SENTINEL

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Topic: LC-SC3-CC-2-2018 of the Horizon 2020 work program: *Modelling in support to the transition to a Low-Carbon Energy System in Europe*

BUILDING A LOW-CARBON, CLIMATE RESILIENT FUTURE: SECURE, CLEAN AND EFFICIENT ENERGY

Project number: *837089*

Project name: ***Sustainable Energy Transitions Laboratory***

Project acronym: SENTINEL

Start date: 01/06/2019 **Duration: 36 months**

Deliverable reference number and title:
D4.1: Observed trends and modelling paradigms

Version: 1

Due date of deliverable: 02.2020 **Actual submission date: 29.02.2020**

Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	
EU-RES	Classified Information: RESTREINT UE (Commission Decision 2005/444/EC)	
EU-CON	Classified Information: CONFIDENTIEL UE (Commission Decision 2005/444/EC)	
EU-SEC	Classified Information: SECRET UE (Commission Decision 2005/444/EC)	

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Note about contributors:

The deliverable's criteria are met by the SENTINEL ETH Zurich Team.

WP leader responsible for the deliverable:

Jakob Zinck Thellufsen (AAU)

Contributors:

Miguel Chang (AAU)
Jakob Zinck Thellufsen (AAU)
Behnam Zakeri (AAU)
Brynmor Pickering (ETHZ)
Stefan Pfenninger (ETHZ)
Henrik Lund (AAU)

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Contents

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

1. Introduction

SENTINEL's overall objective is to develop a new modelling framework that will be an important tool for accelerating the transition to a sustainable energy system in Europe, as part of a global effort to halt climate change while furthering human wellbeing, security, and sustainable development. Consequently, one of the main outcomes of the SENTINEL project is to identify trends and paradigms related to energy system modelling that will come into play when developing such framework.

On that account, this deliverable report presents a focused literature review and survey to developers of energy system models, which provides an overview of different archetypes and approaches currently used in the field, as well as a review of how energy demands are represented in such models. Throughout the review process, a series of customary terms were identified which will also be outlined in this report, in the form of a glossary of key terms, in order to facilitate a common understanding of the terminology used in the practice of energy system analysis and modelling.

1.1. Energy system models reviews: What is out there?

The range of energy models and modelling tools available is vast and continuously changing. Several studies have investigated the developments of the above with a focus on different aspects of these models and the different challenges faced in the field of energy system analysis. For instance, Connolly et al. [1] presents an overview of computational modelling tools capable of analysing the integration of renewable sources in energy systems at large, looking into survey responses from 37 model developers. In Foley et al. [2], a review of system models with a focus only on electricity is presented. Similarly, Després et al. [3] conducts a review of modelling tools focusing on the integration of variable renewables mainly in the power sector. More recently in a study by Ringkjøb et al. [4], a thorough review of 75 energy and electricity system modelling tools is presented, assessing their different modelling scopes, characteristics and limitations.

In addition to these broader overviews of the market of energy system modelling tools available, a relevant body of work exists about the underlying implications that these have on a broader energy planning level. In this regard, a key aspect to consider is the classification of the energy system model, and the choice of specific types of modelling frameworks according to the purpose of a given study. Different classifications of energy system models have been discussed by a number of studies, reflecting on the implications of these classifications regarding decision support for local planning [5], as well as their applicability worldwide [6], their general effectiveness for energy planning purposes [7], and the classification provided with direct feedback from model developers [8]. Another key consideration examined in the literature is the applicability of some of these models in specific context-areas. This has been the case, for instance, in reviewing and narrowing down the applicability of various energy

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

system models and their pitfalls for analysing the energy transition in a European context [9], in a regional Nordic perspective [10], on the country-specific level [11,12], in developing world countries [13], in energy systems of urban scale [14–16], and in standalone and grid-connected hybrid energy systems [17].

In recent years, a number of studies have shifted the spotlight from practical overviews of modelling tools towards posing questions about emerging challenges for energy system modelers and planners under the context of climate change and the transition towards sustainable energy systems. Pfenninger et al. [18] outlines different modelling paradigms and emerging methodological challenges faced in energy system modelling and how current modelling methods could be rethought and could benefit from cross-discipline and cross-sectoral synergies. Similarly, Lund et al. [19] puts into perspective the theorical positioning with regards to selecting a modelling approach and how these should be considered when debating different future energy system scenarios capable of integrating energy-intensive sectors. Correspondingly, the complementarity of these modelling paradigms and approaches, and the potential to integrate models with different features for answering emerging research questions has also been a matter of recent study [20], as the focus towards more cross-sectoral integration becomes more apparent [21]. In addition to these, the openness of data models has also been under the spotlight, being a key aspect for a number of studies [22–25], and a main driver behind the *Open Energy Modelling Initiative* [26,27] *,* which gathers together a growing number of open source energy system models and frameworks.

In all, several trends in the energy modelling community are emerging and a plethora of modelling tools exist. As new issues and technologies emerge, an ever-growing number of modelling tools will continuously evolve to be capable of targeting these new challenges, as illustrated with recent developments stemming from combined efforts in the modelling community like the Energy Modelling Platform for Europe and other related European projects [28–33]. In this report, an attempt is made to identify some of these evolving trends and report on the status of different energy system modelling tools in relation to these.

1.2. Report outline

The work hereby presented can be roughly divided in three parts. The first part presents an overview of different modelling tools based on observations from the literature and a survey of different modelling tools. The classification of these models is presented in Section 2, along with a description of the key trends identified. The second part of this report presents a focused review of a main aspect to consider in energy system modelling, namely the representation of energy demands and demand data in energy system studies presented in Section 3. The third part of this report identifies key terms and concepts, laying out a glossary of terms in Section 4. Finally, in Section 5 the conclusions from these findings are presented.

SENTINEL

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

2. Overview of energy system models and tools

In order to identify the current trends and paradigms in the practice of energy system modelling, a focused review of the literature was conducted looking into previous studies that provide an overview of existing energy system modelling tools. From the list of tools identified in this review, a survey was conducted gathering inputs about these tools from developers and primary users of these. In this process, 137 different modelling tools where identified from the previous literature and survey studies referenced in Section 1.1; and out of those, the tools presented here were selected based on their completion status in the survey. At the time of completion of this report, 43 full descriptions of modelling tools have been gathered from the survey including models within the SENTINEL project (e.g. Calliope, EnergyPLAN, etc.) , plus an additional 5 partial incomplete descriptions. Moreover, additional tool and model descriptions were found in the literature, however some of these are not considered in the following result analysis in order to preserve the consistency of the reported modelling tools' descriptions. It must be noted that these survey results, while not necessarily providing a comprehensive sample of all tools in the market, are indicative of general trends found in the tools and in the energy system modelling field. An overview of all the energy system modelling tools considered is presented in Appendix 1.

2.1. Approaches and formulation

As identified throughout the literature, several model classifications exist which define the tools and models according to their methodological approach and the purpose of their mathematical formulation [5,7,8]. In general, the models examined fell under three broad categories: Simulation, Optimization and Equilibrium models. In the case of the latter further subcategorizations were defined by the developers of the modelling tools, namely computable general equilibrium, partial equilibrium, and market equilibrium. In addition to the above, some simulation tools made further distinctions to describe the novelty of their approach; for instance, by explaining their operation and iterative simulation approach.

In terms of the mathematical formulation, several purposes were identified across the sampled energy modelling tools. More recurring across optimization modelling tools, was the characterizations of one or more purpose-fit objective functions, including different minimization or maximization of indicators such as total system costs, investment costs, dispatch costs, fuel consumption, system emissions, renewable energy penetration, social welfare, among others. In the case of simulation tools, the main purposes identified behind their mathematical formulation included scenario development, multi-criteria analysis and agent-based analysis.

An overview of the corresponding methods for each model and the general purpose behind their mathematical formulation can be seen in Table 4, in **Appendix 2**.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Irrespective of modelling approach and formulation, the definition of multiple objectives or purposes for a given single tool was readily apparent from the gathered data, as is the fact that a significant portion of the models are able to serve multiple purposes with their underlying formulation. Overall, it is clear that a balance between multiple assessment criteria is used across most modelling tools. Taking the specific case of EnergyPLAN, it has been found across a number of energy system studies that the choice of assessment parameter will be dependent on the specific case and the underlying context, resulting in a wide range of choices of assessment criteria [34].

2.2. Modelling resolutions and scope

The integration of high levels of variable renewable energy poses a challenge for energy planning, as the intermittency of these sources calls for models capable of representing the corresponding variability. In a similar manner, the level of detail used for modelling the energy system can also result in more accurate system representations capable of capturing synergies and resource availability that are spatially dispersed by nature.

The choice of temporal resolution used in energy system studies can have a significant impact in capturing the real dynamics of a modelled system and adequately balancing supply and demand. This is illustrated, for example, by Poncelet et al. [35] when assessing the impact of temporal resolution in systems with high uptake of variable renewables, concluding that low temporal resolution can potentially underestimate operational costs and overestimate generation capacity. Similarly, Deane et al. [36] determined that higher temporal resolutions are better able to capture system loads, the inflexibility of big thermal power units, and renewable energy generation; thereby estimating more accurately the corresponding system costs. Nonetheless, increasing time resolution can be computationally expensive, thus the consideration of modelling time-step should be selected with caution, especially when considering coarser resolutions than 1-hour to represent renewable generation fluctuations [37]. In the modelling tools sampled for this study, the 1-hour resolution was most frequently observed, as seen in Figure 1, with some of these models being capable of adjusting their temporal resolution to even higher levels like minutes or seconds, or had lower resolutions (e.g. seasonal time-slices, yearly, and multi-year). In addition to these, time-slices using representative hours, days and weeks were also identified across these tools.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

