Renewable Energy Investment Strategies – A two-dimensional interconnectivity approach

Deliverable D-1.2

D-1.2 2022 Final tool and method documentation

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1 Introduction

This RE-INVEST WP1 report documents the tools and methods of the final modelling platform for analysing the scenarios in WP3. The report syntheses the work on model development following the initial deliverable D-1.1. The modelling environment of RE-INVEST consists of a combination of two tools, i.e. the AAU EnergyPLAN (including the MultiNODE) tool, the AU PowerFLOW tool and the open-source energy model pypsa-eur-sec. All these tools can be used to model the integration and operation of energy sectors. However, as described in deliverable D-1.1 their approaches are different, each with clear strength that complements the shortcomings of the other tools.

RE-INVEST has resulted in both individual further developments of each the models as well as a joint modelling platform (EPlanFlow) in which EnergyPLAN and PowerFLOW can be used in combination.

The purpose of this final report is both to describe and document the qualities of each approach individually, as well as to describe and document the joint modelling platform (EPlanFlow).

Some of the description has already been published in either formal documentations and/or scientific journal papers published as part of the RE-INVEST project. Thus, a part of this report simply refers to these previous publications (included as Appendix 1-3). Moreover, each of the models has a documentation, whichis updated on a running basis, and has been updated during the RE-INVEST project. These documentations can always be found at the following online links:

EnergyPLAN: https://www.energyplan.eu/training/documentation/

MultiNode: https://www.energyplan.eu/wp-content/uploads/2022/01/DocumentationMultinode.pdf

PyPS: https://pypsa-eur-sec.readthedocs.io/en/latest/

2 EnergyPLAN and MultiNODE

EnergyPLAN was developed at Aalborg University [1]. It is an analytically programmed energy system analysis tool that simulates the hourly operation of an energy system over a year [2]. EnergyPLAN is primarily designed to assess national energy systems, as shown in examples for Denmark ([3],[4]), China 28[5] and Ireland ([6],[7]). It has, however, also been applied to cases of cities [8], municipalities ([9]-[11]) and regions ([12]-[14]).

EnergyPLAN is set up for the user to determine several types of input as illustrated in Figure 2.1. Based on such input, EnergyPLAN simulates the energy system based on both user-defined and predetermined criteria to identify the output of the energy system. The user input criteria are energy demands, capacities and efficiencies of plants, fuel usage, CO_2 emissions from fuels and costs. Furthermore, the user has the option to choose the simulation strategy and how to handle excess electricity [15]. EnergyPLAN delivers outputs on the performance of the energy system. Typically, these are: the total annual costs of the system, the primary energy use, CO_2 emissions, hourly balances of energy demand and production and the amount of excess electricity in the system [16].

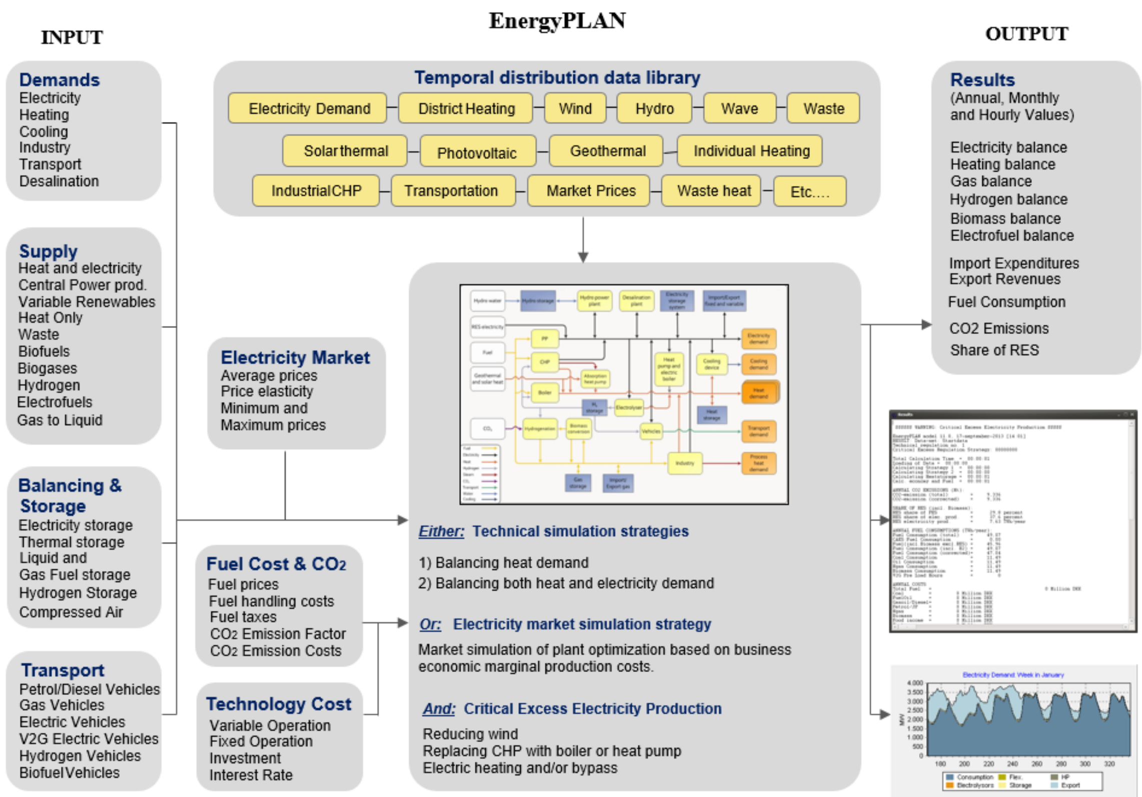

Figure 2.1. Illustration of the setup of an EnergyPLAN analysis. The user defines the energy system based on a pre-set layout. EnergyPLAN then provides outputs such as primary energy, production costs, CO2 emissions and hourly balances.

Energy demands are associated with a set of distribution files to capture variations in and correlations between the different demands across all hours of the year. The same is true regarding the production of variable renewable energy. In terms of production units, the model is set up to aggregate the available plants within each sector. This means that EnergyPLAN needs an aggregated input for all wind turbines, for all power plants and for all power-to-gas facilities. Within district heating, EnergyPLAN differentiates between large-scale combined heat and power plants, small-scale combined heat and power plants and district heating networks with only boilers, providing three groups of district heating networks.

One key feature of EnergyPLAN is that it is able to operate the energy system based on two different overall simulation strategies. Each of them may be subject to different variations, specifications and sub-strategies.

The first is the technical simulation strategy. The main target is to reduce fuel consumption based on a predetermined order of operation.

The predetermined order of operation in the technical strategy follows this basic principle:

i. Plants with no direct fuel usage; this means waste heat and variable renewable energy.

ii. Utilisation of energy in storage.

iii. Combined heat and power plants to produce electricity and utilise the waste heat.

iv. Power plants and boilers; these are determined to be the most inefficient units, as they only have one purpose.

v. Import of electricity.

Overall, these five steps seek to minimise the total fuel consumption in the system as well as the use of electricity sources external to the system.

The second simulation strategy is the market economic simulation. In this, EnergyPLAN simulates the energy system based on short-term marginal costs of a unit. This means that steps 2-5 from above become much more intertwined. In this strategy, EnergyPLAN will first use energy units with no short-term marginal costs. These are identified as waste heat plants and variable renewable energy units. Hereafter, based on user-defined inputs for marginal costs, EnergyPLAN identifies the least-cost unit in every given hour. It furthermore compares this to the external electricity market in order to import, export or store electricity. Overall, this simulates the energy system achieving the smallest marginal costs.

EnergyPLAN has been used in several cases to simulate smart energy systems. This is mostly regarding countries, such as Denmark and Ireland, but also in the case of the city of Copenhagen. EnergyPLAN has been updated over time with the concept of smart energy systems in mind. The current version can simulate the electricity-, thermal- and gas sectors, as well as the necessary technology to convert between the sectors. Storage technology has also been integrated, with both electricity storage, gas storage and thermal storage available. EnergyPLAN is able to model storage while balancing the charge and discharge cycle over a year, and chronologically know the amount of energy available in storage. Put together, these qualities make EnergyPLAN suitable for smart energy systems analysis.

As part of the RE-INVEST project EnergyPLAN has been subject to further development bringing it from version 13 to version 16. Such development has included among others the following elements:

In version 14:

- Market economic simulation strategy changed, so that the electric boilers first operate according to their marginal cost and the electricity market price, and then according to the Critical Excess Electricity Production CEEP regulations, if possible.
- Heat storage can use Heat Pumps to reduce not only CEEP but also export of electricity in general.
- Excess heat can be stored in the solar heat storage.
- Excess heat can be stored in the other heat storage.
- Option to specify year start and end values of the hydro power water storage has been added so that one can model yearly variations in the water dam storage of big systems such as in Norway.
- An option of Zero price strategy added for operation of RES in market operation:
- Concentrated Solar Power (CSP) with a storage: It works in technical simulation to reduce PP/import and CEEP/EEEP, i.e. to level out differences between electricity demands and RES productions. In economical simulations it optimizes the profit of the CSP production.
- Rockbed (Hight Temperature Thermal storage): It consumes electricity to produce steam for PP and CHP3 and thereby reduces fuel demands. It operates to reduce CEEP and EEEP.
- Hydrogen for Industry.

In versions 15 and 15.1:

- Two additional options in the regulation have been added: The first is an option to operate the thermal storage for district heating as a seasonal storage instead of a weekly storage. Depending on the size of the storage, the user can choose between the two options. The next is a new option to make the model iterate its way to a solution of utilizing the electrolysers and hydrogenation units better in the electricity balancing. In the previous versions, one could activate CEEP strategy no. 8 to produce green gas out of available critical excess electricity production due to available capacities in the electrolysers and the hydrogenation units. However, such extra production may lead to too much green gas in the balancing of the gas sector. This option is still available. However, the model can now be asked to find a solution in which CEEP is lowered without increased the resulting green gas production. Such solution is found by iteration and takes additional computation time, but still typically less than a minute.
- Two additional technologies/components have been added: The first is an extra electricity storage unit, so that one can include two. The second is production and demand of ammonia, e.g., for fuelling ships or similar transportation.

- Changes have been made in the market economic simulation. Previously, the setting of prices on the external electricity market did not take into account the influence of the bottlenecks when determining the prices. This has been changed in version 15, where it is possible to choose whether bottlenecks should be taken into account.
- New feature to express an external request for the system to produce a certain import/export. In this way, the EnergyPLAN model can quantify the system's ability to provide balancing for an external system. The purpose is to make it possible for one country/system to assist in the balancing of another country/system, e.g., to use the flexibility of Norwegian hydropower to balance a Swedish, Danish or European system.
- Expansion of the use of "Electricity storage" to include also PP2.
- Expansion of the option to specify electricity storage market operation strategies in terms of adding a potential profit margin and choosing the number of hours for the prognosis. These new options turned out to be relevant for very large electricity storage facilities.
- Rockbed storage now uses percent loss per hour instead of share loss per hour to facilitate very small loss rates.
- The scenario and distribution files included when downloading the tool have been updated to reflect the latest research. The previous files are still available by downloading one of the previous versions.

In version 16:

- A better algorithm to make use of the electrolysers to balance electricity.
- A better algorithm to use the thermal storage.
- An option to enter max and min prices on the external market in the case of bottlenecks.
- An option to include HTL and Pyrolysis in the biomass conversion.
- An option to calculate H2 grids and convert to a 100% H2 solution.
- An option to include other emissions than CO_2.
- An option to include Biochar from Pyrolysis.

All these new developments are carefully described and documented in the EnergyPLAN documentation, which can always be found in an updated version on the EnergyPLAN homepage: https://www.energyplan.eu/training/documentation/

Appendix 1 describes and documents the current version of EnergyPLAN.

MultiNODE

One of EnergyPLAN's strengths is its focus on one specific energy system. However, this poses a challenge when looking at the context of one country in relation to several surrounding countries, such as the Danish energy system in relation to the energy system of the EU28. EnergyPLAN does not simulate the surrounding energy system. In EnergyPLAN, the user has the option of adding a transmission cable and a price to the area, but it is not possible to model the specific layout of the surrounding energy system. To address this challenge, MultiNODE is developed as an add-on to EnergyPLAN. The following section describes MultiNODE further.

The goal of the MultiNODE Add-on Tool to EnergyPLAN is to be able to run and link several EnergyPLAN models, such as linking national models into analysing the European energy system. The concept currently only looks at the electricity sector and defines the link through cables. MultiNODE has the possibility of linking between 2 and 28 different systems. These energy systems can be of all sizes, meaning it is suitable to run both on local-national analyses and when linking multiple national energy systems, e.g., the European Union.

Since MultiNODE is an add-on, it does not make changes to the way EnergyPLAN runs. This is reflected in the overall concept of the MultiNODE add on tool, as exchange possibilities have to be identified in a certain way.

Figure 2.2 shows the overall concept of the MultiNODE add on tool. The figure illustrates how the tool identifies exchange options. First, MultiNODE runs all selected energy systems without any interconnection. From this analysis, MultiNODE identifies two sets of information for each system: 1) the hourly amount of exportable electricity and 2) the potential for electricity import every hour. MultiNODE identifies a potential import demand as hours with:

- Lack of sufficient capacity.
- Hours with power plant production.

From the information regarding the hourly available exportable electricity and hourly potential for importing electricity, MultiNODE now tries to link the exportable electricity with the demand for import. In hours with import demand and available export, each system will try to fulfil its demand for import as much as possible. Each individual energy system will get access to the electricity available for import on the grid based on a merit order.

After utilizing as much of the exportable electricity as possible in each of the energy systems, an import/export balance is created for each energy system and the yearly net export is identified. Together, the balance and the net export identify each system’s interaction with the grid.

Note that the tool uses a total grid capacity for transmission since it views the electricity grid as one unison between all the connected systems

Finally, the MultiNODE add-on tool runs each of the selected energy systems again now with the information regarding import and export. Based on these simulation results the MultiNODE tool has the option of summarizing all systems together.

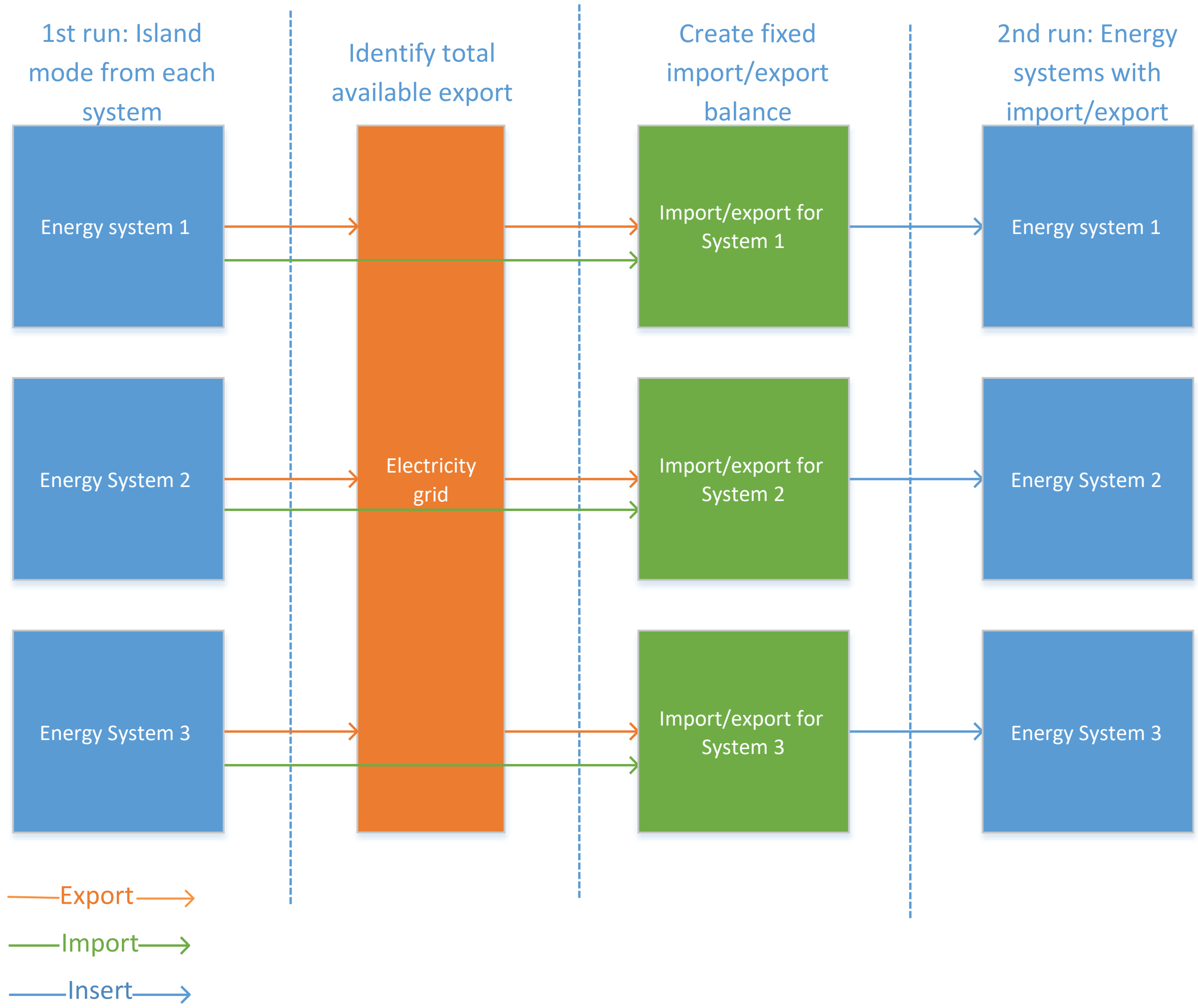

Figure 2.2. Overall concept of the MultiNODE tool.

