desirable or even possible to attempt to quantify all impacts of an energy system in modelling exercises, in view of Agenda 2030 [237] it seems reasonable to expect that energy system modellers in the future need to be aware of and in some cases include external impacts in their modelling tools.

4.4. Validation and transparency

One of the strengths of power system analysis tools is that, unlike long-term energy models, their results are in fact directly testable and verifiable. E.g. IPSA 2 has been developed for over 30 years and has gone through extensive testing and validation against real life results to ensure accurate modelling results [246]. Lammert et al. [53] implemented a generic PV system model in DIgSILENT PowerFactory, achieving perfectly matching results in comparison with a Renewable Energy Model Validation tool that had been validated against real measurements. On a larger scale, the model HYPERSIM was tested and validated on the large AC/DC transmission network of Hydro-Québec [101], SIMPOW performed validation through the Gotland HVDC project [180] and PowerGAMA validated its power flow results of most of the European transmission network by comparison to actual data from ENTSO-E [151].

On the other hand, neither long-term energy tools nor general computable equilibrium models can be properly validated [13,247]. Their long time horizons make it practically impossible to compare their outcomes with real-world observations, and changes happening through time and external events not taken into account in the model can alter the structure of the system [248]. For example, it can not be excluded that political events or unforeseen major technological breakthroughs greatly change how the future energy system will look like. Nonetheless, such models give valuable insight on a multitude of aspects; such as the composition of the future energy systems and possible pathways of how to get there, the effect of various policies, changes in market dynamics etc.

Modelling tools may be highly sensitive and dependent on their assumptions and data used. In many current models, source-code, assumptions and data are not accessible, making it impossible for independent actors to reproduce the work. Transparency and openness in energy modelling should be encouraged, especially since many modelling tools play important roles in policy-making processes. NEMS and PRIMES have for example been used for policy making respectively in the U.S. and for the European Commission [134,249]. As underlined by Pfenninger et al. [250], increased openness leads to improved quality of research, more effective links between science and policy, increased productivity and also increased relevance to important societal debates.

4.5. Future modelling needs

Forecasting of VRES, in particular of wind, is a challenging task. The motion in the atmosphere is chaotic and hard to predict accurately. Only a small change in the initial conditions in a weather model can change its predicted outcome completely. The electricity market is highly dependent on accurate forecasts of wind and solar energy production, both in day-ahead markets, for balancing and reserves planning as well as for longer-term forecasts (i.e. months and seasons). Pineda et al. [251] showed for example that not taking into account forecast errors in expansion planning models can lead to highly suboptimal planning in terms of cost efficiency or penetration of renewables.

The present review has shown that only a few current modelling tools take into account the uncertainty of VRES generation. Most tools are deterministic and VRES generation is based on historical meteorological data. Some examples of models taking into account uncertainty are; EMPS, which considers uncertainty in hydro inflow and market conditions [156]; E2M2, which considers uncertainty in VRES power production by using a multi-stage stochastic program including a recombining tree formulation [252]; and in [230] stochasticity and uncertainty were included for PV production, wind production, hydro production, heat demand in buildings and electricity prices.

Climate change can be responsible for altering energy demand or the resource potential of renewable energies in the long-term [253,254]. Barstad et al. [255] looked at the present and future offshore wind power potential in northern Europe based on downscaled (high resolution) global climate runs. They found that a power reduction of 2–6% is expected in most areas. Similarly, Jerez et al. [256] investigated future solar power outputs in Europe using the EURO-CORDEX ensemble of high resolution climate projections together with a PV production model. They showed that future European PV production would lie in the range of − 14 to + 2% compared to today. However, the largest decrease is seen in Northern Europe where much PV development is not expected, and in Southern Europe the results even show a slight positive trend. Similarly, increased temperatures from global warming can lead to changes in the electricity demand [257,258]. This raises the question whether effects of climate change on regional resource potential should be taken into account in long-term energy modelling tools.

With increased development of offshore wind farms in particular, interaction between the farms themselves is an increasing concern. Similarly to the wake effect within a farm, the farm itself can lie in the “shadow” of another farm and thus generate less electricity. Studies performed at the FINO-1 research platform showed that the effect from the closely placed Alpha Ventus wind farm was responsible for a turbulence intensity increase and a wind speed reduction of up to 50% [259]. With increased offshore development this effect should be accounted for when modelling.

4.6. Conclusion

This paper reviews 75 state of the art energy and electricity modelling tools, ranging from small-scale power system analysis tools to global long-term energy models. The reviewed models offer a broad range of capabilities, aiding modellers in identifying suitable models for their own purposes. The models are categorized by their general logic, spatiotemporal resolution and technological and economic parameters, with validated information as of the date of submission for 95% of the models.

Although this paper shows the massive capabilities of the current landscape of modelling tools, there are still some challenges related to representation of spatiotemporal variability and openness as well as the demand side that should be addressed in future model development and application.

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Supplementary material

An Excel file containing all the information about the reviewed models can be found in the online version of this paper.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2018.08.002.

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