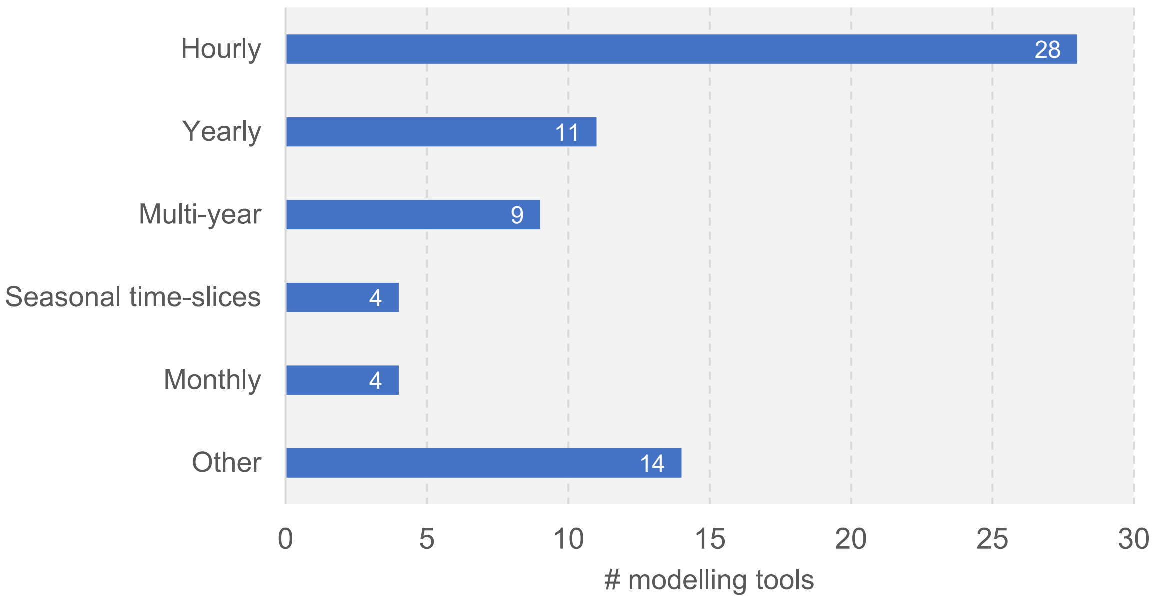

Figure 1.Modelling time resolution

In addition to the aforementioned aspect, the resolution of the technical setup of the tools was also observed. Across the sampled modelling tools, an even distribution was observed between tools working with aggregate technical specifications and those capable of representing individual plants or energy system components. This reflects – in part – the nature of the tools sampled, since some of them are capable of modelling large spatial aggregations on the global and regional scale, where aggregate operational detail provides adequate enough representations of the energy system [38,39], having overall less significant impact than the temporal resolution [35]. On the other hand, some of the tools working with finer operational detail do so due to their underlying purpose and scope; for instance, due to their flexibility to represent project-specific components or setup to represent specific dispatchable units or plants.
Further details about the modelling resolution and technical scope of the tools is provided in Table 6, in Appendix 2.

2.3. Policy support

A key aspect of energy system modelling is the ability to quantify the impacts of changes in the energy system and in this manner contribute to the public debate, while also supporting decisions to guide the energy transition [18,19,40]. Hence, the ability to use these models for supporting policy is paramount. In the survey, an effort has been made to quantify the number of tools that have contributed to policy making. In this specific case, two differentiated categories were considered for tools that have made some policy contributions: Direct use, referring to the use of a modelling tool by an official governmental institution for guidance in official policy; and indirect use, referring to tools used for modelling studies that have contributed to the discussion or are used as reference to contrast and/or validate official policy. An outline of this can be seen in Table 1.

Table 1. Modelling tools and policy support status.

Use for policy making and/or support	# of tools
No	6
Not known	14
Yes, directly	14
Yes, indirectly referred in a relevant official document	14

The results seen in Table 1 show that a significant portion of the tools surveyed have been used for policy support, including both direct use (e.g. PRIMES [41]) and indirect use, with some overlapping usage between these two categories (e.g. EnergyPLAN [42,43]). On the other hand, over a third of the models did not have any identifiable policy contribution. This could respond to the fact that some of these tools are rather new in-house developments used within academic research or have been used for a limited scope of projects.

2.4. Cross-sector coverage

As the global focus shifts towards higher penetration of renewable energy to decarbonize the energy system and halt climate change, more effort has been put towards coupling the main energy-intensive sectors and benefiting from their potential synergies. As identified by Lund et al. [21], cross-sector integration can be a pivotal aspect to incorporate larger shares of variable renewable energy, by facilitating additional flexibility in the energy system. This has been the subject of a number of studies (e.g. [44–46]), which have analysed the potential of integrating the electricity, heat, transport and industrial sectors, and thereby allowing 100% renewable energy shares in future energy system scenarios.

The potential for sector coupling was investigated in the survey of modelling tools by looking into their sectoral coverage. That is, by looking into which sectors can be represent in each. This is shown in Figure 2, and outlines in further detail in Table 5, in Appendix 2.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

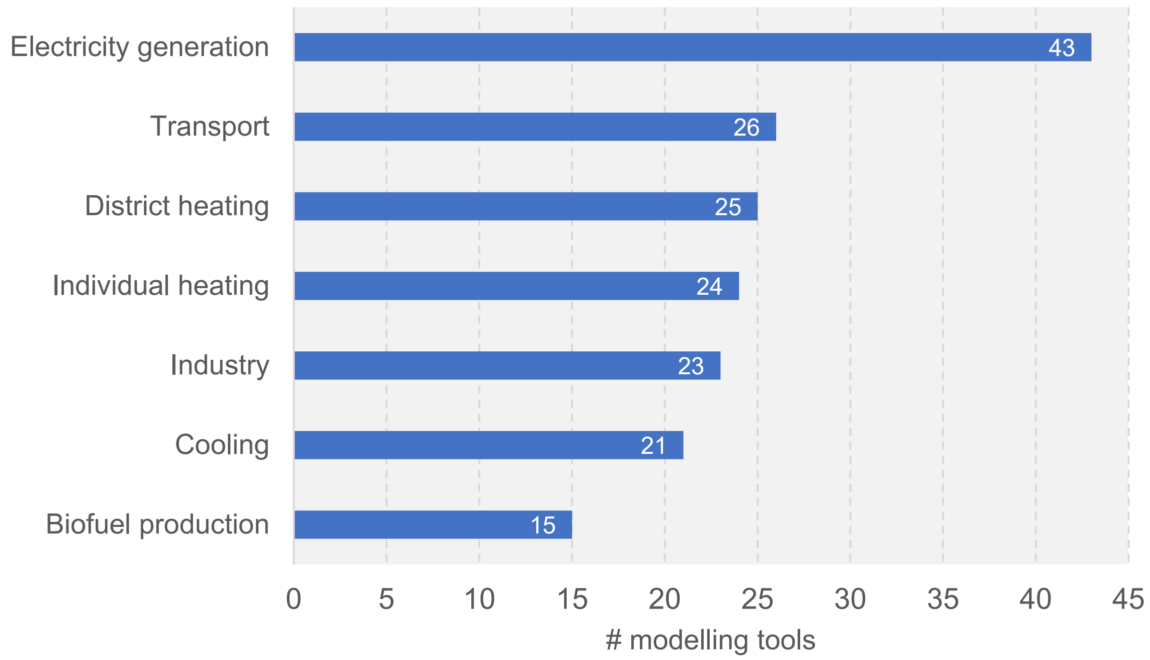

Figure 2. Sector coverage in the 43 surveyed modelling tools

As seen in Figure 2, a focus on the electricity sector is common across all the 43 tools examined. For roughly half of these tools, it is possible to model both the transport and heating sectors (including individual and district heating). Additional sector coverage is seen to a varying degree, when looking at industry or cooling, and is much less prominent considering biofuel production, being modelled by only one third of the tools examined.

2.5. Accessibility and transparency

When looking at energy system tools, there is a current trend and focus on openness [22–25]. As mentioned in the introduction this is also one of the drivers behind the *Open Energy Modelling Initiative* [26,27] *,* which gathers together a growing number of open source energy system models and frameworks. While this openness generates a natural exchange of knowledge between researchers and modelers, and allows for a transparent modelling framework for modelers and users, it is important to focus on user accessibility and third-party replicability [47].
Therefore, we compare the tool openness with the tool's user interface. In Figure 3, the same tool might appear more than once, but in total 25 of the 43 models and tools surveyed are free for other users. Of those, 14 are open source. The other category is to a large extend dominated by in-house tools that are not sold or provided to outside users. From the figure it is possible to see that the open source and other category, is to a large extend dominated

by tools with direct coding options. For many of the tools this is the only option to use the tool, although human-readable text interfaces are also available to handle some tools' code. Within the non-open source tools, whether they are free or commercial, the share of tools with a graphical user interface is bigger. This create an interesting discussion point in terms of the level of accessibility in the tools with full transparency in terms of source code.
Many energy tools are dependent on mathematical solvers to operate and identify solutions. For the accessibility of the free tools it is interesting to see how many can also operate on open-source/free solvers. Of the 30 tools that indicated they use a solver, 17 are dependent on commercial software. This potentially also limits accessibility of open and/or free tools.

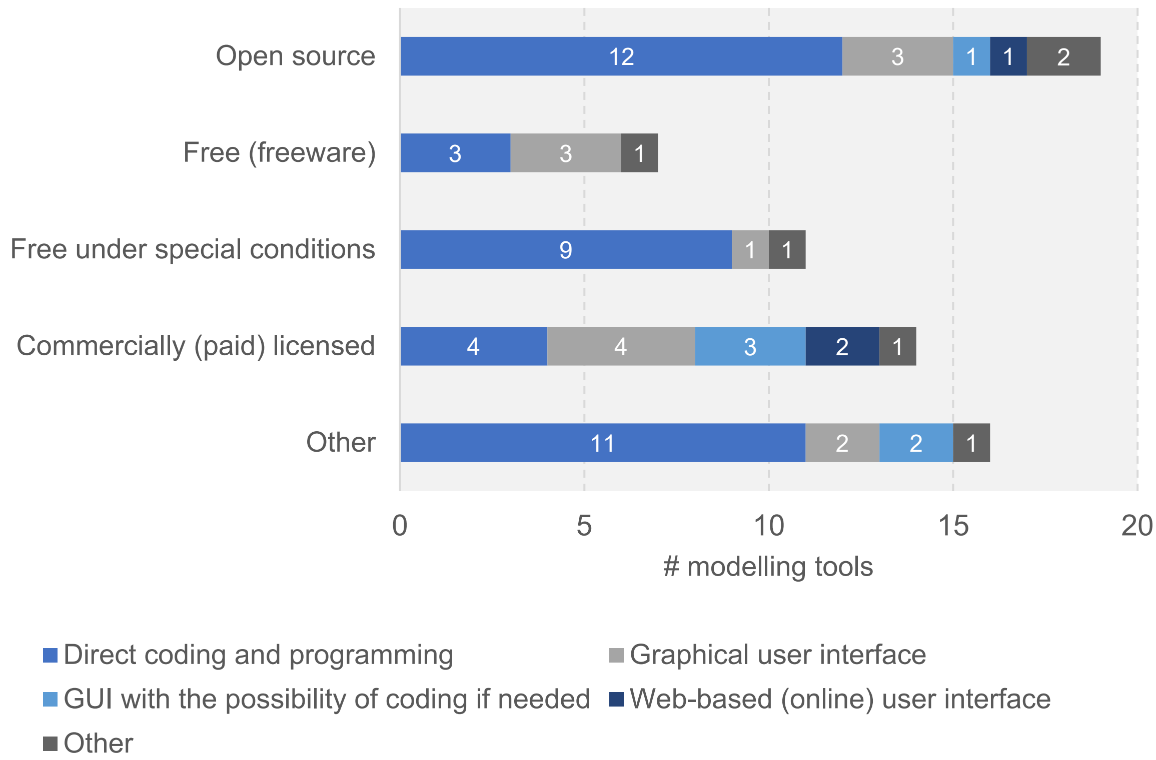

Figure 3. Comparison of tool types with user interface

2.6. Cross-platform integration

With the expanding number of energy tools available, and with models and tools having different focus points it is interesting to see to what extent different tools are linked with each other. By linking tools, more issues can potentially be scrutinized by investigating multiple aspects.
By looking at the survey of energy tools it is possible to see that the most common linking approach is so called "soft-linking" of tools. This means that 26 of the 43 tools have been run

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

with other tools, by applying an external workflow or tool. Soft-linking is in the scope of this review defined as a clear definition of an approach towards how inputs and outputs from different tools can be utilized in combination. Thus, soft-linking does not interlink source-code specifically between two tools, so the operate automatically together. An example of soft linking, could be the energy scenario of one tool, simulated in another energy system tool that can capture more temporal resolution.