MultiNODE models the transmission grid as a central node, to which all the connected energy systems exchange electricity with, only limited by the capacities of the interconnectors. This is illustrated in the star network in Figure 2.3 below. This simplification is in line with the overall principles of EnergyPLAN that aggregates parts of the energy system to achieve simpler and faster calculations without losing the main perspective of the subject analysed. The star network should be seen as a simplification of the grid connecting different energy systems that enables the user to quickly calculate the benefits of interconnection.

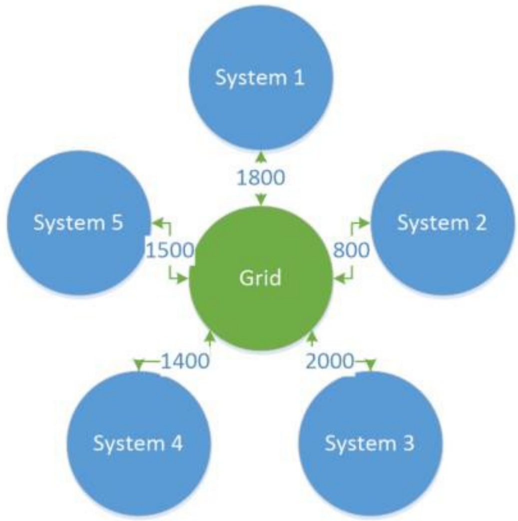

Figure 2.3. Illustration of the star network. MultiNODE models the transmission grid as one central node to which all the modelled energy systems exchange electricity. The only limitation to the exchange is the individual interconnectors.

The key principle of MultiNODE is therefore that through a star network, with a user defined merit order, the exchange of electricity between systems can be identified. This exchange relies on creating an hourly balance between the excess electricity produced in some systems and the need for import of electricity in other systems. The excess electricity comes from combined heat and power plants, waste incineration and variable renewable energy. The need for import is determined as situations with lack of capacity and production of electricity on power plants.

Currently, the tool will only exchange electricity if both of these situations occur. Thus, it will not ramp up a power plant in one system to fill under-production of electricity in another system. Hence, the tool examines how excess electricity can be used and does not guarantee the balancing of production and demand in all hours in all systems. In deliverable D.1.1, an example in which MultiNODE has been applied to 14 European countries, is described.

3 PowerFLOW

PowerFLOW is a software implementation of a general methodology to calculate self-consistent electricity flows in an interconnected network of sources and sinks, i.e., locations with excess electricity are used to cover deficits in other locations to the fullest extend allowed by the physical limitations of the interconnectors in the network. The tool employs a DC power flow approximation for constrained transmission capacities. This approximation is valid at the hourly time scale typically used for dynamic energy system models, but it it would not be valid for, e.g., frequency and voltage stability studies.

Different versions of PowerFLOW have previously been applied to analyze highly renewable electricity networks for Europe ([22],[23]) and the contiguous United States of America (USA) [24]. As shown in Figure 3.1, the former case typically makes use of 30 interconnected countries. Figure 3.2 shows the 10 Federal Energy Regulatory Commission (FERC) regions used in the latter case. In these studies, a main use of PowerFLOW has been to investigate to what extent, electrical interconnection of a large geographical area, i.e., Europe or the USA, can increase the utility value of variable renewable sources by redistributing instantaneous excess generation from one region to another. This is illustrated in Figure 3.3, where it is shown how local excess from wind and solar sources can be exported to other countries to some extent. For model years up to about 2030, all available excess can be redistributed while the amount that can be exported only grows slowly for later years. The reason for this change is that more countries have excess generation occurring at the same time.

In RE-invest, the PowerFLOW methodology was adapted to interact efficiently with EnergyPLAN and together they form the EPlanFlow tool. This is discussed in the following section.

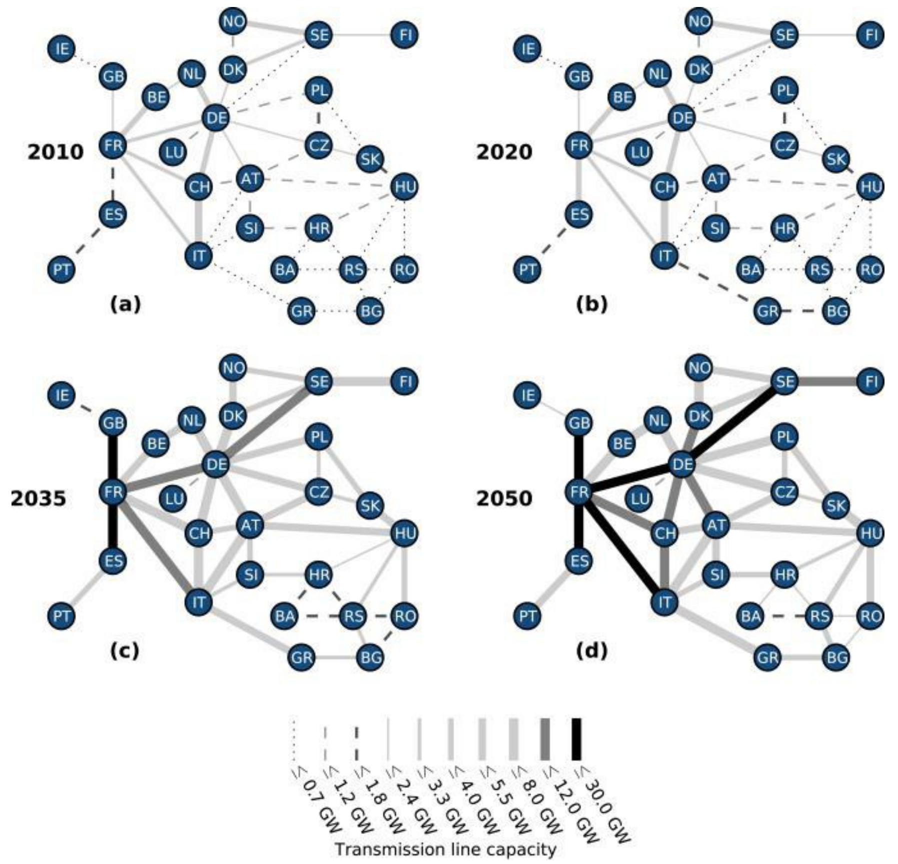

Figure 3.1, Illustration of the networks used in studies of Europe. Excerpt from [23]

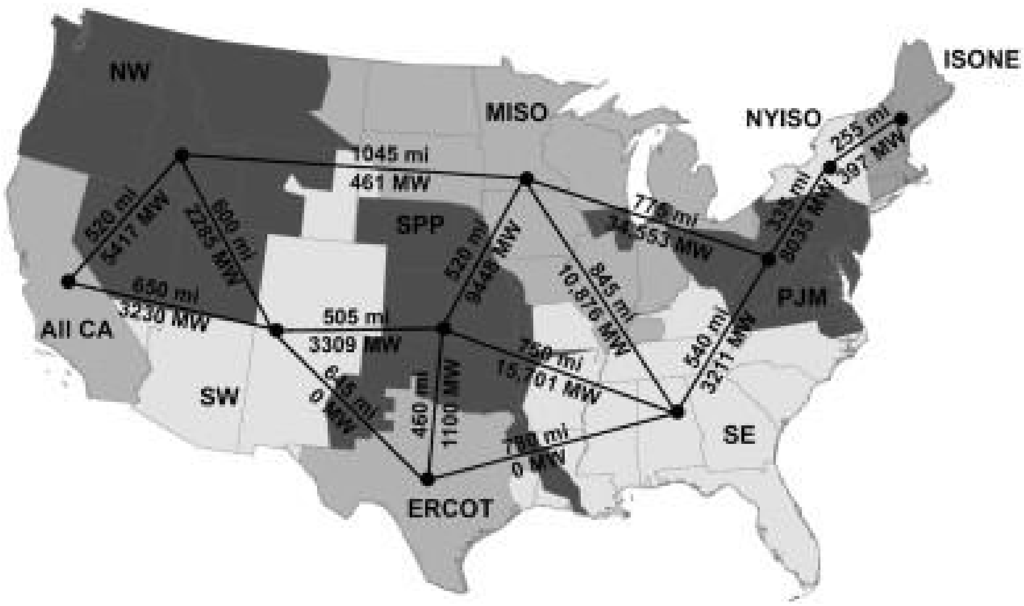

Figure 3.2, Map illustrating the network used in studies of the contiguous USA. Excerpt from [24]

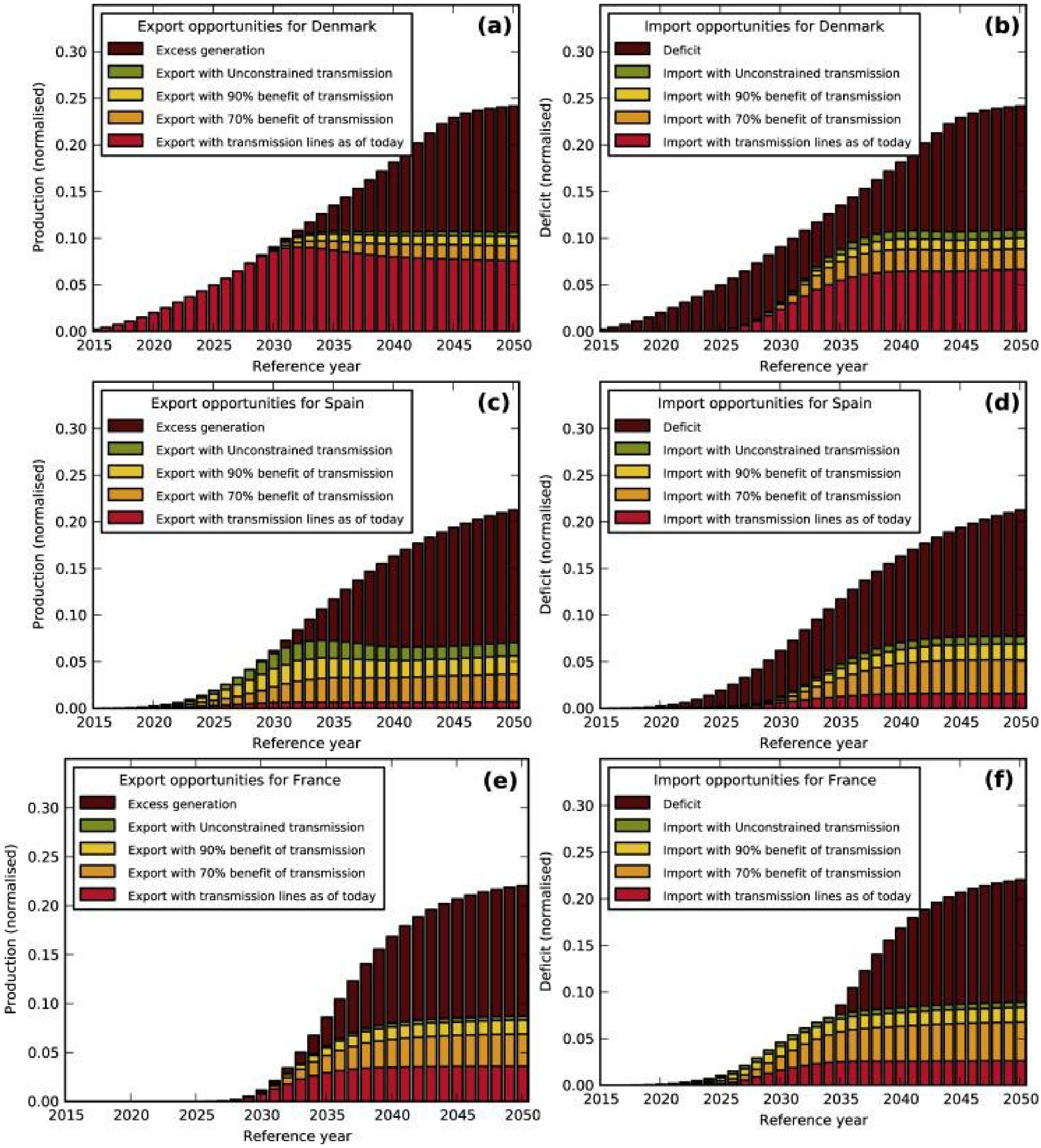

Figure 3.3, Examples of to which extent a selection of countries are able to either export or import surplus renewable energy from other countries in the network. Excerpt from [23]

4 EPlanFlow

As described in the previous chapters, EnergyPLAN is an energy system analysis tool which includes the possibility to model the electricity, heating, cooling, transport and industry sectors and the potential interactions between these sectors. Thus, enabling the analysis of integrated energy systems such as Smart Energy System. EnergyPLAN does this deterministically on an hourly basis, meaning the same inputs always generate the same outputs.

EnergyPLAN models the entire energy system as a fully connected single node, with the option of including an interconnector to an undefined surrounding energy system. This surrounding energy system can be defined with an external hourly market price. Thus, on its own, EnergyPLAN cannot make detailed analysis of the potential influences of specific external energy systems. This is the goal of EPlanFlow, which has been developed as part of the RE-Invest project.

EPlanFlow combine the use of EnergyPLAN and PowerFLOW. As such, EnergyPLAN allows for hourly investigations of sector integration between electricity, heat, cooling, transport and industry by means of EnergyPLAN and by using the PowerFLOW procedure, it allows for the optimisation of electricity flows between multiple energy systems (all modelled in EnergyPLAN). Thus, EPlanFlow allows for the assessment of both cross-sectoral and cross-border perspectives of national energy systems as illustrated by Figure 4.1.

