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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]

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