With two or more tools that are developed to be linked through their source code, we specify that as hard-linked tools. Three of the tools in the survey have been hard linked to other tools. Four of the tools have been integrated into other tools, making new merged tools. The difference between an integrated tool and a hard-linked tool can be very vague. In principle, with hard-linking, it is still two separate tools, while fully integrated tools are linked tools evolved into a new tool. So, in total 7 tools have been integrated with specific coding between tools. 9 of the tools have not been linked to other tools, and one is unknown in terms of linking.

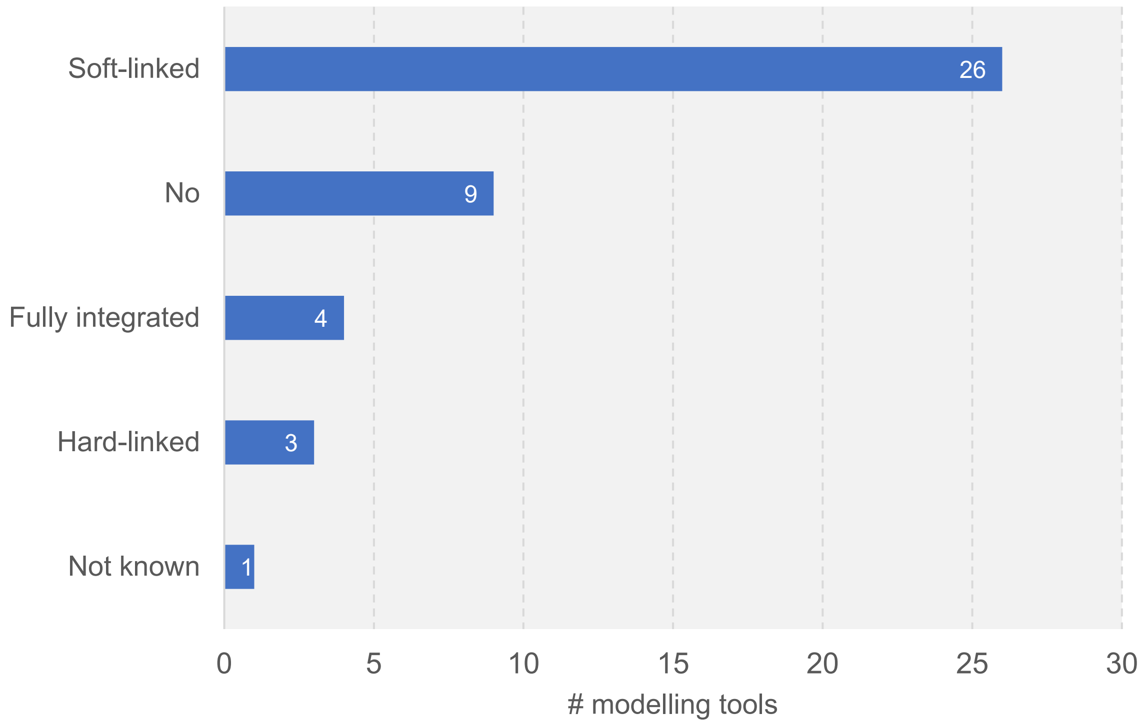

Figure 4. Number of modelling tools with cross-platform integration by type.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

3. Demand representation within energy system models

Energy system models seek to meet energy demand under the conditions of physical and policy constraints. Therefore, energy demand is a common dataset required by all energy system modellers. The majority of models include demand exogenously, either as a static demand or by including some flexible demand options (Figure 5). The source of exogenous demand data is study dependent, since each study will usually cover a different geographic area and require different temporal resolutions, from annual down to hourly. Yet, a review of state-of-the-art modelling efforts shows that many of the same sources are drawn upon, where available, and hurdles to data acquisition are dealt with in similar ways. This review focusses on a selection of recent studies undertaken using eight different energy system models. All studies have a spatial scope large enough to require aggregation of individual demand sources, usually to the national level. A summary table with these studies and their demand representations is presented in Table 7, in Appendix 2.

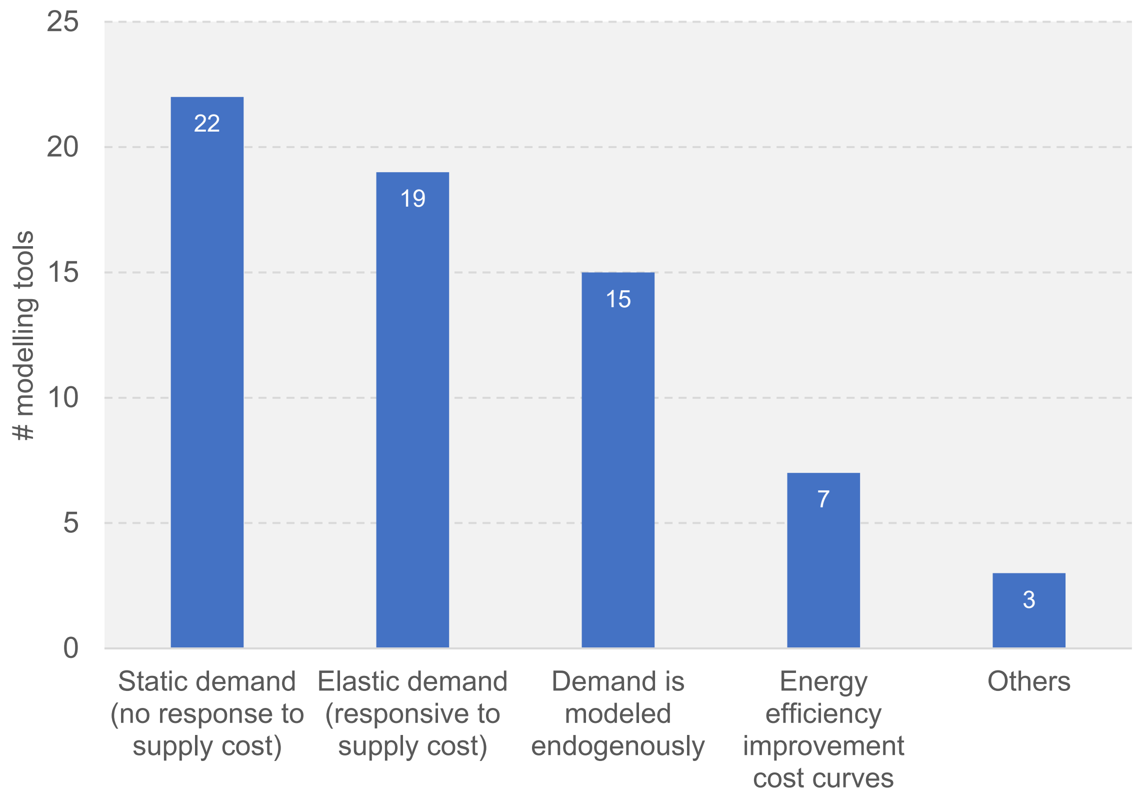

Figure 5. Overview of how energy demands are handled across modelling tools.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

3.1. Electricity demand

Electricity is the most commonly modelled energy carrier, and studies of European systems frequently use historical load profiles provided at an hourly resolution by the European Network of Transmission System Operators for Electricity (ENTSO-E) [48]. These profiles are available at a national resolution, which can be used directly when the studies themselves have a national resolution [49–53]. Although ENTSO-E data could be used for all national scope studies in Europe, some have preference for sourcing data from relevant national bodies [37,54–57], or as a synthesis of ENTSO-E and national statistics, via the Open Power System database [58]. At a subnational level in Europe, local transmission service operators can act as a source of data [54]. Outside Europe, it is government statistics which are the primary source of data, including for studies in Egypt [59], China [60], Korea [61], and Chile [62]. In some of these cases, hourly historical data does not seem to have been published. For example, the Egyptian government only communicate the peak demand from the whole year for each hour of the day [63]. In the USA, the Temoa modelling group use the government nine-region MARKAL database [64] as a source of demand, which itself is built on the Annual Energy Outlook projections [65–67].

Handling limited data availability

Where electricity demand data is not available for the location, scale, or time period specified by a model, accessible datasets are modified to suit. Dominković et al. [50] modelled South-East Europe, with electricity demand data only available for nine of the eleven modelled countries. Demand for Albania and Kosovo was based on scaling the ENTSO-E hourly data from the other nine countries to monthly statistics of electricity consumption in those two countries [50]. Möller et al. [68] scaled German 2013 electricity consumption, also from ENTSO-E, to their subnational region of interest by using the regional masterplan. Usually, however, monthly or annual demand with which to scale profiles is not available. Pfenninger [37,57] addressed this in a 20 region model of the UK by keeping the demand profile shape the same in each region, but scaling the magnitude of demand to regional population. Hörsch et al. [69] took a similar approach, by scaling using both population and regional gross domestic product, with a respective weighting ratio of 40:60, at a NUTS-3 spatial resolution across Europe.

Projecting forwards and backwards in time

Although sources exist to understand historical electricity consumption at some resolution, future demand for electricity in the future is understandably unknown. Frequently, historical demand is used directly when modelling a scenario of a future energy system. When modelling the energy system in 2035, both Diaz Redondo and van Vliet [55], and Kiviluoma et al. [70] use unaltered historical demand data. Schlott et al. [52] fix the demand data at 2012 levels when modelling each of the 88 years from 2012 to 2100 with a focus on the impact of weather data variability. The same approach has been used when projecting further back in time than available data allows, whereby a single year is used to represent all historical years of interest [37]. Yet, it is clear that electricity demand changes over time. Roadmaps for energy systems include estimations of the increase in demand and have been used to scale model input profiles accordingly. Two case studies modelled in OSeMOSYS, in Portugal [71] and Egypt [59], use projected growth rates in demand from the 2016 EIA international energy outlook [72] of 1.2% and 2.6%, respectively. These rates were applied to project decades of demand growth. Demand projections for fixed future years were used for two case studies modelled in EnergyPLAN. In both cases, hourly profiles were scaled to the projected demand in 2020 and beyond [54][73].