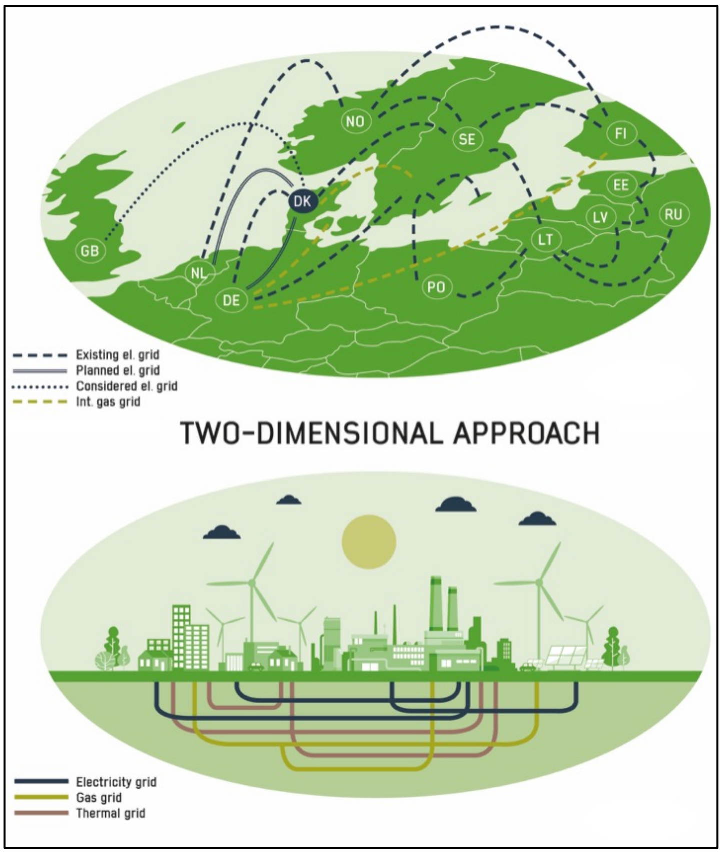

Figure 4.1. Illustration of the two-dimensional approach for the EPlanFlow tool.

To validate and illustrate the use of the model, EPlanFlow has been demonstrated on two principal cases. 1) An interconnection between Denmark and Norway in a current energy system context, and 2) The 14 Heat Roadmap Europe 4 countries based on the year 2015. These test cases are described later in this report.

EPlanFlow can be operated locally by downloading EnergyPLAN (https://energyplan.eu) and Powerflow (https://gitlab.com/anyexingluzk/eplanflow).

EPlanFlow Methodology

The principal methodology of EPlanFlow is to allow for EnergyPLAN to simulate the operation of the energy systems including heating, electricity, transport and industry sectors in the single nodes, where each node represents an energy system. The introduction of the Powerflow module should handle the allocation of the identified potential power flow between each node.
To operationalise this overall concept, EPlanFlow follows the following three steps. The steps are further elaborated in the following sections.

1) EnergyPLAN operates each defined energy system at a number of external market price. For each node, for every hour, a response curve is generated that indicates the potential import/export for each node in every hour at a given price.
2) These response curves are supplied to Powerflow that optimises the flow on the network, to reach a solution with lowest marginal electricity costs. For each node an import/export flow is defined. This step is analogues to how the electricity spot market is settled between different price areas.
3) The import/export flows are fed into EnergyPLAN. EnergyPLAN then simulates each node, so the energy system operates in accordance with the given import/export flow.

For the user to utilise the EPlanFlow tool, the following inputs are needed:

1) An EnergyPLAN scenario file with associated distributions for each node. These EnergyPLAN scenarios should have a well-defined fuel cost section, as EPlanFlow utilises marginal operation to costs to identify the cost response curves.
2) Nodal constraints, if any. This is supplied as a matrix that defines transmission capacities between each node.

Figure 4.2 illustrates the procedure of the EPlanFlow methodology.

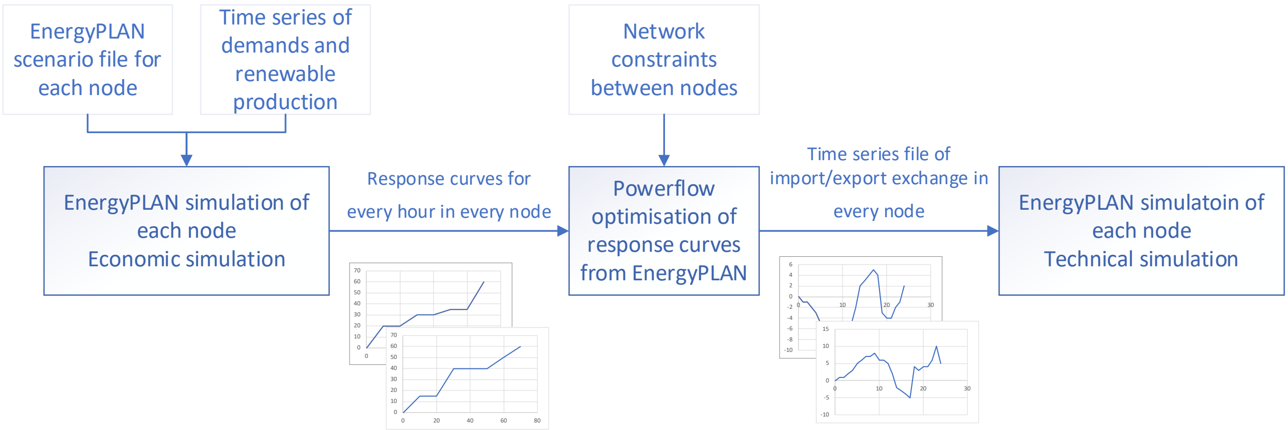

Figure 4.2. Overview of the procedure in the EPlanFlow tool and methodology.

Each step is described in more detail in the following three sub sections.

Step 1: Identifying import/export response curves

The first step in operating the EPlanFlow methodology, is to simulate each nodal energy system based on how it should operate according to different external market prices. Hence the market economic simulation approach is used. Based on fuel prices, efficiencies and variable operation and maintenance costs, EnergyPLAN determines a marginal operation cost for each unit. Then, according to demand, EnergyPLAN will utilise the cheapest units first, ending with the most expensive unit if a demand is still left to be fulfilled. Should the external price be high enough to activate more units and export electricity, EnergyPLAN will allow for export. Should the external price be lower than a local unit, EnergyPLAN will import electricity.

In the first step, EnergyPLAN does not know the external market. Therefore, EnergyPLAN is run 26 times, each time with a constant external price equal to the marginal operation prices of the units in the local. Based on these 26 runs it is possible to construct a nodal response curve, where the import/export balance is plotted against the increase in external market prices. An example of these curves is seen in Figure 4.3.

During these operations, it is assumed that the transmission line capacity is infinite, and there is no price elasticity. This is done since each simulation combined generates the nodal responses.

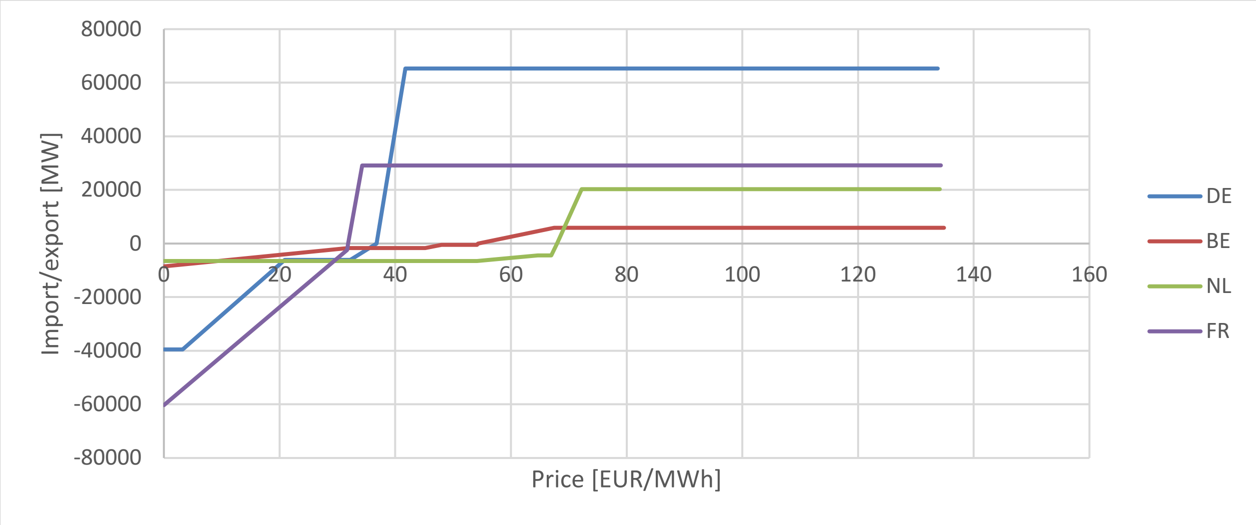

Figure 4.3. Example of import/export price-relation curves

These nodal responses are submitted to Powerflow, which optimizes a balanced power flow between each node.

Step 2: Powerflow optimization of nodal response curves

As aforementioned, EnergyPLAN is able to determine the nodal response, denoted by $R_n(t)$, at a given price $S_n(t)$ on the inter-connector to an external market.

$$R_n(t) = f^{-1}\big(S_n(t)\big) \geq f^{-1}(S_n(t) = 0) = R_n^0(t) \tag{1}$$

The nodal response implies import or export plus potential curtailment. On the one hand, $R_n(t)<0$ means that the node would prefer to import electricity instead of using its own expensive generators at time t. On the other hand, $R_n(t)>0$ stands for exporting electricity to the external market, or curtailing if the transmission line is limited. When the price is 0 Eur/MWh at the inter-connector, the nodal response suggests the mismatch between local demand and renewable generation at node n, or the nodal residual demand, denoted by $R^0{}_n(t)$, which is also the lower bound of $R_n(t)$.

If we define the injection $P_n(t)$ as the net import or export and curtailment as $C_n(t)$, the nodal response can be expressed as,

$$R_n(t) = P_n(t) + C_n(t), C_n(t) \geq 0 \tag{2}$$

The nodal marginal cost is determined by the mismatch between residual demand and flow between external market according to varying price at the inter-connector, thus the sum of nodal marginal costs forms a power flow optimization

$$\underset{R_n}{minimize} \sum_n (R_n - R_n^0) \cdot f(R_n) + \epsilon \sum_l F_l^2$$
$$R_n(t) = P_n(t) + C_n(t), R_n(t) \geq R_n^0(t), C_n \geq 0, \forall n \tag{3}$$
$$P_n = \sum_n K_{ln} F_l, \bar{f}_l \leq F_l \leq f_l, \forall n, l$$

The overall goal is to minimize the total system cost, which implies maximization of the renewable usage and reduction of back-up generation throughout the network. To avoid transferring curtailment through the interconnector instead of curtailing locally, an extra cost is added to the total nodal costs weighted by Є, ensuring that

$$(R_n - R_n^0) \cdot f(R_n) \gg \epsilon \sum_l F_l^2 \tag{4}$$

Apart from the constraints introduced by Equation 1 and 2, the optimization is subject to two more constraints, i.e., a flow-injection relation and lower/upper bounds for the transmission network. Under the assumption of DC power flow, the flow-injection relation guarantees the Kirchhoff's first law, ensuring the global energy is balanced.

Step 3: EnergyPLAN simulation of each energy system

The balanced power flow between each node is translated into an import/export file for each node (for instance each country). These files determine the amount of electricity each node either imports or exports in every hour. Figure 4.4 shows an example for the first 24 hours in the year.

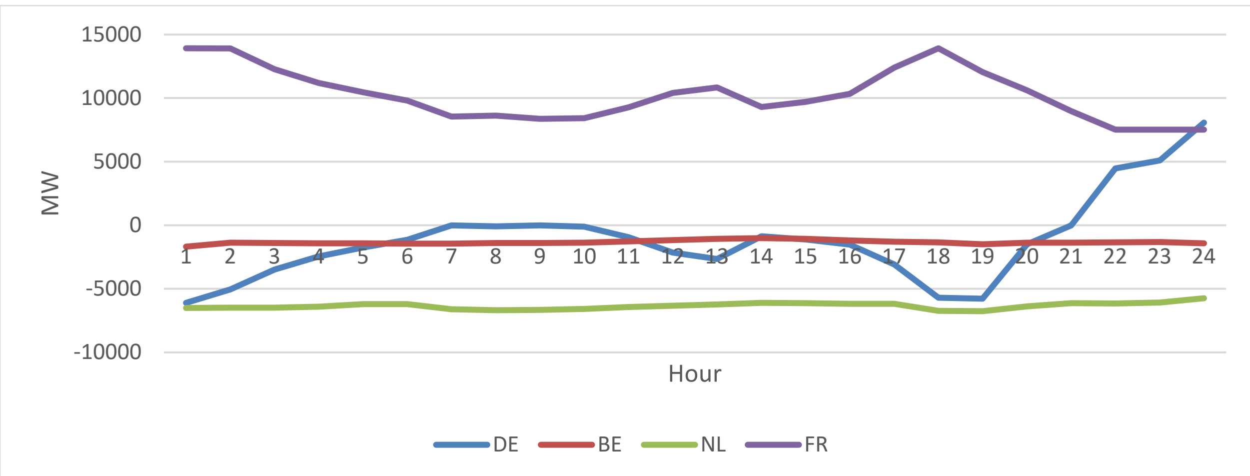

Figure 4.4. Example of hourly import/export curves from individual countries.

The import/export balance for each country are then defined in EnergyPLAN as a fixed import/export that each country has to fulfil as an obligation to obtain the least cost flow between countries.

To determine the operation of the energy system after determining the import/export obligation, EnergyPLAN simulates each node using the technical simulation strategy. The technical simulation strategy operates the energy system with the goal of minimising fuel consumption. In EPlanFlow, it does this with the intention of balancing both heating and electricity demands. This means that for instance a combined heat and power plant will operate according to both heat and electricity demands with the objective of not over producing electricity that would have to be curtailed.

The technical simulation strategy is based on a merit order, in which variable renewable energy will be used first, both in the electricity and heating sector. Then, cross sectoral technologies will be used to achieve the lowest fuel consumption. This means that combined heat and power plants, heat pumps, and potentially electric boilers for district heating will be operating to utilise the most variable renewable energy. This operation can be enhanced by implementing a thermal storage. Finally, power plants and fuel only boilers will be utilised to fulfil any remaining demand. By implementing electricity storage either as stand-alone storages or part of electric vehicles, EnergyPLAN will try and minimise power plant operation to reduce fuel consumption. The user can prioritise the use of electricity storages. EnergyPLAN will in this in every hour use them based on this prioritisation.

From the technical simulation, a result for each node is fed back to the user, showing the operation of each energy system taking the interconnection into account.

Testing the EPlanFlow methodology

To test the EPlanFlow methodology, the study uses two cases. The three cases are 1) a simple interconnection between two countries (Denmark and Norway), and 2) the 14 Heat Roadmap Europe countries with their current system configuarion (2015 models).

Together these cases illustrate some of the potential consequences of using the EPlanFlow compared to simulating the energy systems without considering interconnection. The energy system scenarios used for the test cases are all documented else where as parts of other studies. The goal here is therefore not to validate those models, but simply illustrate the application of the EPlanFlow methodology.

Simple two-country test case (Norway-Denmark)

To show the operation of the interconnector between two countries, an example case between Norway and Denmark was set up. Both systems use a 2015 reference energy system. The Norway model is documented in [1] and the Denmark model is documented here [2]. To simulate the systems, the same fuel prices and marginal costs are assumed. These are both based on the Danish model. The transmission capacity is 1600 MW, which includes all four interconnectors between Denmark and Norway.

For the case, the scenarios before interconnection and after interconnection are shown in Table 4.1. In Figure 4.5 the interconnection between the two countries is shown. For comparison, the actual scheduled flow on the interconnector for 2015 is shown as well.

Table 4.1. Main results for the two-country case of Denmark-Norway with and without interconnection.