3.2. Other sources of demand

Although less well understood than electricity demand, thermal and transport energy demand are frequently included in large scale energy system models. Their inclusion is often in the context of their potential for electrification and role in integrated energy system. Indeed, it is expected that these demands being incorporated into the electricity system will markedly increase total electricity demand [45]. Although national annual data may be available for these demands, greater spatial and temporal disaggregation requires the combination of many data sources.

Thermal demand

Thermal demand usually refers to space heating demand. In the European context nationally aggregated annual heat demand data is available in the Odyssee database and the partially validated When2Heat dataset [74], via the Open Power System database. Higher spatial resolution data has also been simulated, including at the regional level, in the Hotmaps project, and at the hectare resolution in the Pan-European Thermal Atlas, as part of the Heat Roadmap Europe project [75]. Yet, only the Odyssee database and Heat Roadmap Europe are known to have been used in subsequent energy system modelling efforts. At a national scale, government statistics may directly provide the annual thermal demand used in modelling studies [54,60]; sub-nationally, energy suppliers may also be able to provide the necessary data [73]. Without direct statistics, a bottom-up simulation approach is often taken to understand demand. Lombardi et al. [58] model thermal demand for cooking by combining an understanding of cooking habits with likely technology choices. Heat Roadmap Europe also relies on a bottom-up approach to model cooling demand, whereby the cooling energy demand is combined with an estimation of total cooled floor area, based on sales of cooling technologies [76].

To incorporate thermal demand into energy system models, hourly profiles are usually required. Brown et al. [49] scaled the Odyssee database data to daily demand using the heating degree day method, which estimates heat demand as linearly increasing with the

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

deviation between average daily temperature and a reference temperature of approximately 15 °C [49]. Hourly demand was then inferred from weekday and weekend profiles modelled for the context of Aalborg, Denmark [77]. Other studies rely on the heating degree days method, even applying the method at an hourly level [50,53]. Child and Breyer [54] scale measured data from Finnish combined heat and power plants to national annual demand, but only for heat demand; cooling demand relies on using a 'default' EnergyPLAN hourly profile.

Transport demand

Transport demand is the mobility need of a population. Mobility can be met by many energy carriers, currently dominated by oil fuels. Annual transport demand statistics are either published in terms of fuel use [53,54,67,73] or total distance travelled [49]. Eshraghi et al. [67] use this data directly, but it is more common to use the data as the basis for understanding the future demand of battery electric vehicles. Indeed, it is the influence on the electricity system due to the expected electrification of mobility which is most commonly analysed.

Battery electric vehicle demand differs from conventional transport demand, as the load profile (i.e. vehicle charging) can influence system design. Consequently, understanding driving patterns is necessary. The current approach is to combine national annual transport demand with assumptions made from surveys of vehicle movements or vehicle counting data. Zappa [53] uses projected 2050 demand for energy from vehicles [78] to scale charging profiles. Those profiles are generated using a combination of driving patterns from a subset of countries and the charge speed and distribution of different charging station types [79]. Brown et al. [49] similarly uses vehicle counting points on highways in Germany scaled to passenger kilometers from the Odyssee database; electricity demand is then inferred by assuming an offset between ending a journey and plugging in. Kiviluoma et al. [70] uses a travel survey in Finland to inform their more sophisticated battery charging model on the arrival and departure of different parts of the vehicle fleet; charging rates of parked vehicles is based on assumed charging infrastructure.

3.3. Sector disaggregation of demand

The source of demand can prove important to energy system modellers, due to both data sourcing and the interaction of sectors with national energy systems. Key sectors that are distinguished are 'residential', 'commercial', and 'industrial' [54,59,67], although residential and commercial may also be combined into 'buildings' [50,60]. Transport is also often distinguished as a separate sector.

A combination of electricity and high temperature heat, industrial demand is of varying importance as a source of demand, depending on the country. Anjo et al. [71] assume that industry contributes to one third of Portuguese electricity demand, while other studies obtain industrial demand directly as part of national statistics [50,54,60]. This sectoral

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

disaggregation is important in studies for different reasons. Anjo et al. [71] allocate different demand side management flexibilities depending on sector, with industry having the largest possible time shift between supply and demand. Child and Breyer [54] distinguish between high (industry) and low (building) temperature heat supply in their model, requiring the two sectoral demands to be disaggregated.

3.4. Handling demand data

Many steps can go into the generation of a demand profile, including the acquisition of annual demand, construction of an hourly profile, and matching low and high resolution data. Although it is possible to clearly indicate each of these steps, the sources of datasets, and necessary assumptions made (e.g. [49,57]), it is also possible to omit some vital sources (e.g. industry and transport demand in [50]). Either way, validation of demand profiles is rarely possible. Unvalidated datasets continue to be used by later studies, even when they do not transparently communicate the source of their published hourly profile shapes [60,67,70]. Even measured data is fallible; Child et al. [73] pointed to a known anomaly in one month of their electricity demand data and Hirth et al. [80] identified a range of shortcomings in the data available on the ENTSO-E transparency platform.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

4. Glossary of key terms and concepts

In the review process, several key terms where identified pertaining to energy system analysis, energy system models, and modelling tools. Given the large body of work in the energy system modelling community and the large availability of different models and tools, it is imperative to foster a common ground of understanding and dialogue among practitioners. In many ways, gathering information for the range of tools presented and harmonizing some of the terminology linked to said tools serves as a starting point for this effort. To lay out this common ground of understanding, some recurring descriptive terms and their rough definitions were identified. These are presented Table 2. It must be noted that the definitions presented here aim at to be simplistic and are by no means all-inclusive of all concepts in the field. Moreover, additional insight into key terminology used within each modelling tool is needed and could prove to enforce the dialogue and common understanding across different modelling platforms with different definitions for the same indicators.

Table 2. Glossary of terms and concepts used for the description of modelling tool.

Term	Description
Agent-based models:	Simulation models used to represent actions and decision-making of agents and assess their effects on a system.
Backcasting:	Planning method that defines a future scenario, and link this to the present by means of identifying actions (e.g. policy) and changes in the system by going back in time.
Computable general equilibrium models: (CGE)	Economic models capable of representing multiple markets/sectors and their interactions, by balancing the supply and demand in each of these using prices.
Cross-sector integration:	The linking and modelling of multiple sectors of the energy system. E.g. electricity and heating.
Energy system model:	A model of a country/region etc. created within or by an energy system tool.
Energy system tool:	A computational application and/or framework with defined mathematical formulations which allow users to develop their own models, based on user-based inputs and assumptions.
Forecasting:	Planning method that predicts a future scenario by using present and past data.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Freeware:	The software can be downloaded free of charge, with no adds or any other commercial constraints.
Graphical user interface: (GUI)	The user is presented with a user interface that combines icons, fields and indicators instead of text based user interfaces, that has to be coded.
Hard-linking:	When linking two or more models by programming connections directly in the source code.
Integrated assessment model: (IAM)	These models combine multiple economic sectors, typically represented by modules which can represent energy systems, land-use change, societal choices, etc. in order to assess the impact of climate change.
Multi-criteria analysis:	Analysis based on assessing multiple decision-making criteria and their trade-offs. Weighting of indicators can be used to prioritize more relevant criteria.
Objective-function:	The mathematical function that the energy system tool solves.
Open source:	A type of software where the source code is free and openly available to the public. This allows for users to study, change and distribute the software.
Optimization:	A modelling approach in which the system characteristics are formulated to be resolved as mathematical problems, which are solved by optimizing one or multiple objective functions (eg. cost minimization, welfare maximization, etc.).
Partial equilibrium:	Economic models capable of representing only a part of markets, to balance the supply and demand in said market based on its prices.
Power flow (Load flow) model:	A mathematical model capable of analysing the electric power flow in an interconnected system, and optimizing electricity transmission between multiple nodes.
Simulation:	A modelling approach in which a system is represented by means of a given set of conditions that recreate its potential operation.
Solver:	A mathematical software, potentially a stand-alone program, that solves the mathematical problems posed by the energy system tool.
Soft-linking:	When linking two or more models, by setting up methodologies for utilising inputs and outputs across the models.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

5. Concluding remarks

As highlighted in the introduction, many review papers exist which all investigate the current set of energy system tools available for modelling the energy transition. Where the results presented in this deliverable stand out is that we engage in communication with the modellers and developers, to see how they understand their tool under a given vocabulary. A few items become evident in both the process of conducting the survey and in the results.
First, it is hard to establish a specific vocabulary that all tool developers understand in the same way. For instance, what some modellers would call optimization others would call simulation. This highlights the need for communication between modellers when they work towards the linking of different tools.
Second, when investigating many tools that can do different things in modelling the energy transition, it becomes clear that it is impossible to build a tool that can do it all. All the tools have been developed to fulfil a specific task within a certain scope. It might have received updates and an increased number of capabilities, but the underlying methodology, technology, and terminology remains the same. We would argue that efforts should be targeted towards linking these different tools to each other, utilising the many capabilities that are already present. Individual tool development is obviously still required and necessary, but there is a limit to how much can be computed efficiently.
Third, common input datasets exist among energy system models, irrespective of their research focus. Energy demand is one such dataset for which efforts to collate and simulate data could be harmonised across linked models. We find that data sharing platforms, such as the ENTSO-E transparency platform and the Open Power System Data platform, already act as nuclei for model data. However, there is still a lack of accessible data for modellers to understand projected changes in demand, and to model high spatial and temporal resolution systems. In particular, there is a dearth of high resolution heating, transport, and industry demand data, which leads to varying approximations with limited scope for validation.
We conclude that linking different tools is valuable, but to do so requires establishing a common vocabulary and "surfaces" that indicate where, what and how you can link to a specific tool. Such a framework of mutual understanding will facilitate the relevance of data sharing platforms and will make it possible to tackle energy planning problems from multiple, novel perspectives while contributing to the public debate.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

References

[1] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87:1059–82. doi:10.1016/j.apenergy.2009.09.026.

[2] Foley AM, Ó Gallachóir BP, Hur J, Baldick R, McKeogh EJ. A strategic review of electricity systems models. Energy 2010;35:4522–30. doi:10.1016/j.energy.2010.03.057.

[3] Després J, Hadjsaid N, Criqui P, Noirot I. Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools. Energy 2015;80:486–95. doi:10.1016/j.energy.2014.12.005.

[4] Ringkjøb 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. doi:10.1016/j.rser.2018.08.002.

[5] Van Beeck NMJ. Classification of energy models. FEW Res Memo 1999.

[6] Jebaraj S, Iniyan S. A review of energy models. Renew Sustain Energy Rev 2006;10:281–311.