	Without interconnection	With interconnection
Primary energy [TWh]	746.04	736.9
CO2 [Mton]	137.51	135.4
Curtailment [TWh]	11.09	6.2

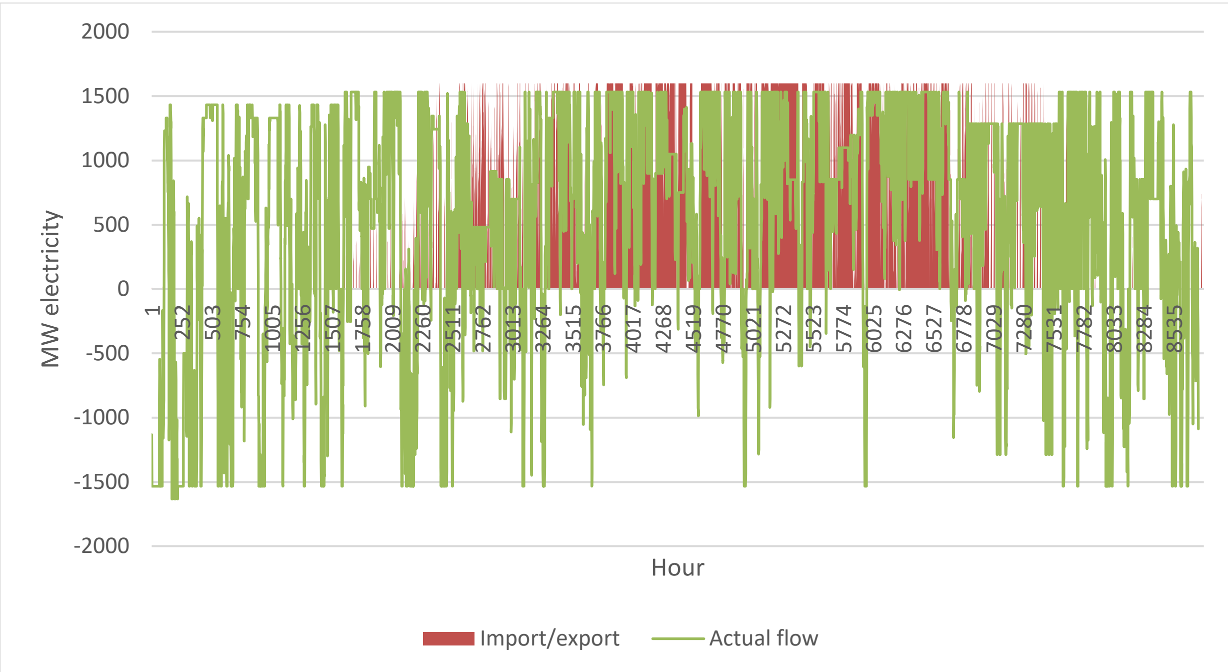

Figure 4.5. Hourly exchange results for the two-country case of Denmark-Norway with and without interconnection.

14 countries 2015 baselines based on Heat Roadmap Europe

The second test case are the 2015 baseline scenario in the 14 countries investigated Heat Roadmap Europe 4 study. The purpose of this test case is to assess the performance of the tool with more countries and a bigger electricity network. The basis for these results is the following 14 countries all with their current energy system layout: Austria, Belgium, Czechia, Germany, Estonia, Finland, France, Hungary, Italy, Netherlands, Poland, Romania, Sweden and United Kingdom. All the countries have a 2015 EnergyPLAN scenario documented in the specific country reports. To conduct the analysis the following changes have been made to all scenarios:

- The current exchange between countries have been set to zero to have the tool identify the exchange.
- Marginal operation costs of turbines in pumped hydro have been set to zero to speed up calculation time.

Table 4.2 shows the transmission lines capacity between each country. These are used as constraints for the flow of electricity through the network.

Table 4.2. Capacity on interconnectors between countries. ENTSO-E data, in the transparency platform [3].

	AT	BE	CZ	DE	ES	FI	FR	HU	IT	NL	PL	RO	SE	UK
AT	-	0	1908	2519	0	0	0	1474	285	0	0	0	0	0
BE	0	-	0	0	0	0	3400	0	0	2400	0	0	0	0
CZ	1908	0	-	2745	0	0	0	0	0	0	1881	0	0	0
DE	2519	0	2745	-	0	0	3200	0	0	3850	2424	0	610	0
ES	0	0	0	0	-	0	2997	0	0	0	0	0	0	0
FI	0	0	0	0	0	-	0	0	0	0	0	0	2050	0
FR	0	3400	0	3200	2997	0	-	0	2324	0	0	0	0	2000
HU	1474	0	0	0	0	0	0	-	0	0	0	1102	0	0
IT	285	0	0	0	0	0	2324	0	-	0	0	0	0	0
NL	0	2400	0	3850	0	0	0	0	0	-	0	0	0	1000
PL	0	0	1881	2424	0	0	0	0	0	0	-	0	600	0
RO	0	0	0	0	0	0	0	1102	0	0	0	-	0	0
SE	0	0	0	610	0	2050	0	0	0	0	600	0	-	0
UK	0	0	0	0	0	0	2000	0	0	1000	0	0	0	-

To compare the performance of EPlanFlow, the results are compared to running each country as island mode, without any interconnection. The comparison between the two scenarios can be seen in Table 4.3, that illustrates that with EPlanFlow, it is possible to lower the primary energy of all the countries together, thus reducing CO_2 emissions and the variable costs of the system. From Figure 4.6, the primary energy is further compared, which illustrates that by exchanging electricity the natural gas consumption drops, while the coal consumption and renewable energy production increases. While the differences are not great, it is possible to see from Figure 4.7, the consequence in each country. Here it can be identified that energy production in certain countries do increase, while other countries have a decreased energy production. Overall to achieve a more cost-efficient solution.

Table 4.3. Comparison of primary energy, CO2 emissions and curtailment in the HRE14 2015 scenario.

	Without interconnection	**With interconnection**
Primary energy [TWh]	16229	16141
CO2 [Mton]	3069	3063
Curtailment [TWh]	51.6	0.3
Variable costs incl. fuel [M€]	486732	481586

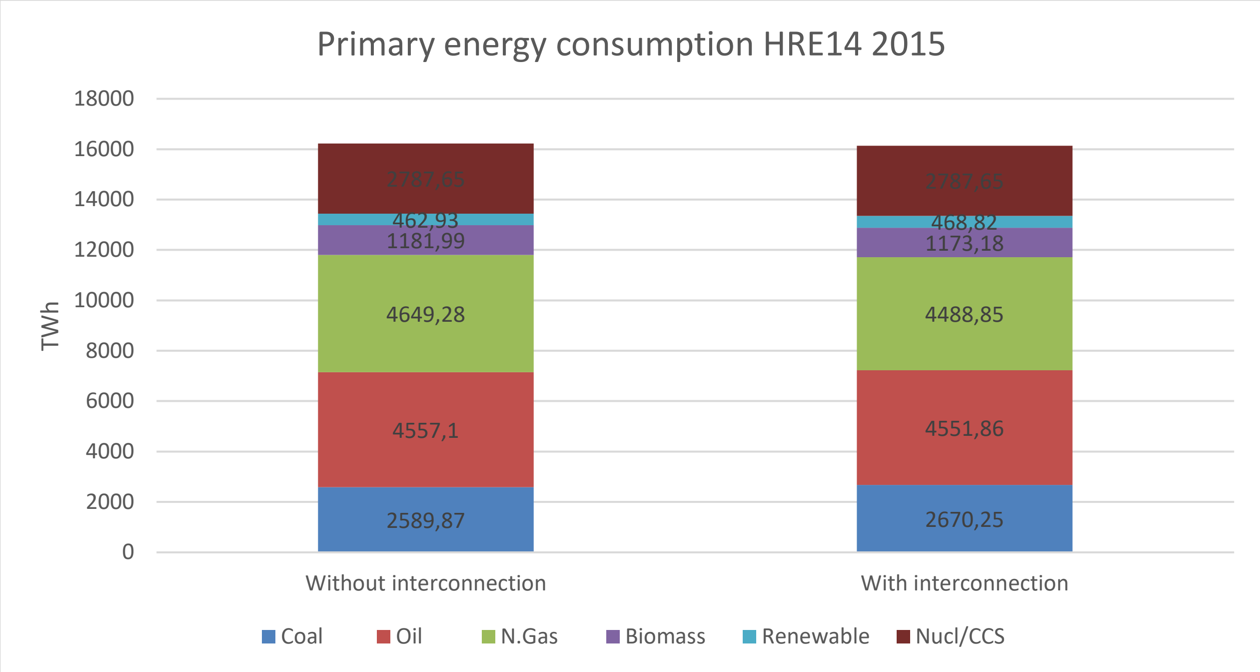

Figure 4.6. Primary energy results as a whole of the 14 country HRE case

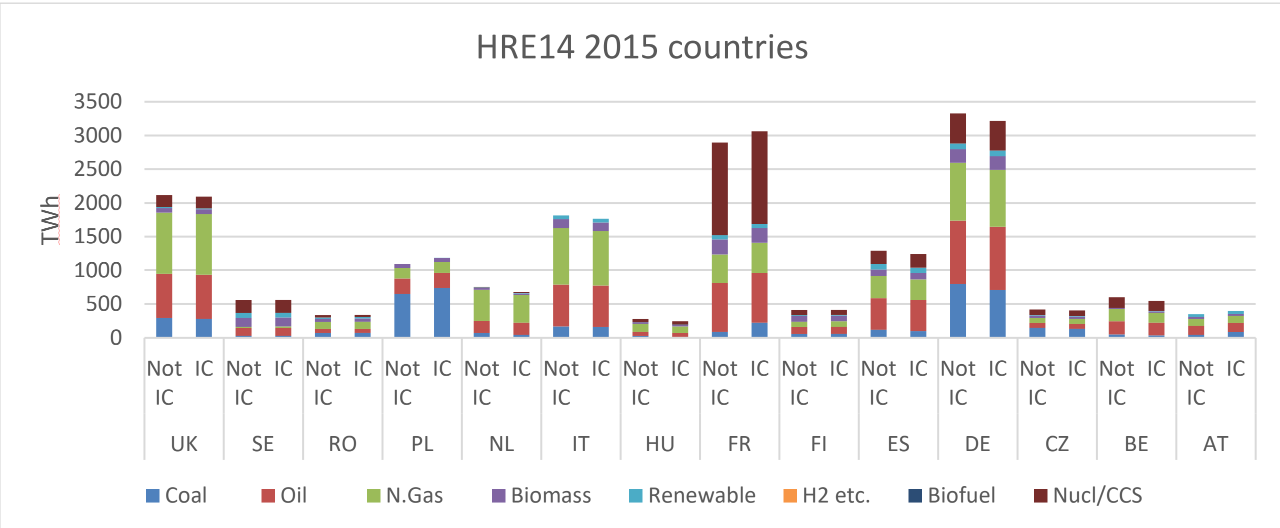

Figure 4.7. Primary energy results of each of the 14 countries in the HRE case.

5 Python for power system analysis (pypsa-eur-sec)

PyPSA-Eur-Sec is an open model dataset of the European energy system at the transmission network level that covers the full ENTSO-E area. PyPSA-Eur-Sec builds on the electricity generation and transmission model PyPSA-Eur to add demand and supply for the following sectors: transport, space and water heating, biomass, industry and industrial feedstocks (see Figure 5.1). This completes the energy system and includes all greenhouse gas emitters except waste management, agriculture, forestry and land use. As such PyPSA-Eur-Sec combines extensive sector coupling (vertical integration) with interconnection between energy systems, e.g., in different countries (horizontal integration) in one unified framework.

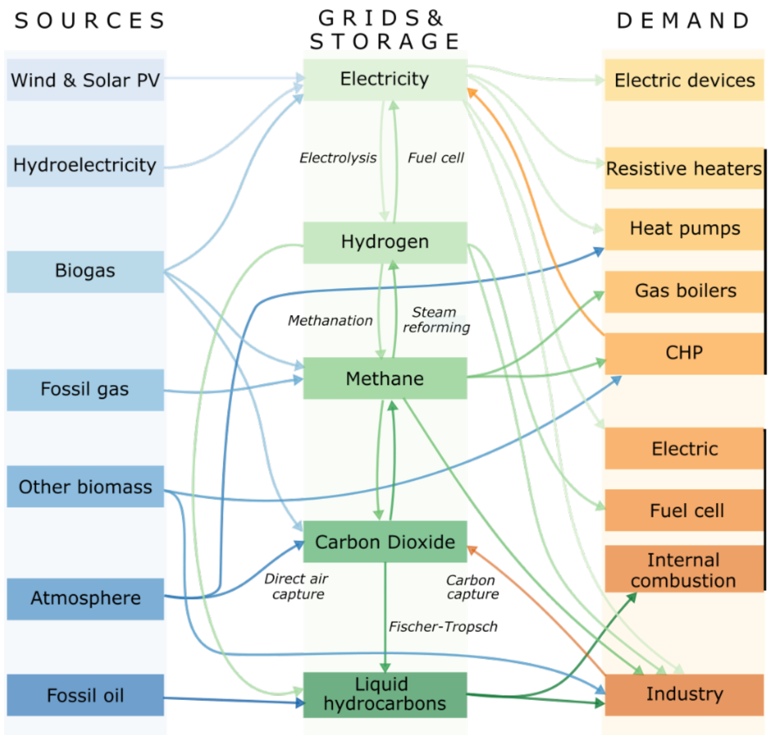

Figure 5.1 Energy and material flows in the PyPSA-Eur-Sec model. Source: https://pypsa-eur-sec.readthedocs.io

PyPSA-Eur-Sec is developed as collaborative effort among several universities and research institutions. Aarhus University is contributing to this effort and the Reinvest related contributions are described below. The lead developer of PyPSA-Eur-Sec is Prof. Dr. Tom Brown from Technische Universität Berlin. He was formerly associated with the international Reinvest partner Frankfurt Institute for Advanced Studies (FIAS), where the work on PyPSA-Eur-Sec was initiated.

Description of the PyPSA-Eur-Sec methodology

The model employs a combined investment and dispatch optimization to identify cost optimal solutions to the European energy system. It is a so-called techno-economic optimization. This means that the technical limitations of operating the energy infrastructure are formulated as constraints for the model which seeks to identify the cheapest way of providing the required energy services, i.e., the final demand for electricity, heating, transportation, fuels, feedstocks etc. Other political constrains, such as the allowed CO_2 emissions, land use for renewable generators and the amount of over-head transmission cables are also typically included. The model assumes long-term market equilibrium as well as perfect competition and foresight.

The PyPSA-Eur-Sec framework defines a model spanning 33 ENTSO-E (European Network of Transmission System Operators for Electricity) member countries, i.e. the model includes EU-27 without Cyprus and Malta, along with Norway, Switzerland, Serbia, Bosnia-Herzegovina, Albania, Montenegro, Macedonia and, United Kingdom. Timeseries of weather data with a resolution of about 40x40 km^2 for all of Europe and a conversion to renewable energy generation is included in the framework. Demand data and geo-referenced energy system infrastructure data is sourced from public sources such as ENTSO-E's transparency platform.

A PyPSA-Eur-Sec typically includes hourly simulation of all the individual countries (or regions) of interest. However, the time resolution is sometimes reduced to increase simulation speed. It may also be reduced to, e.g., 15 minutes if a certain study requires it.

Typical use-cases of the model includes:

- Green-field scenarios are cases where an energy system is constructed and operated to full-fill the energy demands without considering existing infrastructure. This type of scenario is typically used to explore highly decarbonized far-future scenarios. E.g. for 2050.
- Brown-field scenarios are used when the existing energy infrastructure has to be considered, e.g. for near-future scenarios such as 2030. Here, new investments are made if they either are i) economically favorable even if sunk cost for past investments must still be paid off, or ii) if the investments are required to make the energy system fulfill, e.g., tighter CO2 emission constraints that would not be possible to meet using the existing infrastructure.
- Myopic transition path scenarios are cases where a string of Brown-field scenarios are tied together to form an energy transition. E.g. a green transition of Europe in the timespan 2020 to 2050 [https://www.nature.com/articles/s41467-020-20015-4].
- Dispatch optimization where no new investments are done. Here, the user of the model decides on a particular energy scenario and simulates the hourly dispatch of all the generators. This mode is similar to how tools like EnergyPLAN operates and can provide information on fuel-use etc. Note that dispatch is also simulated as part of the other cases mentioned above.

RE-invest contributions to PyPSA-Eur-Sec

As part of Reinvest, Aarhus University has contributed to PyPSA-Eur-Sec with the following model features:

- The capability of performing studies of the European energy transition (2020-2050) using so-called Myopic pathways, i.e., pathways where changes to the energy system takes into account previously installed power plants and other energy infrastructure. This update also includes a geo-referenced database of existing energy infrastructure with associated technical lifetimes already installed or planned in the European countries. For more information see [https://www.nature.com/articles/s41467-020-20015-4] and the associated supporting material.

- The industrial sector with associated demands for both energy and feedstock was added. This includes adding technologies that can be used to decarbonize the industrial sector, e.g., carbon free production of high, medium and low temperature heat and various power-to-X technologies. Furthermore, a geo-referenced database of existing industrial demands was added for all European countries. This work is described in more detail in [https://arxiv.org/abs/2109.09563].
- Initial work on new ways of using the model in combination with high-performance computing has been investigated and prototyped. This work focuses on so-called near-optimal solutions, i.e., energy systems that may be considered alternatives to the single-point scenarios that are typically presented. Typically, between 10,000 to 1,000,000 scenarios with different properties can be explored using these techniques. The initial work is described in [https://doi.org/10.1016/j.energy.2021.121294] and [https://arxiv.org/abs/2112.07247].

Other Reinvest studies have required significant model modifications that were relevant for the study in question, but not necessarily for the general model development. These studies include:

- Detailed analysis of the interaction between model solutions and CO2 price. See [https://doi.org/10.1016/j.apenergy.2018.12.016] and [https://doi.org/10.1016/j.adapen.2021.100012].
- Analysis of the role of storage technologies throughout the decarbonisation of the sector-coupled European energy system. See [https://doi.org/10.1016/j.enconman.2019.111977].
- Analysis of the interaction between climate change and the European energy system. See [https://doi.org/10.1016/j.isci.2021.102999] and [https://doi.org/10.1016/j.apenergy.2020.114500].

6 Perspectives

In the transition towards 100% renewable energy systems [4] it is necessary to identify solutions that are feasible under a number of different circumstances. For instance, the uncertainty of fuel and electricity prices in the future needs to be taken into account, to not arrive at solutions that might be infeasible in many scenarios ([5],[6]). Other examples are the uncertainty in energy policies ([7],[8]) and emerging technologies ([9],[10]) might also affect the choices to make when transitioning to 100% renewable energy systems.

Energy system models are crucial to plan energy transition pathways and understand their impacts. A vast range of energy system modelling tools is available, providing modelling practitioners, planners, and decision-makers with multiple alternatives to represent the energy system according to different technical and methodological considerations ([11],[12]). A comprehensive overview of releavnt tools are given in the paper in Appendix 3. The paper identify current trends in the field of energy system modelling. First, we survey previous review studies, identifying their distinct focus areas and review methodologies. Second, we gather information about 54 energy system modelling tools directly from model developers and users. Unlike previous questionnaire-based studies solely focusing on technical descriptions, we include application aspects of the modelling tools, such as perceived policy-relevance, user accessibility, and model linkages. We find that, to assess the possible applications and to build a common understanding of the capabilities of these modelling tools, it is necessary to engage in dialogue with developers and users. We identify three main trends of increasing modelling of cross-sectoral synergies, growing focus on open access, and improved temporal detail to deal with planning future scenarios with high levels of variable renewable energy sources.

First, it is challenging to agree on a specific vocabulary that all tool developers reach consensus in the same way. For instance, multiple studies have focused on proposing new classification schemes and to categorize different modelling approaches or methodologies. While some of these categories are unambiguous, other descriptive labels assigned to tools might fall within an overlapping spectrum which is harder to define.

Second, modelling tools rely on exogenous demand datasets. Yet, there is still a lack of accessible data for modellers to understand projected and uncertain changes in demand, and to model high spatial and temporal resolution systems. Where available, standard input datasets are relied upon in energy system models, irrespective of their research focus, representing the frontier of data availability. The modelling of cross-sectoral decarbonization will open new challenges, including the integration of sectors for which ever more data is required and the need to specify demand that is matched to the weather conditions influencing the increasing prevalence of variable renewable generation. For this, coupling with demand modelling tools is necessary, but nascent.

Third, when investigating many tools that can do different things in terms of modelling energy transitions, it becomes clear that it is impossible to build a tool that can do it all. Most of the tools have been developed to fulfil a specific task within a defined scope or according to specific user-needs. It might have received updates and an increased number of capabilities, but the underlying general architecture, technology, and terminology remains the same. We would argue that efforts should be targeted towards linking these different tools to each other, utilizing the many capabilities that are already present. Individual tool development is obviously still required and necessary, but there is a trade-off between the details and granularity of a model and computational resources.

Finally, the transparency and policy-relevant applications of energy system modelling tools should be put into a real-world perspective. For example, the complexity of linking modelling tools should not jeopardize the interpretability of the underlying modelling assumptions and outcomes, as this would detract modellers and output consumers (e.g. decision/policy-makers). In line with this, model development should be conducted in such a way that it leads to actionable research, and in which policy and decision support takes center stage. In this regard, further research could be conducted to identify how user-needs and policy-making processes mark the development of modelling tools actually used for decision-support, and which features these have and need. However, it seems infeasible to make a tool beyond all tools, with no limitations and 100% accuracy, as the computational time will be immense. As Goderbauer, Comis and Williamowski argues, the design of decentralised energy systems is an NP-hard problem [13]. Thus, the proposal is to that for future energy planning and energy modelling the goal should be to enable tools with different capabilities to work together.

As described in this report, RE-invest makes use of a range of different tools, each with their own strength and weaknesses. These tools have been developed as part of the project to allow us to perform a two-dimensional approach to energy system analysis [14].

7 References

[1] Zinck J. Contextual Aspects of Smart City Energy Systems Analysis n.d.

[2] Lund H. EnergyPLAN Documentation Version 12. Aalborg, Denmark: 2015.

[3] Lund H, Hvelplund F, Mathiesen BV, Østergaard PA, Christensen P, Connolly D, et al. Coherent Energy and Environmental System Analysis. 2011.

[4] Mathiesen BV, 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. Aalborg, Denmark: 2015.

[5] Xiong W, Wang Y, Mathiesen BV, Lund H, Zhang X. Heat roadmap China: New heat strategy to reduce energy consumption towards 2030. Energy 2015;81:274–85. doi:http://dx.doi.org/10.1016/j.energy.2014.12.039.

[6] Connolly D, Lund H, Mathiesen BV, Leahy M. The first step towards a 100% renewable energy-system for Ireland. Appl Energy 2011;88:502–7. doi:10.1016/j.apenergy.2010.03.006.

[7] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100% renewable energy system. Int J Sustain Energy Plan Manag 2014;1:7–28. doi:doi.org/10.5278/ijsepm.2014.1.2.

[8] Mathiesen, Brian Vad; Lund, Rasmus Søgaard; Connolly, David; Ridjan, Iva; Nielsen S. Copenhagen Energy Vision 2050: A sustainable vision for bringing a capital to 100% renewable energy. Copenhagen, Denmark: 2015.

[9] Lund H, Østergaard PA. Sustainable Towns: The Case of Frederikshavn – 100% Renewable Energy. Sustain. Communities, New York, NY: Springer New York; 2010, p. 155–68. doi:10.1007/978-1-4419-0219-1_11.

[10] Østergaard PA, Mathiesen BV, Möller B, Lund H. A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. Energy 2010;35:4892–901. doi:10.1016/j.energy.2010.08.041.

[11] Østergaard PA, Lund H. A renewable energy system in Frederikshavn using low-temperature geothermal energy for district heating. Appl Energy 2011;88:479–87. doi:10.1016/j.apenergy.2010.03.018.

[12] Waenn A, Connolly D, Gallachóir BÓ. Investigating 100% renewable energy supply at regional level using scenario analysis. Int J Sustain Energy Plan Manag 2014;3:21–32.

[13] Hagos DA, Gebremedhin A, Zethraeus B. Towards a flexible energy system – A case study

for Inland Norway. Appl Energy 2014;130:41–50. doi:10.1016/j.apenergy.2014.05.022.

[14] Brandoni C, Arteconi A, Ciriachi G, Polonara F. Assessing the impact of micro-generation technologies on local sustainability. Energy Convers Manag 2014;87:1281– 90. doi:10.1016/j.enconman.2014.04.070.

[15] Lund H. Excess electricity diagrams and the integration of renewable energy. Int J Sustain Energy 2003;23:149–56. doi:10.1080/01425910412331290797.

[16] 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.

[17] Lund H, Thellufsen JZ, Mathiesen BV, Østergaard PA, Lund R, Ridjan I, et al. EnergyPLAN - Documentation Version 13. 2017.

[18] Thellufsen JZ. MultiNode v1 for EnergyPLAN Documentation. 2016.

[19] Thellufsen JZ. Smart Cities and National Energy Systems. Proc 10th Dubrovnik Conf Sustain Dev Energy, Water Environ Syst 2015.

[20] Thellufsen JZ, Lund H. Roles of local and national energy systems in the integration of renewable energy. Appl Energy 2016;183. doi:10.1016/j.apenergy.2016.09.005.

[21] Thellufsen JZ, Lund H. Cross-border versus cross-sector interconnectivity in Renewable Energy Systems. Energy 2017. doi:10.1016/j.energy.2017.02.112.

[22] Rodríguez RA, Becker S, Andresen GB, Heide D, Greiner M. Transmission needs across a fully renewable European power system. Renew Energy 2014;63:467–76. doi:10.1016/J.RENENE.2013.10.005.

[23] Becker S, Rodriguez R a., Andresen GB, Schramm S, Greiner M. Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply. Energy 2014;64:404–18. doi:10.1016/j.energy.2013.10.010.

[24] Becker S, Frew BA, Andresen GB, Zeyer T, Schramm S, Greiner M, et al. Features of a fully renewable US electricity system: Optimized mixes of wind and solar PV and transmission grid extensions. Energy 2014;72:443–58. doi:10.1016/j.energy.2014.05.067.

[25] Schäfer M, Bugge Siggaard S, Zhu K, Risager Poulsen C, Greiner M. Scaling of transmission capacities in coarse-grained renewable electricity networks. EPL (Europhysics Lett 2017;119:38004. doi:10.1209/0295-5075/119/38004.

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EnergyPLAN – Advanced analysis of smart energy systems

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ABSTRACT

EnergyPLAN is an energy system analysis tool created for the study and research in the design of future sustainable energy solutions with a special focus on energy systems with high shares of renewable energy sources. It has been under development since 1999 and has formed the basis for a substantial number of PhD theses and several hundreds of research papers. EnergyPLAN is designed to exploit the synergies enabled from including the whole energy system, as expressed in the smart energy system concept. Thus, with EnergyPLAN, the user can take a holistic approach focusing on the analysis of the cross-sectoral interaction. Traditionally disparate demand sectors, such as buildings, industry and transport, are linked with supply technologies through electricity, gas, district heating and cooling grids. In this way, EnergyPLAN enables the analysis of the conversion of renewable electricity into other energy carriers, such as heat, hydrogen, green gases and electrofuels, as well as the implementation of energy efficiency improvements and energy conservation. This article describes the overall structure of EnergyPLAN and the essential algorithms and computational structure.

1. Introduction

To minimise carbon dioxide emissions and thereby meet the Paris Agreement targets [1], energy systems must transition away from being predominantly fossil fuel-based to being based on renewable energy sources (RES). This is a transition away from freely dispatchable production units towards units employing resources that are frequently of a fluctuating and possibly use-it-or-lose-it nature. The robust planning and decision-making of such a transition and the study of the implications of different choices call for advanced tools to handle the increasingly complex nature of the energy system.

Currently, a wide range of computer tools allow users to model and analyse energy systems at the national and regional levels to help design transition pathways [2]. These model are often very different from one another [3], and therefore decision makers and researchers should choose the most suitable energy system modelling tool depending on the specific purpose and objectives of their analysis [4].

The three most common methodological approaches to energy system modelling are optimisation, simulation and equilibrium tools or models. Optimisation tools include endogenous system design optimisation; simulation tools simulate exogenously defined energy systems, and equilibrium tools include a larger econometric model of the society.

Each approach has strengths as indicated by the main characteristic but also weaknesses. Thus, while optimisation tools are dominant within energy systems analysis [5], their complexity can cause difficulties in interpreting the results and can influence their accuracy [6]. In their systematic analysis investigating power system optimisation models, Priesmann and co-authors even found that the higher model complexity does not guarantee higher accuracy [7].

Likewise, it has been highlighted that uncertainties and variations in inputs for simulation models for low-carbon energy systems can have significant impact on the energy system performance [8].

Lastly, top-down equilibrium models have shown significant sensitivity when analysing the integration of RES and potentially need to be enhanced or be used as a part of integrated mixed models [9].

One example of a widely used simulation tool is the freeware EnergyPLAN. This is one of the most commonly used tools for the evaluation of energy systems with high shares of RES [10]. Some authors consider it the most suitable tool to identify a feasible RES

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Abbreviations

BEV	Battery Electric Vehicle
CAES	Compressed Air Energy Storage
CEEP	Critical Excess Electricity Production
CSP	Concentrated Solar Power
EEEP	Exportable Excess Electricity Production
HP	Heat Pump
PP	Power Plant
PV	Photo Voltaic
PtX	Power-to-X
RES	Renewable Energy Source
V2G	Vehicle to Grid
VRES	Variable Renewable Energy Source

integration within an energy system, e.g., in China [11], Denmark [12] and Ireland [13].

Different aspects of EnergyPLAN have been described and communicated in the scientific literature as integrated sections of the many published articles employing it. However, due to the nature and complexity of EnergyPLAN, the individual papers have found neither the space nor the necessity to describe the overall structure and details of the tool, but have typically focused on the parts pertinent to the analyses at hand.

For a simulation tool as widely applied as EnergyPLAN, it is a significant gap in the scientific literature that there is no standard reference article describing it. Therefore, the aim of this paper is to provide this description in the hope that it will ease the writing and publication of studies applying EnergyPLAN in the future. More specifically, the goal of the paper is to demonstrate the core principles of EnergyPLAN and to document how it identifies the optimal operation of the units of the energy systems. This is based on both technical and economic simulation strategies.

The paper first describes the purpose and guiding principles behind the tool along with general characteristics; then it relates the tool to the context and approach of smart energy systems. Subsequently, the structure and essential equations and procedures of its simulation approach are documented and, finally, the main conclusions are drawn.

2. General characteristics and applications

This section presents the main purpose and characteristics of EnergyPLAN along with an overview of typical applications.

2.1. Purpose of EnergyPLAN

The main purpose of EnergyPLAN is to assist in the design of national energy planning strategies with technical and economic analyses of the consequences of different choices and investments. As further explained in Ref. [14], the purpose of EnergyPLAN is not to provide the basis for prescribing or predicting the future energy system, but rather to form a basis for an informed, transparent and conscious deliberation of potential development pathways for the energy system.

While the main motive for the development of EnergyPLAN was the national-scale energy systems, many other geographical scales have set the frame for EnergyPLAN analyses [10].

2.2. Guiding principles

The overarching guiding principle for the development and use of EnergyPLAN is the establishment of alternatives; it was important to create a tool which would enable the consistent comparison of various alternative development strategies of the energy system. This is founded on the idea of *choice* [15], where an energy transition pathway is developed in a process with a conscious and transparent evaluation of the consequences of alternative strategies.

As a result, EnergyPLAN is developed with the capability for the user to consider alternative energy system combinations in mind, and as a consequence, also with speed, user friendliness and ease of implementing changes in mind.

Specifically regarding the establishment of scenarios, the guiding principle resulted in the following objectives [16]:

- **Character of technological change**

EnergyPLAN should enable the user to analyse the type of technological change which is required when transitioning to 100% renewable energy systems. To accommodate this, EnergyPLAN includes a variety of new technologies such as wave power, district heating and cooling, tidal power, concentrated solar power, thermal storage, biogas production, biomass gasification, and various Power-to-X technologies.