[7] Mougouei FR, Mortazavi MS. Effective approaches to energy planning and classification of energy systems models. Int J Energy Econ Policy 2017;7:127–31.

[8] Müller B, Gardumi F, Hülk L. Comprehensive representation of models for energy system analyses: Insights from the Energy Modelling Platform for Europe (EMP-E) 2017. Energy Strateg Rev 2018;21:82–7. doi:10.1016/j.esr.2018.03.006.

[9] Pilavachi PA, Dalamaga T, Rossetti di Valdalbero D, Guilmot JF. Ex-post evaluation of European energy models. Energy Policy 2008;36:1726–35.

[10] NEP. Coordinated use of Energy system models in Energy and Climate policy analysis. 2010.

[11] Hall LMH, Buckley AR. A review of energy systems models in the UK: Prevalent usage and categorisation. Appl Energy 2016;169:607–28. doi:10.1016/j.apenergy.2016.02.044.

[12] Lopion P, Markewitz P, Robinius M, Stolten D. A review of current challenges and trends in energy systems modeling. Renew Sustain Energy Rev 2018;96:156–66. doi:10.1016/j.rser.2018.07.045.

[13] Bhattacharyya SC, Timilsina GR. A review of energy system models. Int J Energy Sect Manag 2010;4:494–518. doi:10.1108/17506221011092742.

[14] 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. doi:10.1016/j.rser.2012.02.047.

[15] 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. doi:10.1016/j.rser.2015.07.123.

[16] Van Beuzekom I, Gibescu M, Slootweg JG. A review of multi-energy system planning and optimization tools for sustainable urban development. 2015 IEEE Eindhoven PowerTech, PowerTech 2015 2015:1–7. doi:10.1109/PTC.2015.7232360.

[17] Sinha S, Chandel SS. Review of recent trends in optimization techniques for solar photovoltaic-wind based hybrid energy systems. Renew Sustain Energy Rev 2015;50:755–69. doi:10.1016/j.rser.2015.05.040.

[18] Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first century energy challenges. Renew Sustain Energy Rev 2014;33:74–86. doi:10.1016/j.rser.2014.02.003.

[19] Lund H, Arler F, Østergaard PA, Hvelplund F, Connolly D, Mathiesen BV, et al. Simulation versus optimisation: Theoretical positions in energy system modelling. Energies 2017;10:1–17. doi:10.3390/en10070840.

[20] Crespo del Granado P, van Nieuwkoop RH, Kardakos EG, Schaffner C. Modelling the energy transition: A nexus of energy system and economic models. Energy Strateg Rev 2018;20:229–35. doi:10.1016/j.esr.2018.03.004.

[21] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. doi:10.1016/j.energy.2017.05.123.

[22] Bazilian M, Rice A, Rotich J, Howells M, DeCarolis J, Macmillan S, et al. Open source software and crowdsourcing for energy analysis. Energy Policy 2012;49:149–53. doi:10.1016/j.enpol.2012.06.032.

[23] Pfenninger S, DeCarolis J, Hirth L, Quoilin S, Staffell I. The importance of open data and software: Is energy research lagging behind? Energy Policy 2017;101:211–5. doi:10.1016/j.enpol.2016.11.046.

[24] Morrison R. Energy system modeling: Public transparency, scientific reproducibility, and open development. Energy Strateg Rev 2018;20:49–63. doi:10.1016/j.esr.2017.12.010.

[25] Oberle S, Elsland R. Are open access models able to assess today's energy scenarios? Energy Strateg Rev 2019;26:100396. doi:10.1016/j.esr.2019.100396.

[26] openmod. Open Energy Modelling Initiative 2020. https://openmod-initiative.org/

(accessed February 23, 2020).

[27] Pfenninger S, Hirth L, Schlecht I, Schmid E, Wiese F, Brown T, et al. Opening the black box of energy modelling: Strategies and lessons learned. Energy Strateg Rev 2017;19:63–71. doi:10.1016/j.esr.2017.12.002.

[28] REEEM Energy Systems Modelling Project. Role of Technologies in an Energy Efficient Economy – Model Based Analysis Policy Measures and Transformation Pathways to a Sustainable Energy System 2018.

[29] MEDEAS. Modelling the Energy Development under Environmental and Socioeconomic Contraints. 2018 n.d. http://www.medeas.eu/ (accessed February 24, 2020).

[30] SET-nav. Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation 2018. http://www.set-nav.eu/ (accessed February 24, 2020).

[31] REFLEX. Analysis of the European Energy System under the Aspects of Flexibility and Technological Progress 2018. http://reflex-project.eu/.

[32] openENTRANCE. Open Energy Transition Analyses for a low-Carbon Economy 2019. https://openentrance.eu/ (accessed February 24, 2020).

[33] SENTINEL. Sustainable Energy Transitions Laboratory 2019. https://sentinel.energy/ (accessed February 24, 2020).

[34] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy 2015;154:921–33. doi:10.1016/j.apenergy.2015.05.086.

[35] Poncelet K, Delarue E, Six D, Duerinck J, D'haeseleer W. Impact of the level of temporal and operational detail in energy-system planning models. Appl Energy 2016;162:631–43. doi:10.1016/j.apenergy.2015.10.100.

[36] Deane JP, Drayton G, Ó Gallachóir BP. The impact of sub-hourly modelling in power systems with significant levels of renewable generation. Appl Energy 2014;113:152–8. doi:10.1016/j.apenergy.2013.07.027.

[37] Pfenninger S. Dealing with multiple decades of hourly wind and PV time series in energy models: A comparison of methods to reduce time resolution and the planning implications of inter-annual variability. Appl Energy 2017;197:1–13. doi:10.1016/j.apenergy.2017.03.051.

[38] Thellufsen JZ, Paardekooper S, Chang M, Lund H. Benefits to single country modelling: Comparing 14 interconnected individual country models to a single 14-country model. 5th Int. Conf. Smart Energy Syst. 4th Gener. Dist. Heating, Electrif. Electrofuels Energy Effic. - Langelin. Pavillonen, Copenhagen, Denmark, Copenhagen, Denmark: 2019, p.

244.

[39] Thellufsen JZ, Chang M. Modelling an individual country within the context of the surrounding energy systems – the importance of detail. Proc. 2nd LA SDEWES Conf., 2020.

[40] Koppelaar RHEM, Keirstead J, Shah N, Woods J. A review of policy analysis purpose and capabilities of electricity system models. Renew Sustain Energy Rev 2016;59:1531–44. doi:10.1016/j.rser.2016.01.090.

[41] European Commission. In-depth analysis in support of the Commission Communication COM(2018) 773 A Clean Planet for all. Brussels: 2018.

[42] Mathiesen B V., Lund H, Hansen K, Ridjan I, Djørup SR, Nielsen S, et al. IDA's Energy Vision 2050: A Smart Energy System strategy for 100% renewable Denmark. Dep Dev Planning, Aalborg Un 2015:156 pp. doi:ISBN: 978-87-91404-78-8.

[43] Lund H, Thellufsen JZ, Østergaard PA, Nielsen S, Sperling K, Djørup SR, et al. Smart Energy Aalborg. 2019.

[44] Connolly D, Lund H, Mathiesen B V. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. doi:10.1016/j.rser.2016.02.025.

[45] Connolly D. Heat Roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries. Energy 2017;139:580–93. doi:10.1016/j.energy.2017.07.037.

[46] Mathiesen B V., Lund H, Connolly D, Wenzel H, Ostergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. doi:10.1016/j.apenergy.2015.01.075.

[47] DeCarolis JF, Hunter K, Sreepathi S. The case for repeatable analysis with energy economy optimization models. Energy Econ 2012;34:1845–53. doi:10.1016/j.eneco.2012.07.004.

[48] ENTSO-E. ENTSO-E Transparency Platform n.d. https://transparency.entsoe.eu/ (accessed October 3, 2018).

[49] Brown T, Schlachtberger D, Kies A, Schramm S, Greiner M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. Energy 2018;160:720–39. doi:10.1016/j.energy.2018.06.222.

[50] Dominković DF, Bačeković I, Ćosić B, Krajačić G, Pukšec T, Duić N, et al. Zero carbon energy system of South East Europe in 2050. Appl Energy 2016;184:1517–28. doi:10.1016/j.apenergy.2016.03.046.

[51] Schill W-P, Zerrahn A. Long-run power storage requirements for high shares of renewables: Results and sensitivities. Renew Sustain Energy Rev 2018;83:156–71. doi:10.1016/j.rser.2017.05.205.

[52] Schlott M, Kies A, Brown T, Schramm S, Greiner M. The impact of climate change on a cost-optimal highly renewable European electricity network. Appl Energy 2018;230:1645–59. doi:10.1016/j.apenergy.2018.09.084.

[53] Zappa W, Junginger M, van den Broek M. Is a 100% renewable European power system feasible by 2050? Appl Energy 2019;233–234:1027–50. doi:10.1016/j.apenergy.2018.08.109.

[54] Child M, Breyer C. Vision and initial feasibility analysis of a recarbonised Finnish energy system for 2050. Renew Sustain Energy Rev 2016;66:517–36. doi:10.1016/j.rser.2016.07.001.

[55] Díaz Redondo P, van Vliet O. Modelling the Energy Future of Switzerland after the Phase Out of Nuclear Power Plants. Energy Procedia 2015;76:49–58. doi:10.1016/j.egypro.2015.07.843.

[56] Hilbers AP, Brayshaw DJ, Gandy A. Importance subsampling: improving power system planning under climate-based uncertainty. Appl Energy 2019;251:113114. doi:10.1016/j.apenergy.2019.04.110.

[57] Pfenninger S, Keirstead J. Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. Appl Energy 2015;152:83–93. doi:10.1016/j.apenergy.2015.04.102.

[58] Lombardi F, Rocco MV, Colombo E. A multi-layer energy modelling methodology to assess the impact of heat-electricity integration strategies: The case of the residential cooking sector in Italy. Energy 2019;170:1249–60. doi:10.1016/j.energy.2019.01.004.

[59] Rady YY, Rocco M V, Serag-Eldin MA, Colombo E. Modelling for power generation sector in Developing Countries: Case of Egypt. Energy 2018;165:198–209. doi:10.1016/j.energy.2018.09.089.

[60] Burandt T, Xiong B, Löffler K, Oei P-Y. Decarbonizing China's energy system – Modeling the transformation of the electricity, transportation, heat, and industrial sectors. Appl Energy 2019;255:113820. doi:10.1016/j.apenergy.2019.113820.

[61] Chung Y, Paik C, Kim YJ. Open source-based modeling of power plants retrofit and its application to the Korean electricity sector. Int J Greenh Gas Control 2019;81:21–8. doi:10.1016/j.ijggc.2018.12.005.

[62] Paardekooper S, Lund H, Chang M, Nielsen S, Moreno D, Thellufsen JZ. Heat Roadmap Chile: A national district heating plan for air pollution decontamination and

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

decarbonisation. 2019.

[63] Egyptian Electricty Holding Company. Annual Report. 2019.

[64] Lenox C, Dodder R, Gage C, Loughlin D, Kaplan O, Yelverton W. EPA U.S. Nine-region MARKAL DATABASE, DATABASE DOCUMENTATION. Cincinnati, OH, USA: 2013.

[65] U.S. Energy Information Administration. Annual energy outlook 2015: With projections to 2040. Washington, DC: 2015.

[66] DeCarolis JF, Babaee S, Li B, Kanungo S. Modelling to generate alternatives with an energy system optimization model. Environ Model Softw 2016;79:300–10. doi:10.1016/j.envsoft.2015.11.019.

[67] Eshraghi H, de Queiroz AR, DeCarolis JF. US Energy-Related Greenhouse Gas Emissions in the Absence of Federal Climate Policy. Environ Sci Technol 2018;52:9595–604. doi:10.1021/acs.est.8b01586.

[68] Möller C, Kuhnke K, Reckzügel M, Pfisterer H-J, Rosenberger S. Energy storage potential in the Northern German region Osnabrück-Steinfurt. 2016 Int. Energy Sustain. Conf., 2016, p. 1–7. doi:10.1109/IESC.2016.7569497.

[69] Hörsch J, Hofmann F, Schlachtberger D, Brown T. PyPSA-Eur: An open optimisation model of the European transmission system. Energy Strateg Rev 2018;22:207–15. doi:10.1016/j.esr.2018.08.012.

[70] Kiviluoma J, Meibom P. Methodology for modelling plug-in electric vehicles in the power system and cost estimates for a system with either smart or dumb electric vehicles. Energy 2011;36:1758–67. doi:10.1016/j.energy.2010.12.053.

[71] Anjo J, Neves D, Silva C, Shivakumar A, Howells M. Modeling the long-term impact of demand response in energy planning: The Portuguese electric system case study. Energy 2018;165:456–68. doi:10.1016/j.energy.2018.09.091.

[72] U.S. Energy Information Administration. International Energy Outlook 2016. Washington, DC: 2016.

[73] Child M, Nordling A, Breyer C. Scenarios for a sustainable energy system in the Åland Islands in 2030. Energy Convers Manag 2017;137:49–60. doi:10.1016/j.enconman.2017.01.039.

[74] Ruhnau O, Hirth L, Praktiknjo A. Time series of heat demand and heat pump efficiency for energy system modeling. Sci Data 2019;6:1–10. doi:10.1038/s41597-019-0199-y.

[75] Paardekooper S, Lund RS, Mathiesen BV, Chang M, Petersen UR, Grundahl L, et al. Heat Roadmap Europe 4: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. 2018.

[76] Fleiter T, Elsland R, Rehfeldt M, Steinbach J, Reiter U, Catenazzi G, et al. EU Profile of heating and cooling demand in 2015. 2017.

[77] Ashfaq A, Ianakiev A. Cost-minimised design of a highly renewable heating network for fossil-free future. Energy 2018;152:613–26. doi:10.1016/j.energy.2018.03.155.

[78] European Climate Foundation. Roadmap 2050: a practical guide to a prosperous, low-carbon Europe. 2010.

[79] Pasaoglu G, Fiorello D, Zani L, Martino A, Zubaryeva A, Thiel C. Projections for electric vehicle load profiles in Europe based on travel survey data. Netherlands: 2013.

[80] Hirth L, Mühlenpfordt J, Bulkeley M. The ENTSO-E Transparency Platform – A review of Europe's most ambitious electricity data platform. Appl Energy 2018;225:1054–67. doi:10.1016/j.apenergy.2018.04.048.

[81] Horschig T, Thrän D. Are decisions well supported for the energy transition? A review on modeling approaches for renewable energy policy evaluation. Energy Sustain Soc 2017;7. doi:10.1186/s13705-017-0107-2.

[82] Pfenninger S, Keirstead J. Comparing concentrating solar and nuclear power as baseload providers using the example of South Africa. Energy 2015;87:303–14. doi:10.1016/j.energy.2015.04.077.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Appendix 1: Overview of surveyed models

Table 3. Overview of modelling tools

Model	**Data**	**Model**	**Data**
AEOLIUS		ENPEP-BALANCE	
AURORA		ENTIGRIS	X
BALMOREL	X	ESO-XEL	X
BCHP Screening Tool		ERIS	
Calliope	X	ERJ	
CASPOC		ETM (EUROfusion Times Model)	
CLEWS		ETM (Energy Transition Model)	
COMPETES		ETSAP-TIAM	
COMPOSE	X	EUCAD	X
CYME		EUPower-Dispatch	X
DER-CAM		Ficus	
DESSTinEE		GALLM	
DIETER	X	GAMAMOD	
DIgSILENT/PowerFactory		GCAM	
Dispa-SET	X	GEM-E3	
DynPP		GET	
E2M2 (European Electricity Market Model)	X	GENeSYS-MOD	
E4CAST		GridCal	
EA-PSM		GridLAB-D	
ELMOD		GTMax	
ELTRAMOD		H2RES	
EMCAS		HOMER (Grid)	X
EMINENT		HYDROGEMS	
EMLab-Generation	X	HYPERSIM	
EMMA	X	iHOGA	
EMPIRE	X	IKARUS	
EMPS		IMAKUS	*
Enerallt		IMAGE	X
EnergyBALANCE / INFORSE		INVERT/EE-LAB	X
EnergyNumbers-Balancing		IPSA 2	
EnergyPlan	X	IRiE (EMPS-IRiE)	
energyPro	X	IWES (Integrated Whole-Energy System)	X

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

EnergyRt		JMM (Joint Market Model)	
EnergyScope	X	LEAP	*
Enertile	X	LIBEMOD	X
LIMES-EU	X	RAPSim	
LOADMATCH	X	ReEDS (Regional Energy Deployment System)	X
LUSYM	X	Region4FLEX	
Maon	X	ReMIND	X
MARKAL		REMix	
MEDEAS		Renpass	
MERGE-ETL		RETScreen	
Mesap PlaNet		SAM	
MESSAGE		SciGRID	
METIS		SIMPOW	
MOCES		SimREN	
MiniCAM		SimSES	
MultiMod		SIREN	
NEMO (National Electricity Market Optimiser)		SIVAEL	
NEMS (National Energy Modeling System)	X	SNOW	
Oemof		SDDP	
OMEGAlpes		StELMOD	*
OnSSET		SteMES	
OpenDSS	X	STREAM	
OptEnGrid	X	SWITCH	
ORNL (ORCED)		Temoa	
OSeMOSYS		TIMES	
PLEXOS		TransiEnt Library	X
PERSEUS-NET		TRNSYS	*
POLES	X	UniSyD5.0	X
POLES-JRC	X	Urbs	*
POTEnCIA	X	WASP	
PowerGAMA		WEGDYN	X
PowerMatcher		WEM	
PRIMES	X	WeSIM	
ProdRisk		WILMAR Planning Tool	
PSR - SDDP	X	WITCH	X
PyMedeas	X		

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

PyPSA	X		
RamsesR	X		

X: denotes complete descriptions. *: denotes partial survey descriptions gathered.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Appendix 2: Supplementary figures and tables

Table 4. Overview of modelling method and purpose

Tool	Method	Purpose behind the mathematical formulation
Balmorel	Simulation	Investment cost minimization
Calliope	Optimization	Investment cost minimization/ Dispatch cost minimization
COMPOSE	Optimization	Investment cost minimization/ Dispatch cost minimization / Electricity import/export minimization / Social welfare maximization / Fuel minimization / Multicriteria analysis / Agent-based analysis
DIETER	Optimization	Investment cost minimization / Dispatch cost minimization
Dispa-SET	Optimization	Dispatch cost minimization / Electricity import/export minimization / Fuel minimization / Multi-criteria analysis
E2M2 - European Electricity Market Model	Optimization	Investment cost minimization / Dispatch cost minimization
EMLab-Generation	Simulation	Agent-based analysis
EMMA	Optimization	Total system cost minimization
EMPIRE	Optimization	Investment cost minimization / Dispatch cost minimization
EnergyPLAN	Simulation	Scenario development / Fuel minimization / Electricity import/export minimization
energyPRO	Simulation	Dispatch cost minimization
EnergyScope	Optimization	Investment cost minimization / Dispatch cost minimization / Multi-criteria analysis
Enertile	Optimization	Investment cost minimization / Dispatch cost minimization / Electricity import/export minimization
ENTIGRIS	Optimization	Investment cost minimization / Dispatch cost minimization
ESO-XEL	Optimization	Investment cost minimization / Dispatch cost minimization / Electricity import/export minimization
EUCAD	Optimization	Dispatch cost minimization
EUPowerDispatch	Optimization	Dispatch cost minimization
Homer Grid	Optimization	Net present cost minimization (capex and opex)
IMAGE	Simulation	Scenario development - exploring alternative routes (mostly cost minimizing)
Integrated Whole-Energy System (IWES) model	Optimization	Investment cost minimization / Dispatch cost minimization / Social welfare maximization

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

INVERT/EE-Lab	Simulation	Agent-based analysis / Other (please specify): Dynamic bottom-up simulation model, with myopical, multinominal, nested logit approach for optimizing objectives of decision makers
LIBEMOD	Equlibrium: Multi-good, Multi-energy market	Multi-criteria analysis / Cost minimization / Main puropose is to find equilibirum in a future European energy market under various assumptions about policy goals and targets
LIMES-EU	Optimization	Investment cost minimization / Dispatch cost minimization
LOADMATCH	Trial-and-error simulation: It marches forward in time and can only finish if there is no load loss; otherwise, it must be restarted with different inputs until it finishes all time steps.	Zero load loss with 100% clean, renewable wind-water-solar electricity and heat (including electrolytic hydrogen) and storage (electricity, heat, cold, and H2) among all energy sectors (electricity, transport, building heating/cooling, industry, etc.) at low cost (but not necessarily lowest cost)
LUSYM	Optimization	Dispatch cost minimization
Maon	Optimization	Dispatch cost minimization / Electricity import/export minimization / Social welfare maximization / Fuel minimization
National Energy Modeling system (NEMS)	Partial equilibrium (heterogeneous, some models simulate, others optimize, but all iterate to a common (partial) equilibrium (but with active macro feedback)	Multi-criteria analysis
None	Optimization	Multi-criteria analysis
OpenDSS	Simulation	Electrical Circuit Analysis in the Freqency Domain
OptEnGrid	Optimization	Investment cost minimization / Dispatch cost minimization / Electricity import/export minimization / CO2 minimization
POLES	Simulation	Myopic anticipation
POLES-JRC	Simulation	Fuel choice by multinomial logit
POTEnCIA	Simulation	Simulation
PRIMES	Market Equilibrium	Market equilibrium
PSR - SDDP	Optimization	Dispatch cost minimization
pymedeas	Simulation	Projections of energy systems under biophysical constraints usign system dynamics techniques
PyPSA	Optimization	Investment cost minimization / Dispatch cost minimization
RamsesR	Optimization	Dispatch cost minimization
Regional Energy Deployment System (ReEDS)	Optimization	Investment cost minimization / Dispatch cost minimization