- **Multiple alternatives**

EnergyPLAN should enable the transparent and consistent comparison of multiple transition alternatives. Thus, EnergyPLAN is designed to quantify the impacts of many different alternatives, instead of producing just a single optimal solution through endogenous energy system design optimisation. It is often difficult to define one ideal metric to measure the benefits of energy systems [17]. For example, an inexpensive energy system that relies on a high proportion of energy imports may be less desirable than a more expensive energy system that utilises primarily domestic resources. Therefore, if an energy system is designed based on the optimal solution that produces the lowest cost, then other issues may be overlooked. Furthermore, long-term projections of, e.g., energy prices have shown to be prone to large uncertainties [18], making endogenous system designs equally uncertain. A scenario simulation can be completed in less than 10 s in EnergyPLAN with the implication that users can demonstrate the impacts of various alternatives in a relatively short period of time.

- **Free of institutional inertia**

Alternatives designed and analysed in EnergyPLAN should not be limited by existing institutional and market frameworks. This is particularly an issue within the electricity system, where some models are constructed based on the design of the day-ahead markets in current electricity markets. However, in the future energy system, the current design of electricity markets may not be suitable for 100% renewable energy systems, especially since renewable electricity technologies often have zero marginal production costs. To overcome this, EnergyPLAN has various operation strategies, including a market simulation strategy, which is based on the design of existing European electricity markets, and a technical simulation strategy. The technical simulation strategy is independent of market designs and temporal market prices and operates the energy system in order to minimise the consumption of fuels.

Under these objectives, EnergyPLAN has been developed and expanded on a continuous basis since 1999 by the Sustainable Energy Planning Research Group at Aalborg University.

2.3. Geographical scope and resolution

EnergyPLAN is primarily designed for national energy system analysis, and thus has been used to investigate energy systems and energy transitions in countries such as Germany [19], Denmark [20,21], Ireland [13], Norway [22], Hungary [23], Romania [24], Portugal [25], Singapore [26], Hong Kong [27] Jordan [28], Chile [29] and China [30]. However, to a large extent, it has also been applied to other geographical settings, such as islands like Gran Canaria [31], Pico and Faial [32] and Favignana Island [33] and cities like Aalborg [34] and Bozen-Bolzano [35]. Regions like Beijing-Hebei-Tianjin [36] and Inland Norway [37] as well as continents like Europe [38] have also been focal points of analyses.

Within the system (country, region or island) described in the model, EnergyPLAN simulates the electricity and the gas supplies with no spatial representation of supply and demand. The connection to the outside world is modelled as a single transmission line. However, by use of add-ons, one can build individual models of a number of countries or regions and analyse the electric transmission lines between them.

2.4. Type of applications

Besides forming the modelling basis for energy transition strategies, EnergyPLAN is also frequently applied in analyses covering the role of certain technologies or technological systems. This includes, but is not limited to: the role of Compressed Energy Storage [39] and hydro power in the energy system [22]; the role of biogas and biomass in the energy system [40,41]; the role of district heating [30,42] as well as heating infrastructures [43] in the energy system; heat pumps [44] and V2G [45] in the energy system; the energy system value of flexible electricity demands [46], future energy market prices [21,47,48] and market designs [49], as well as buildings and energy efficiency [50,51] and the comparison of integrated and non-integrated energy systems [52,53]. In general, the versatility of EnergyPLAN has led to a wide range of applications [54].

2.5. Sectorial aggregation

In the interest of speed – computational as well as in the setting up of models – EnergyPLAN is aggregated in its system description instead of modelling each individual station and component. District heating systems are, e.g., aggregated and defined as three principal technology groups and RES technologies are likewise aggregated into, e.g., one stock of wind turbines with a set of common characteristics. The same applies to, e.g., power stations and waste incineration plants as well as to all demands.

District heating is given particular attention; thus, three different types of district heating system may be modelled as they show different behaviours in the district heating system. These are:

1. District heating systems based on fuel boilers
2. District heating systems based on backpressure CHP plants
3. District heating systems based on extraction CHP plants

These three typologies are referred to as district heating Groups 1–3.

2.6. Fundamental modelling approach

EnergyPLAN uses what we denote “analytical programming”. Rather than establishing a series of balance equations that are solved numerically as in optimisation and equilibrium models, EnergyPLAN is based on a series of endogenous priorities within, e.g., power and heat production and pre-defined procedures for simulating the operation of units that are freely dispatchable. The approach is purely deterministic with no stochastic elements.

As noted, EnergyPLAN simulates user-defined systems and does not make endogenous system optimisation. Various simulation strategies (see Section 3) determine the concrete optimisation criterion applied in an EnergyPLAN simulation (primary energy consumption, energy system balance, operational expenditure); however, in the design of scenarios, users can apply any of the outputs of EnergyPLAN or derivatives thereof. Thus, users have employed total system costs, renewable energy shares, employment generation, emissions and many more [10] in exogenous system optimisation.

Some users have combined EnergyPLAN with other tools for exogenous scenario design based on various objectives, e.g. Refs. [55–60]. Such work has, e.g., applied genetic algorithms to identify optimal scenarios based on multiple criteria.

2.7. Coding and execution

EnergyPLAN is programmed and maintained in Delphi Pascal. The tool along with manuals, reports and descriptions of algorithms in the tool are available from www.energyplan.eu. The training period required to use the tool can take from a few days up to a month, depending on the level of competency required.

EnergyPLAN is a freeware. Users can be involved on a semi open-source basis in which independent add-ons and help tools can be added. EnergyPLAN has a facility to include such add-ons based on any type of coding as long as they provide an exe-file. In the current version, EnergyPLAN includes several help tools. Moreover, the tool may be executed from other platforms such as Excel or MATLAB, which allows multi-execution [55,61].

2.8. Considerations regarding time

EnergyPLAN simulates a one leap-year time period in total; thus, for longer-spanning analyses, several simulations would have to be run. Within the one-year period, EnergyPLAN simulates the energy system on an hourly resolution level [11]. This entails that all demands and productions are exogenously defined using hourly time series.

The reason is that the integration of RESrenewable energy is a key focus for EnergyPLAN. Thus, it is important to adequately factor in associated intermittencies. The hourly simulation level that this requires is contrary to some scenario tools, which simulate the system on an annual basis or some optimisation tools that are based on time slicing, where hourly sample periods are identified for more in-depth analyses.

The hourly resolution allows the user to investigate hourly, daily, weekly and seasonal differences in electricity and heat demands and productions and, e.g., water inputs to large hydropower systems.

2.9. Grid stability

EnergyPLAN seeks the balance between electricity production and demand with an hourly resolution. Thus, active power and frequency stability are considered at this time step. Voltage stability and short-circuit power are not modelled explicitly; however, EnergyPLAN gives the user the option of requiring certain units to have a minimum production at all hours. This requires that in each hour, a minimum share of the power production comes from ancillary service-providing units, and that the share of each production category that should be interpreted as providing ancillary service should be defined. See e.g. Refs. [62,63] for analyses where this has been a focal point.

2.10. Inputs and outputs

Fig. 1 provides an overview of inputs as well as outputs of the model. EnergyPLAN comes with a graphical user interface in which the user can type in inputs and maintain an overview of the model.

Overall, the following input structure of EnergyPLAN refers to the aspects of an energy system:

- Energy demands (heat, electricity, transport, etc.)
- Energy production units and resources (wind turbines, power plants, oil boilers, storage, etc.) including energy conversion units such as electrolysers, biogas and gasification plants as well as hydrogenation units.
- Simulation (defining the simulation and operation of each plant and the system including technical limitations such as transmission capacity, etc.)
- Costs (fuel costs, exchange of electricity and gas, taxes, variable and fixed operational costs and investment costs)

The outputs produced by EnergyPLAN are energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs including income from the exchange of electricity. With a temporal resolution of 1 hour, results can be presented down to this resolution as well. Through the export facility, the results can be imported into a spreadsheet for further investigation or illustration.

More immediately, results are presented in monthly and yearly overviews of production and demands within different technology categories as well as gas and electricity imports/exports. Yearly aggregates also include carbon dioxide emissions, money flows to/from an external electricity market and fuel consumption.

2.11. The smart energy systems approach of EnergyPLAN

EnergyPLAN has been developed in parallel with the concept of smart energy systems as defined in a series of papers [16,64–66].

The design of EnergyPLAN thus emphasises the option of looking at the complete energy system as a whole (see Fig. 2). E.g., the challenge of integrating variable RES-based power into the electricity grid by the use of smart grids should not be looked upon as an isolated issue, but should be seen as one out of various means and challenges of approaching sustainable energy systems in general. Therefore, EnergyPLAN is designed to be a tool in which, e.g., electricity smart grids can be coordinated with the utilisation of RES for other purposes than electricity production.

In EnergyPLAN, RES are converted into other forms of energy carriers than electricity via different power-to-x technologies, including heat, hydrogen, e-gases and electrofuels. EnergyPLAN can also model renewable energy systems by including different types of energy conservation and efficiency improvements, such as the cogeneration of heat and power (CHP) fuel cells.

All these measures have the potential to replace fossil fuels or improve the fuel efficiency of the system. The long-term relevant systems are those in which such measures are combined with energy conservation and system efficiency improvements. Consequently, EnergyPLAN can be used for analyses which illustrate, e.g., why electricity smart grids should be seen as part of overall smart energy systems.

Consequently, EnergyPLAN does not only calculate an hourly electricity balance, but also hourly balances of district heating, cooling, hydrogen and natural gas, including contributions from biogas, gasification as well as electrolysis and hydrogenation. Figs. 3–5 present a view of the production and conversion units involved in the balancing of the different grid structures.

3. Computational approach

This section details the computational core of EnergyPLAN focusing on how it simulates energy systems.

3.1. General computational strategy

As displayed in Fig. 6, the very first calculations are made as data is entered. E.g., if wind capacity is entered and an hourly wind distribution file is chosen from the library, EnergyPLAN will simultaneously calculate the annual and the hourly electricity production.

Afterwards (Stage 2 in Fig. 6), EnergyPLAN completes a number of initial computations which do not involve electricity balancing, such as the amount of heat provided by industry, the hourly demand of heat in the three district heating systems and the hourly non-flexible electricity demand.

Based on a user-specified simulation strategy, EnergyPLAN then branches: For the technical simulation (Stage 3A in Fig. 6 – See also section 3.2), EnergyPLAN identifies the least fuel-consuming solution, while for the market-economic simulation (Stage 3B in Fig. 6 - See also section 3.3), it identifies the consequences of operating each unit on the electricity market with the aim of optimising the business-economic profit.

For both simulation strategies, EnergyPLAN will finish by computing the socio-economic consequences of the system (total energy systems costs and carbon dioxide externality). As the entire calculation process only takes a few seconds, both simulation strategies can be easily completed and compared.

In the following, the technical and market-economic simulations are further detailed.

3.2. Technical simulation strategy

With the technical energy systems simulation strategy, the computation is carried out in the following steps as illustrated in Fig. 7. After each of the steps, a calculation is made of condensing mode power and import/export including CEEP and EEEP (Critical and Exportable Excess Electricity Production). The steps represent the calculation sequence and not necessarily the importance of each measure and technology.

Step 1. First, EnergyPLAN calculates the electricity and heat productions of the units in the district heating supply systems. As a start, all heat units are producing solely according to the heat demand, and these units are given priority on an hourly basis according to the following sequence:

1. Solar Thermal
2. Industrial excess heat incl. electrolysers and thermal gasification
3. Heat production from waste fuel
4. Heat plant CHP
5. Heat pumps
6. Peak load boilers

Hourly electricity productions from variable RES are already calculated in Stage two.

Step 2. Next, EnergyPLAN identifies the potential to utilise flexible electricity demand, if any, which is specified as an input. The electricity demand can either be made flexible, as specified in the next steps, or within short periods according to four time horizons. The user can choose to stipulate an annual demand that may be shifted within three timeframes – 24h, 1w or 4w – within a capacity constraint.

EnergyPLAN calculates the best use of flexible demands to achieve a balance between demand and supply with two

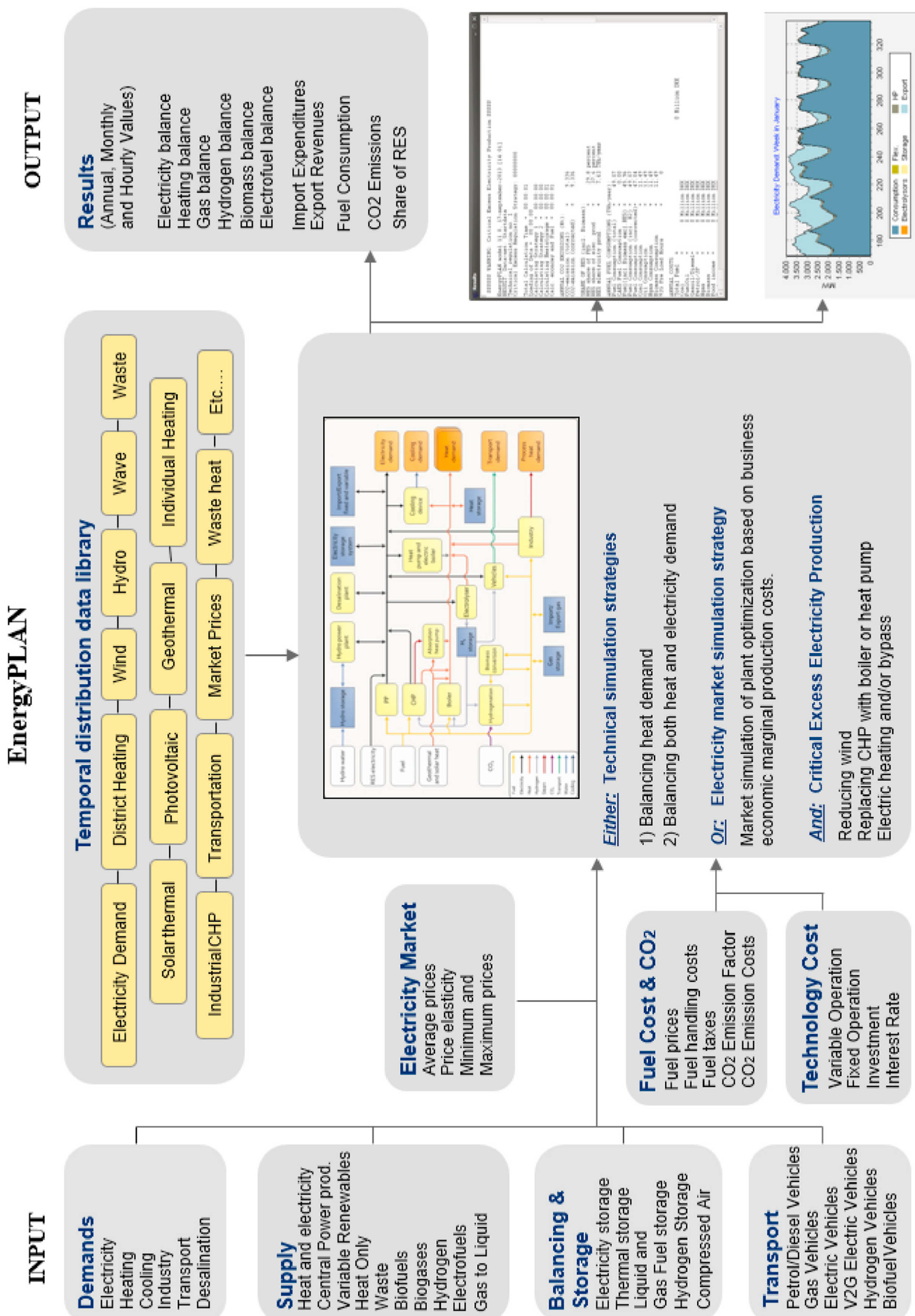

Fig. 1. Data inputs and outputs of EnergyPLAN.

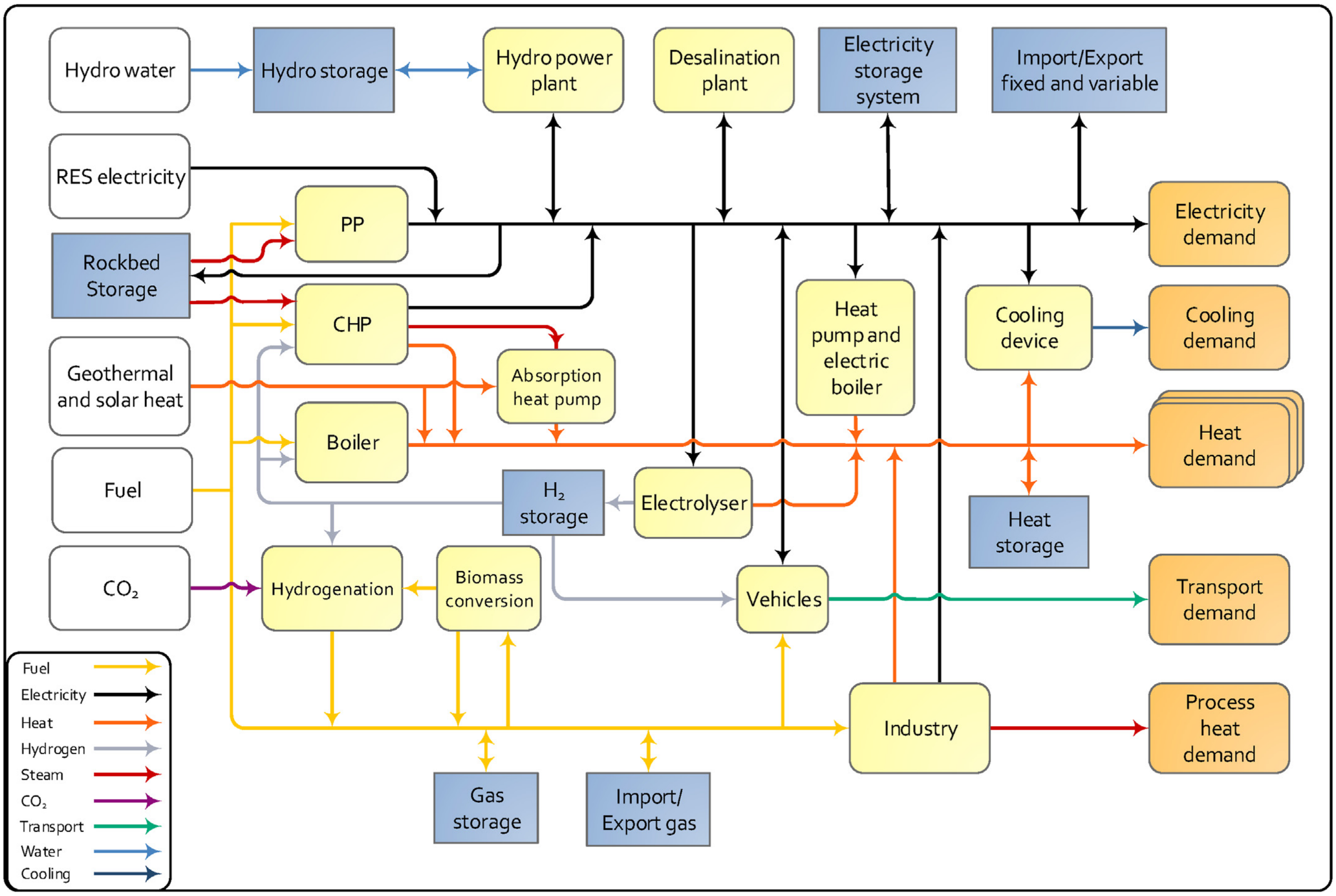

Fig. 2. The overall technology and flow model on which EnergyPLAN is based (adopted from Ref. [67]).

limitations: It must be positive at any time and it should be below the stipulated capacity constraint. A normalisation of the variation ensures that the average demand for the period equals the yearly average.

Step 3. As input, one can choose if the operation of CHP and heat pumps for district heating should seek to balance the electricity supply and demand of the overall system. If this strategy is chosen, the calculations of Step 1 are replaced by a strategy in which the export of electricity is minimised mainly by the use of heat pumps at CHP plants. This will simultaneously increase the electricity demand to the heat pumps and decrease the electricity production from CHP units, as the CHP units must decrease their heat production. By utilising unused capacity at the CHP plants in the given hour combined with heat storages, any production at condensing-mode plants is minimised and replaced by CHP production.

Step 4. Hydropower is then used for replacing the condensing-mode plants and decreasing, first, Critical Excess Electricity production (CEEP) and, secondly, Exportable Excess Electricity production (EEEP) in the following way: First, the potential of replacing the condensing-mode power plant ($e_{Hydro\text{-}Inc}$) is determined as the minimum value of the production of the condensing unit and the difference between hydropower capacity and hydropower production.

$$e_{Hydro\text{-}Inc} = MIN\,(e_{PP},\,(C_{Hydro} - e_{Hydro}))$$

The hydro production, e_{Hydro}, is the production identified in Stage 1. The potential to decrease hydropower in the case of CEEP ($e_{Hydro\text{-}Dec\text{-}CEEP}$) is determined as the minimum value of the CEEP and the hydropower production. At the same time, the potential is limited by the fact that the hydropower plant potentially forms part of grid stabilisation:

$$e_{Hydro\text{-}Dec\text{-}CEEP} = MIN\,(e_{CEEP},\,e_{Hydro})$$

$$e_{Hydro\text{-}Dec\text{-}CEEP} \leq e_{Hydro} - e_{Hydro\text{-}Min\text{-}Grid\text{-}Stab}$$

In the case of reverse hydropower, i.e., a pump and both a lower and a higher water reservoir, the potential to further decrease CEEP ($e_{Hydro\text{-}Pump\text{-}Dec\text{-}CEEP}$) is determined as the minimum value of the CEEP (minus the share that is already dispatched), the pump capacity, and the content of the lower water storage, $s_{Hydro\text{-}PUMP}$:

$$e_{Hydro\text{-}Pump\text{-}Dec\text{-}CEEP} = MIN\,[(e_{CEEP} - e_{Hydro\text{-}Dec\text{-}CEEP}),\,C_{Hydro\text{-}PUMP},\,s_{Hydro\text{-}PUMP}\,/\,\mu_{Hydro\text{-}PUMP}\,]$$

In the same way, the potential to decrease hydropower in the case of EEEP ($e_{Hydro\text{-}DEC\text{-}EEEP}$) is found. Knowing the potentials to increase and decrease the hydropower production, a balance is found in which the annual hydropower production is maintained. The reduction of CEEP is given priority over the reduction of EEEP.

$$\Sigma\, e_{Hydro\text{-}Inc} = \Sigma\, e_{Hydro\text{-}Dec\text{-}CEEP} + \Sigma\, e_{Hydro\text{-}Dec\text{-}EEEP}$$

The hydropower production (e_{Hydro}) is modified in accordance

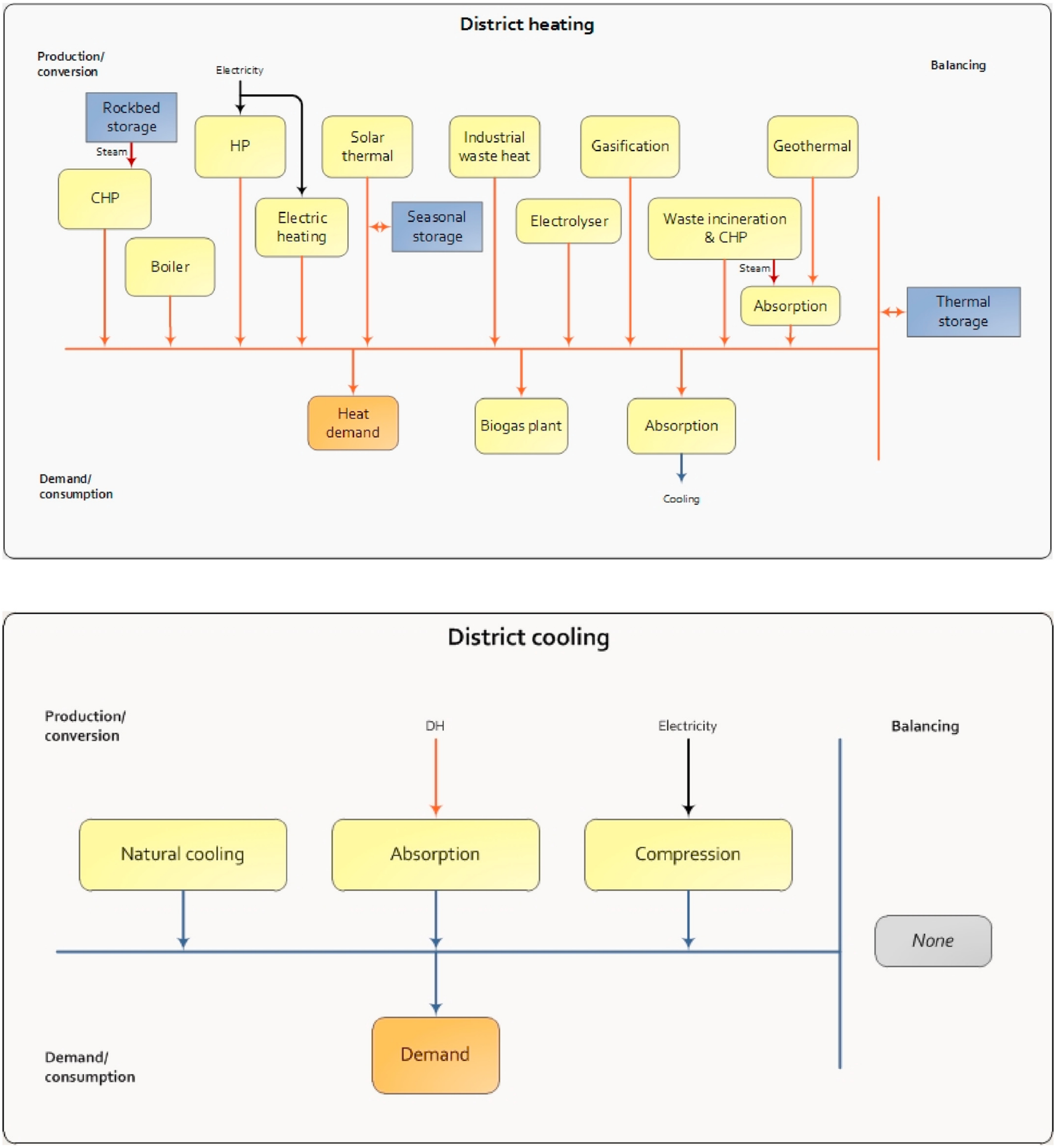

Fig. 3. Units involved in EnergyPLAN's simulation of the hourly balancing of the District Heating and Cooling system including interactions with other parts of the entire system. In EnergyPLAN, district heating is divided into three separate systems: One for boiler-only systems; one for small CHP systems, and one for large extraction CHP plant-based systems.

with the generator capacity, the hourly distribution of the water supply, and the storage capacity in the following way:

$$\text{Hydro storage content} = \text{Hydro storage content} + w_{Hydro}$$

$$e_{Hydro} = e_{Hydro} + e_{Hydro\text{-}Inc} - e_{Hydro\text{-}Dec\text{-}CEEP} - e_{Hydro\text{-}Dec\text{-}EEEP}$$

$$e_{Hydro\text{-}Input} \leq (\text{Hydro storage content} - S_{Hydro})^{*}\ \mu_{Hydro}$$

$$e_{Hydro\text{-}Input} \leq C_{Hydro}$$

Differences in the storage content at the beginning and at the end of the calculation period may cause errors in the calculations. To correct these errors, the above calculation seeks to identify a solution in which the storage content at the end is the same as at the beginning. Initially, the storage content is defined as 50% of the

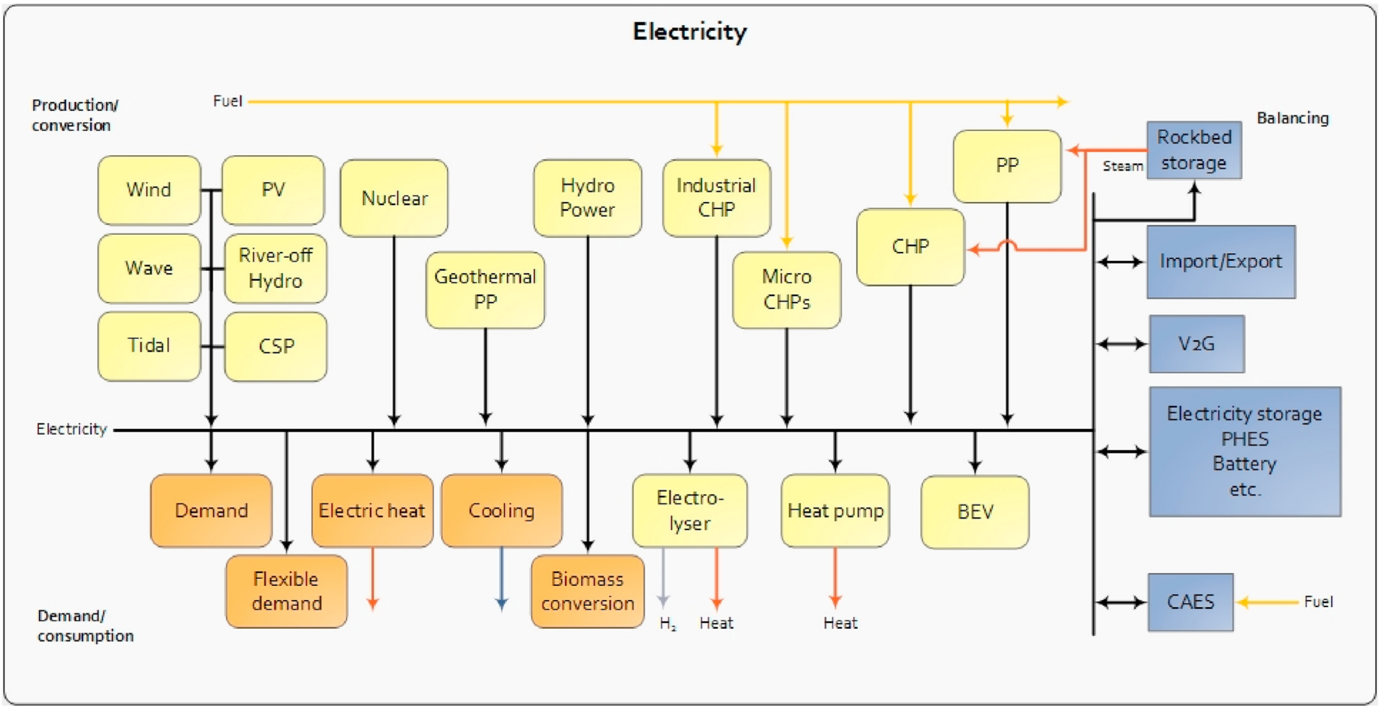

Fig. 4. Units involved in EnergyPLAN's simulation of the hourly balancing of the Electricity system including interactions with other parts of the whole system.