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

REMIND	Optimization	Social welfare maximization
TransiEnt Library	Simulation	Multi-criteria analysis / Resilience maximization / Emission minimization
UniSyD5.0	Optimization	System dynamics model - Resource utilisation to meet consumer demand at minimum dispatch price
WEGDYN	Computable General Equilibrium	Macroeconomic scenario analysis
WITCH	Optimization	Social welfare maximization

Table 5. Sector coverage summary

Modelling tool	**Sector coverage**
Balmorel	Electricity generation
Calliope	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry / Biofuel production
COMPOSE	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry / Biofuel production
DIETER	Electricity generation / Individual heating / Transport
Dispa-SET	Electricity generation / Individual heating / District heating / Transport
E2M2 - European Electricity Market Model	Electricity generation / District heating
EMLab-Generation	Electricity generation
EMMA	Electricity generation
EMPIRE	Electricity generation
EnergyPLAN	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry / Biofuel production
energyPRO	Electricity generation / District heating / Cooling / Biofuel production
EnergyScope	Electricity generation / Individual heating / District heating / Transport / Industry
Enertile	Electricity generation / Individual heating / District heating / Transport
ENTIGRIS	Electricity generation
ESO-XEL	Electricity generation / Other
EUCAD	Electricity generation
EUPowerDispatch	Electricity generation
Homer Grid	Electricity generation / Other
IMAGE	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry / Biofuel production
Integrated Whole-Energy System (IWES) model	Electricity generation / Individual heating / District heating / Cooling / Transport
INVERT/EE-Lab	Individual heating / Cooling

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

LIBEMOD	Electricity generation / District heating / Industry / Biofuel production
LIMES-EU	Electricity generation / Industry
LOADMATCH	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry
LUSYM	Electricity generation
Maon	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry / Biofuel production
National Energy Modeling system (NEMS)	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry / Biofuel production / Other
OpenDSS	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry
OptEnGrid	Electricity generation / Individual heating / Cooling / Transport / Industry
POLES	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry / Biofuel production / Other
POLES-JRC	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry / Biofuel production / Other
POTEnCIA	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry
PRIMES	Electricity generation / Individual heating / District heating / Cooling / Transport / Biofuel production
PSR - SDDP	Electricity generation
pymedeas	Electricity generation / Transport / Industry / Other
PyPSA	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry / Biofuel production
RamsesR	Electricity generation / District heating
Regional Energy Deployment System (ReEDS)	Electricity generation / Transport / Other
REMIND	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry / Biofuel production
TransiEnt Library	Electricity generation / Individual heating / District heating / Cooling / Industry
UniSyD5.0	Electricity generation / Individual heating / District heating / Cooling / Transport / Industry / Biofuel production
WEGDYN	Electricity generation / Transport / Industry
WITCH	Electricity generation / Transport / Industry / Biofuel production

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Table 6. Summary of tools' modelling resolution and scope.

Modelling tool	**Spatial resolution**	**Technical resolution**	**Temporal resolution**	**Output time-horizon**
Balmorel	Global	Aggregated values	Hourly	1-day
Calliope	Global / Regional / National / Local / Project-specific resolution/Building	Individual plant/component(s) inputs	Hourly/Monthly / Seasonal time-slices / Yearly / Multi-year / Minutes	1-year/1-day/Multi-year/User-defined
COMPOSE	Project-specific resolution	Individual plant/component(s) inputs	Hourly	Multi-year
DIETER	Regional / National / Project-specific resolution	Aggregated values	Hourly	1-year
Dispa-SET	Global	Individual plant/component(s) inputs	Hourly	1-year
E2M2 - European Electricity Market Model	Global / Regional / National / Local / Project-specific resolution	Individual plant/component(s) inputs	1/4h, Representative hours	1-day / 1-year / Multi-year / Other
EMLab-Generation	Regional / National	Individual plant/component(s) inputs	Hourly / Monthly / Seasonal time-slices / Other (hourly variant and there is a segmented variant which groups hours together.)	Multi-year
EMMA	National	Aggregated values	Hourly	Other
EMPIRE	Regional / National / Local	Aggregated values	Hourly / Seasonal time-slices / Other (represents a year by four weeks with hourly resolution. Being a stochastic model, it also represents several years per strategic (investment) period, in order to reflect operational uncertainty from the perspective of the invesrment decision.)	Multi-year
EnergyPLAN	Regional / National / Local	Aggregated values	Hourly	1-year

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

energyPRO	Regional / Local	Individual plant/component(s) inputs	Hourly	Multi-year
EnergyScope	Global / Regional / National / Local	Aggregated values	Hourly	1-year
Enertile	Regional / National / Local	Aggregated values	Hourly / Multi-year	Multi-year / Other
ENTIGRIS	Regional / National / Project-specific resolution	Individual plant/component(s) inputs	Hourly / Multi-year	Multi-year
ESO-XEL	Regional / National / Local / Project-specific resolution	Aggregated values	Hourly / Yearly / Multi-year / Clustering approach for representative days	1-year / Multi-year / Other
EUCAD	National / Project-specific resolution	Aggregated values	Hourly	1-day / 1-year / Other
EUPowerDispatch	Regional	Individual plant/component(s) inputs	Hourly	1-year
Homer Grid	Global	Individual plant/component(s) inputs	Hourly	Multi-year
IMAGE	Global / Regional	Aggregated values	Yearly	1-year
Integrated Whole-Energy System (IWES) model	Global / Regional / National / Local	Aggregated values	Hourly	1-year
INVERT/EE-Lab	Regional / National / Project-specific resolution	Aggregated values	Yearly / Multi-year	1-year / Multi-year
LIBEMOD	National	Other	Yearly (carriers other than electricity) / Seasonal time-slices	Multi-year
LIMES-EU	National / EU Member States (excluding Malta and Cyprus) plus Switzerland, Norway and aggregated Balkan region	Aggregated values	Representative days using clustering algorithm from Nahmmacher et al. (2014), with 3-hour blocks	Multi-year

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

LOADMATCH	Global / Regional / National / Local / Project-specific resolution	Individual plant/component(s) inputs	Other (please specify)	Multi-year
LUSYM	Regional	Individual plant/component(s) inputs	Quarter-hourly	1-year
Maon	ENTSOE/E members	Individual plant/component(s) inputs	Coupled hours	1-year
National Energy Modeling system (NEMS)	National	Individual plant/component(s) inputs	Monthly / Seasonal time-slices / Yearly / Multi-year / Other (gas is monthly, electricity uses 9 time slices, informed by an offline analysis with 288 slices...)	Multi-year
OpenDSS	Local / Project-specific resolution	Individual plant/component(s) inputs	Hourly / Seconds	1-year / Multi-year
OptEnGrid	Project-specific resolution	Individual plant/component(s) inputs	Hourly	1-year
POLES	Global / Regional / National	Aggregated values	Hourly / Yearly	Multi-year
POLES-JRC	Global / Regional / National	Aggregated values	Hourly (for power dispatch) / Yearly (others)	Multi-year
POTEnCIA	National / EU member states	Other	Yearly	Multi-year
PRIMES	Regional / National	Individual plant/component(s) inputs	Hourly / Yearly / Multi-year	Multi-year
PSR - SDDP	Global / Regional / National	Individual plant/component(s) inputs	Hourly	Multi-year
pymedeas	Global / Regional / National	Aggregated values	Monthly	Multi-year
PyPSA	Global / Regional / National / Local / Project-specific resolution	Individual plant/component(s) inputs	Hourly	1-year
RamsesR	Regional / National / Local	Individual plant/component(s) inputs	Hourly	1-day / 1-year / Multi-year

SENTINEL

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Regional Energy Deployment System (ReEDS)	Regional / National	Aggregated values	Investment decisions are make annually; operations are modeled using time-slices	Other
REMIND	Global / Regional / National / Project-specific resolution	Aggregated values	Multi-year	Multi-year
TransiEnt Library	National / Local / Project-specific resolution	Individual plant/component(s) inputs	Hourly	1-day / 1-year
UniSyD5.0	Global / Regional / National / Local / Project-specific resolution	Individual plant/component(s) inputs	Hourly	Multi-year
WEGDYN	Global / Regional / National	Aggregated values	Yearly	Multi-year
WITCH	Regional	Aggregated values	Multi-year	Multi-year

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Modelling tool	User interface	Tool accessibility	Solver required	Solver access
Balmorel	Graphical user interface	Open source	Yes	Open source
Calliope	Direct coding and programming / Other: Text based (human readable) inputs	Open source	Yes	Open source / Commercial (paid) licensed
COMPOSE	Graphical user interface	Free under special conditions	Yes	Free under special conditions
DIETER	Direct coding and programming	Open source / Other: All code provided under the MIT license, but use the software GAMS which requires a license. Data pre- and post-processing is increasingly done with the open software Python.	Yes	Commercially (paid) licensed
Dispa-SET	Direct coding and programming	Open source	Yes	Free under special conditions
E2M2 - European Electricity Market Model	Direct coding and programming	Commercially (paid) licensed	Yes	Commercially (paid) licensed
EMLab-Generation	Direct coding and programming / GUI with the possibility of coding if needed	Open source	Yes	Open source
EMMA	Direct coding and programming	Open source	Yes	Commercially (paid) licensed
EMPIRE	Direct coding and programming	Free under special conditions	Yes	Commercially (paid) licensed
EnergyPLAN	Graphical user interface	Free (freeware)	No	
energyPRO	GUI with the possibility of coding if needed	Commercially (paid) licensed	No	
EnergyScope	Direct coding and programming	Open source	Yes	Open source
Enertile	Graphical user interface / Direct coding and programming / GUI with the possibility of coding if needed	Other: Only for internal use	Yes	Commercially (paid) licensed

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

ENTIGRIS	Direct coding and programming	Commercially (paid) licensed	Yes	Commercially (paid) licensed
ESO-XEL	Direct coding and programming	Open source / Free under special conditions	Yes	Free under special conditions
EUCAD	Direct coding and programming	Other: Jointly-owned by University Grenoble Alpes and Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA)	No	
EUPowerDispatc h	Direct coding and programming	Free under special conditions	Yes	Commercially (paid) licensed
Homer Grid	Graphical user interface	Commercially (paid) licensed	No	
IMAGE	Direct coding and programming	Other: Not open source	Yes	Commercially (paid) licensed
Integrated Whole-Energy System (IWES) model	Direct coding and programming	Other: Used internally	Yes	Commercially (paid) licensed
INVERT/EE-Lab	Other: Linux bash based control interface	Other: not publicly available, apart from partner institutions	No	
LIBEMOD	Direct coding and programming / Other: web-based graphical user interface is now beeing developed as a pilot	Free under special conditions	No	
LIMES-EU	Direct coding and programming	Other: Internal use only	No	
LOADMATCH	Direct coding and programming	Free under special conditions	No	
LUSYM	Direct coding and programming	Other: Available on request for academic purposes	Yes	Commercially (paid) licensed
Maon	Graphical user interface / Web-based (online) user interface / Direct coding and programming / GUI with the possibility of coding if needed	Commercially (paid) licensed	Yes	Commercially (paid) licensed
National Energy Modeling system (NEMS)	Direct coding and programming	Free under special conditions / Other: freely distributable code, but several commercial	Yes	Commercially (paid) licensed

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

		licenses are required to operate		
OpenDSS	Graphical user interface / Direct coding and programming	Open source / Free (freeware)	Yes	Open source
OptEnGrid	Graphical user interface	Commercially (paid) licensed	No	
POLES	Direct coding and programming	Other: Jointly owned and developped by Joint Research Centre, Enerdata and University Grenoble Alpes	No	
POLES-JRC	GUI with the possibility of coding if needed	Other: Internal use only	No	
POTEnCIA	Direct coding and programming	Commercially (paid) licensed	No	
PRIMES	Graphical user interface	Other: Not given to others	Yes	Commercially (paid) licensed
PSR - SDDP	Graphical user interface / Web-based (online) user interface / GUI with the possibility of coding if needed	Commercially (paid) licensed	No	
pymedeas	Direct coding and programming	Open source / Free (freeware)	No	Free (freeware)
PyPSA	Web-based (online) user interface / Direct coding and programming	Open source	Yes	Open source
RamsesR	Other: Excel	Open source / Free (freeware)	Yes	Free (freeware)
Regional Energy Deployment System (ReEDS)	Direct coding and programming	Free under special conditions	Yes	Other: NREL uses a commercial solver, but the model could theoretically use free, open-source solvers.
REMIND	Direct coding and programming	Open source / Free under special conditions	Yes	Commercially (paid) licensed
TransiEnt Library	Graphical user interface / Direct coding and programming	Open source / Free (freeware)	Yes	Commercially (paid) licensed

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

UniSyD5.0	Other: GUI is within system dynamics software - STELLA	Commercially (paid) licensed	No	
WEGDYN	Direct coding and programming	Other: Model code is developed in-house. For database and solvers licence is needed.	Yes	Commercially (paid) licensed
WITCH	Direct coding and programming	Free under special conditions	Yes	Commercially (paid) licensed

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Modelling tool	Demand-side representation	Demand side flexibility to integrate variable renewable energy
Balmorel	Static demand (no response to supply cost)	Yes, electricity and heat
Calliope	Static demand (no response to supply cost) / Elastic demand (responsive to supply cost)	Yes, electricity and heat
COMPOSE	Static demand (no response to supply cost)	Yes, electricity, heating, cooling, and mobility services
DIETER	Static demand (no response to supply cost)	Yes, electricity and heat / Other: DSM, several types of flexible power-to-heat, flexible EVs and flexible H2 generaiton (and storage) in the model
Dispa-SET	Others: Constant demand + Flexible (shiftable in time) demand	Yes, electricity and heat
E2M2 - European Electricity Market Model	Static demand (no response to supply cost)	Yes, only electricity
EMLab-Generation	Static demand (no response to supply cost)	No
EMMA	Static demand (no response to supply cost)	No
EMPIRE	Static demand (no response to supply cost) / Energy efficiency improvement cost curves	Yes, only electricity
EnergyPLAN	Static demand (no response to supply cost) / Elastic demand (responsive to supply cost)	Yes, only electricity
energyPRO	Static demand (no response to supply cost) / Elastic demand (responsive to supply cost)	Yes, electricity and heat
EnergyScope	Static demand (no response to supply cost) / Others: We implement the End use demand rather than the Final energy consumed	Other: As the End use demand is implemented, the model can implement technologies for demand side management, such as heat pumps or industrial heating with thermal storage.
Enertile	Elastic demand (responsive to supply cost) / Demand is modeled endogenously	Yes, electricity and heat / Other: charging of electric cars, h2 electrolysis
ENTIGRIS	Static demand (no response to supply cost)	No
ESO-XEL	Static demand (no response to supply cost)	No
EUCAD	Elastic demand (responsive to supply cost)	Yes, only electricity
EUPowerDispatch	Elastic demand (responsive to supply cost)	Yes, only electricity
Homer Grid	Static demand (no response to supply cost)	Yes, only electricity / Other: Storage

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

IMAGE	Elastic demand (responsive to supply cost) / Demand is modeled endogenously	No
Integrated Whole-Energy System (IWES) model	Others: Flexibility in demand is modelled	Yes, electricity and heat
INVERT/EE-Lab	Elastic demand (responsive to supply cost) / Energy efficiency improvement cost curves	No
LIBEMOD	Demand is modeled endogenously	Yes, only electricity
LIMES-EU	Static demand (no response to supply cost)	No
LOADMATCH	Static demand (no response to supply cost)	Yes, electricity and heat
LUSYM	Elastic demand (responsive to supply cost)	Yes, only electricity
Maon	Static demand (no response to supply cost) / Elastic demand (responsive to supply cost) / Demand is modeled endogenously	Yes, electricity and heat
National Energy Modeling system (NEMS)	Demand is modeled endogenously	Yes, electricity and heat
OpenDSS	Static demand (no response to supply cost)	Yes, only electricity
OptEnGrid	Elastic demand (responsive to supply cost)	Yes, electricity and heat
POLES	Elastic demand (responsive to supply cost) / Energy efficiency improvement cost curves / Demand is modeled endogenously	Yes, only electricity
POLES-JRC	Energy efficiency improvement cost curves / Demand is modeled endogenously	Yes, only electricity
POTEnCIA	Demand is modeled endogenously	Yes, electricity and heat
PRIMES	Demand is modeled endogenously	Yes, electricity and heat
PSR - SDDP	Static demand (no response to supply cost) / Elastic demand (responsive to supply cost)	Yes, only electricity
pymedeas	Elastic demand (responsive to supply cost) / Energy efficiency improvement cost curves	Yes, electricity and heat
PyPSA	Elastic demand (responsive to supply cost)	Yes, electricity and heat
RamsesR	Static demand (no response to supply cost) / Elastic demand (responsive to supply cost)	Yes, only electricity

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Regional Energy Deployment System (ReEDS)	Static demand (no response to supply cost) / Demand is modeled endogenously	Yes, only electricity
REMIND	Elastic demand (responsive to supply cost) / Demand is modeled endogenously	No
TransiEnt Library	Static demand (no response to supply cost) / Elastic demand (responsive to supply cost) / Energy efficiency improvement cost curves / Demand is modeled endogenously	Yes, electricity and heat
UniSyD5.0	Elastic demand (responsive to supply cost) / Energy efficiency improvement cost curves / Demand is modeled endogenously	Yes, electricity and heat
WEGDYN	Demand is modeled endogenously	Yes, electricity and heat
WITCH	Demand is modeled endogenously	Yes, only electricity

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Table 7. Summary of studies reviewed with their corresponding demand representation.

Ref.	Model	Demand types	Sector	Spatial scope (scale | resolution)	Location	Temporal scope (scale | resolution)	Model year
[71]	OSeMOSYS	Electricity	Industrial, Residential Tertiary	National | 1 node	Portugal	35 years | 96 timeslices per year	2015-2050
[49]	PyPSA	Electricity Thermal Transport	Buildings Transport	Continental | 30 nodes	Europe	1 year | hourly	2011
[60]	OSeMOSYS	Electricity Thermal Transport	Buildings Industrial Transport	National | 33 nodes	China	35 years | 5-year periods, every 73rd hour in year	2015-2050
[73]	EnergyPLAN	Electricity Thermal Transport	Buildings Transport	Subnational | 1 node	Åland, Norway	1 year | hourly	2014, 2020, 2030
[54]	EnergyPLAN	Electricity Thermal Transport	Commercial Industrial Residential Transport	National | 1 node	Finland	1 year | hourly	2012, 2020, 2050
[61]	OSeMOSYS	Electricity	All (combined)	National | 1 node	Korea	15 years | 10 timeslices per year	2015-2029
[66]	Temoa	Electricity	All (combined) Transport	National | 1 node	USA	35 years | 5-year periods, 4 timeslices per 5 years	2015-2050
[55]	Calliope	Electricity	All (combined)	National | 1 node	Switzerland	1 year | hourly	2035
[50]	EnergyPLAN	Electricity Thermal Transport	Buildings Industrial Transport	Multinational | 11 nodes	South East Europe	1 year | hourly	2012, 2050
[67]	Temoa	Electricity Thermal Transport	Commercial Industrial Residential Transport	National | 1 node	USA	25 years | 5-year periods, 12 timeslices per 5 years	2015-2040
[56]	Calliope	Electricity	All (combined)	National | 1 node	UK	36 years | hourly (years modelled independently)	1980-2015
[81]	PyPSA	Electricity	All (combined)	Continental | 3657 nodes / 100 clusters	Europe	N/A | hourly	N/A
[70]	WILMAR	Electricity Thermal Transport	All (combined)	National | 1 node	Finland	1 year | hourly	2035
[58]	Calliope	Electricity Thermal	All (combined)	National | 1 node	Italy	1 year | hourly	2015
[68]	oemof	Electricity	All (combined)	Subnational | 1 node	Osnabrück-Steinfurt, Germany	1 year | hourly	2013
[82]	Calliope	Electricity	All (combined)	National | 20 nodes	South Africa	3 years | 12-hourly except 1 week at hourly	2008-2010
[37]	Calliope	Electricity	All (combined)	National | 20 nodes	UK	25 years | hourly (years modelled independently)	1989-2013

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

[57]	Calliope	Electricity	All (combined)	National | 20 nodes	UK	1 year | hourly	2012
[59]	OSeMOSYS	Electricity	Commercial Industrial Residential and more.	National | 1 node	Egypt	32 years | 15 timeslices per year	2008-2040
[51]	DIETER	Electricity	All (combined)	National | 1 node	Germany	1 year | hourly	2013
[52]	PyPSA	Electricity	All (combined)	Continental | 30 nodes	Europe	1 year | hourly	2012-2100
[53]	PLEXOS	Electricity Thermal Transport	All (combined)	Continental | 30 nodes	Europe	1 year | hourly	2050