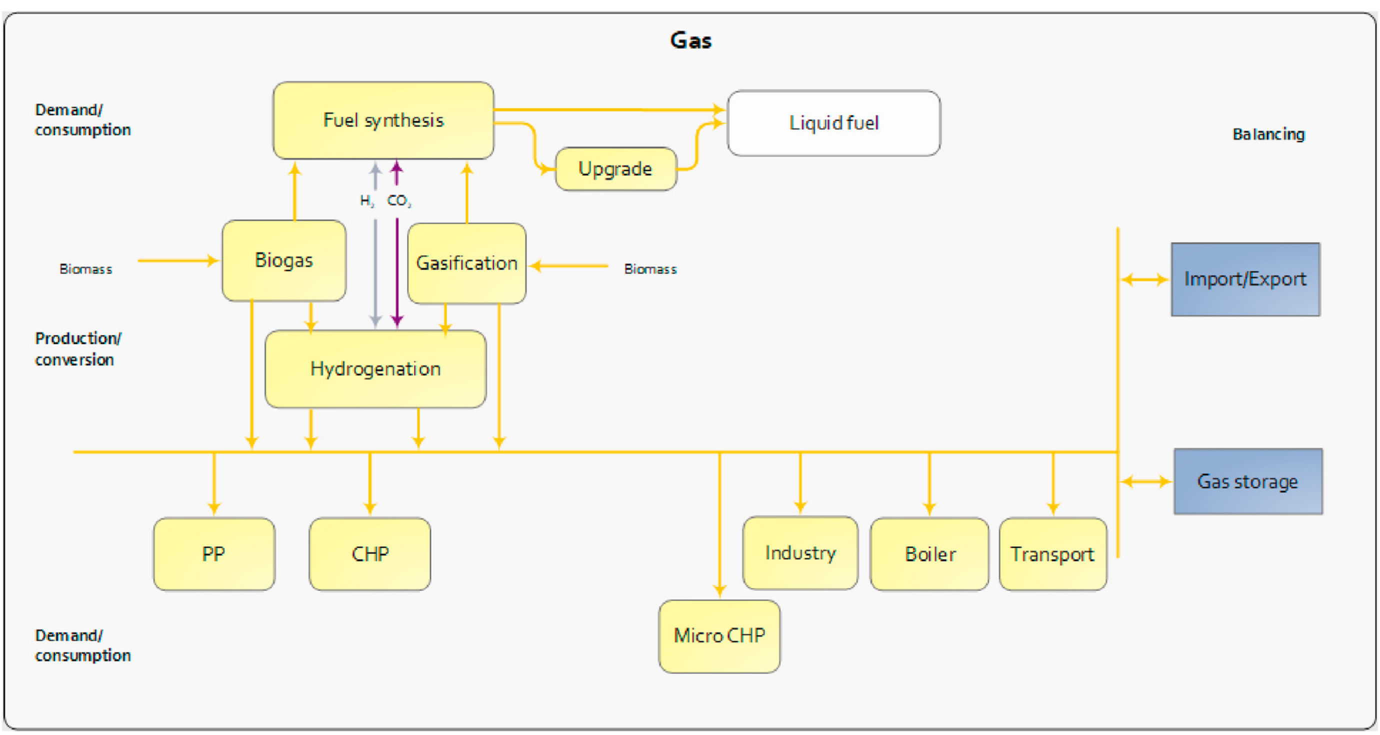

Fig. 5. Units involved in EnergyPLAN's simulation of the hourly balancing of the gas system including interactions with other parts of the whole system.

storage capacity. After the first iteration, a new initial content is defined as the resulting content at the end of the calculation. However, one may as input specify a start and end value of the hydro storage. In this case, these values will be used.

Step 5. The calculations of individual CHP and heat pump systems are based on the computation in Stage 1 in which solar thermal (if any) is given priority. If heat storage capacity is specified, EnergyPLAN will exploit the option of using the electricity productions and demands of these units to balance the electricity supply and demand of the overall system. This will update the productions on the individual CHP and heat pump systems.

Step 6. Four electrolyser systems are described in the model. Two

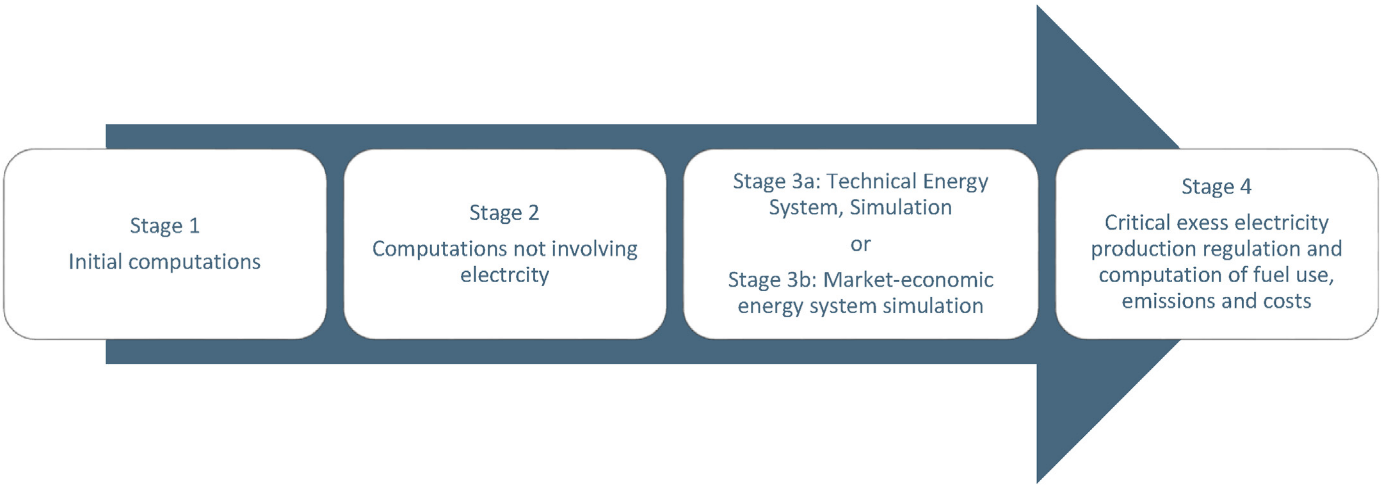

Fig. 6. Overall structure of the energy system simulation procedures.

of these are systems which are assumed to be located next to the district heating based on backpressure units and extraction plants, respectively, along with the CHP units, heat pumps and boilers. Here, the waste heat production of the electrolysers can be utilised in the district heating supply. The two other systems produce hydrogen for micro CHP systems or for transport and hydrogenation. The electrolyser is assumed to be a hydrolyser (producing hydrogen), but it may be used for modelling any kind of equipment converting electricity into fuel and heat.

The calculation is based on the result of the Stage 1 calculation in which the minimum capacity of the electrolyser is identified together with the electricity demand, d_{ElcM}. EnergyPLAN seeks to avoid CEEP/EEEP and condensing-mode power generation by reorganising the production. First, the potential to increase the production at hours of excess production, $d_{ElcM\text{-}inc\text{-}pot}$, is identified as the lower value of CEEP and the difference between the capacity, C_{ElcM}, and the production of the electrolyser:

$$d_{ElcM\text{-}inc\text{-}pot} = \text{Min}\ [\ e_{CEEP}, (C_{ElcM} - d_{ElcM})\ ]$$

Secondly, the potential to decrease production at hours of power-only production, $d_{ElcM\text{-}dec\text{-}pot}$, is identified as the minimum of the power production, e_{PP}, and the electrolyser demand:

$$d_{ElcM\text{-}dec\text{-}pot} = \text{Min}\ [\ e_{PP}, d_{ElcM}\ ]$$

Then a balance is created in which either the potential to increase or the potential to decrease is lowered to achieve the same level as that of the annual potentials:

If $D_{ElcM\text{-}dec\text{-}pot} > D_{ElcM\text{-}inc\text{-}pot}$ **then** $d_{ElcM\text{-}dec\text{-}pot} = d_{ElcM\text{-}dec\text{-}pot} * D_{ElcM\text{-}inc\text{-}pot} / D_{ElcM\text{-}dec\text{-}pot}$

If $D_{ElcM\text{-}inc\text{-}pot} > D_{ElcM\text{-}dec\text{-}pot}$ **then** $d_{ElcM\text{-}inc\text{-}pot} = d_{ElcM\text{-}inc\text{-}pot} * D_{ElcM\text{-}dec\text{-}pot} / D_{ElcM\text{-}inc\text{-}pot}$

A new optimal temporal distribution of the electrolyser electricity demand (producing exactly the same annual fuel as before) is calculated as:

$$d_{ElcM} := d_{ElcM} - d_{ElcM\text{-}dec\text{-}pot} + d_{ElcM\text{-}inc\text{-}pot}$$

Finally, the temporal distribution is evaluated against the hydrogen storage capacity. First, the changes in storage content are calculated.

If the storage content based on this calculation is below zero, the production of the electrolyser is increased.

If the storage content exceeds the storage capacity, the production of the electrolyser is decreased.

Step 7. Thermal storage in district heating systems is used to improve the possibilities for minimising the electricity export. The heat storage capacity is included in the model for each of the district heating groups 2 and 3. The storage capacities are used for minimising the excess and condensing mode power generation in the system.

Step 8. Electric vehicles including the concept of vehicle to grid (V2G) can be operated with smart charge as well as smart discharge. One important input is the hourly distribution of the transport demand (δ_{V2G}), which is used for two purposes. One is to determine the number of V2G battery electric vehicles which are driving and consequently not connected to the grid in the hour in question. This, together with the $V2G_{Max\text{-}Share}$ (the maximum share of V2G battery electric vehicles which are driving during peak demand hour) and the $V2G_{Connection\text{-}Share,}$ determines the fraction of the V2G fleet that is available to the electrical system in any given hour. The other purpose of defining δ_{V2G} is to determine the discharging of the battery storage caused by driving. The hourly transport demand, and thereby the discharging of the battery (t_{V2G}), is calculated as follows:

$$t_{V2G} = [\ D_{V2G} * \delta_{V2G} / \Sigma\ \delta_{V2G}\ ] * \eta_{CHARGE}$$

The grid connection capacity of the total V2G fleet on an hourly basis (c_{V2G}) is calculated as follows:

$$c_{V2G} = C_{Charger} * V2G_{Connection\text{-}Share} * ((1 - V2G_{Max\text{-}Share}) + V2G_{Max\text{-}Share} * (1 - \delta_{V2G}/\text{Max}(\delta_{V2G})))$$

This equation includes three factors. The first factor is $C_{Charger}$, the power capacity of the entire V2G fleet. This is multiplied by $V2G_{Connection\text{-}Share}$, the fraction of the parked vehicles which is assumed to be plugged. The third factor, in parentheses, calculates the fraction of vehicles on the road in each hour. The third parenthesised factor is based on the sum of two terms. The first term, (1-$V2G_{Max\text{-}Share}$), represents the minimum fraction of vehicles parked. The second term is the additional fraction of vehicles parked during non-rush hours. The hourly fraction of vehicles parked is derived from the known input of hourly energy demand for the fleet. This equation yields c_{V2G}, the power capacity of all connected V2G

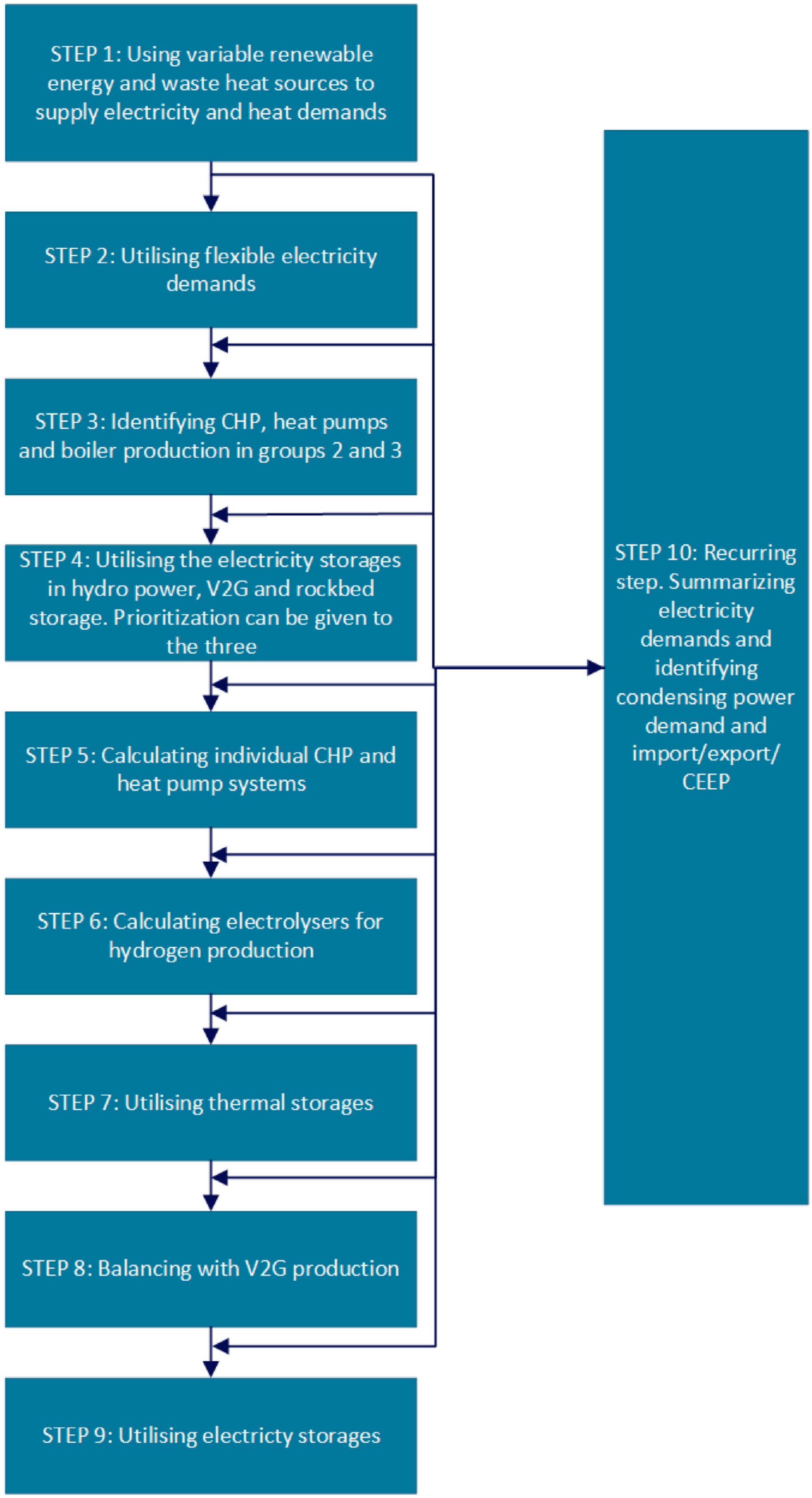

Fig. 7. Graphical representation of Stage 3A: Technical Simulation Strategy in EnergyPLAN.

vehicles, in any given hour. For each hour, the model calculates as follows.

The V2G battery electric vehicles will charge in the case of available excess electricity production (e_{CEEP}) and available battery energy capacity ($S_{V2G\text{-}Battery}$ - $s_{V2G\text{-}Battery}$) within the limitations of the power capacity of the grid connection (c_{V2G}) for that particular hour. Thus, the equation is the minimum of three values:

$$e_{Charge} = \min \left[e_{CEEP}, (S_{V2G\text{-}Battry} - s_{V2G\text{-}Battery}) / \mu_{Charge}, c_{V2G}\right]$$

Moreover, as mentioned above, the charging is forced in the case in which the transport demands of the present and the next "y" hours cannot be supplied by the battery content. Initially, the "y" value is set to 1 h. If this leads to lack of battery content, the value is raised in steps of 1 h.

The minimum battery content needed is calculated:

$$S_{V2G-Battary-min} = \sum_{a+y}^{x=a} t_{V2G}$$

Then, the charging of the battery is adjusted accordingly, by requiring that:

$$e_{Charge} \geq \left[s_{V2G\text{-}battery} - s_{V2G\text{-}Battary\text{-}min}\right] / \mu_{Charge}$$

If e_{Charge} becomes higher than the capacity of the grid connection, c_{V2G}, the number of hours, y, is raised by one, and the calculations start again. The new battery content is then calculated by adding the above charging and subtracting the discharging caused by driving (t_{V2G}):

$$s_{V2G\text{-}Battery} := s_{V2G\text{-}Battery} - t_{V2G} + (e_{Charge} * \mu_{Charge})$$

The V2G battery electric vehicles are simulated supplying the grid in the case of a potential replacement of production from power plants (e_{PP}) and available stored electricity in the battery after the supply of the transport demand:

$$e_{Inv} = \min \left[e_{PP}, ((s_{V2G\text{-}Battery} - s_{V2G\text{-}Battery\ \text{-}min})^* \mu_{Inv}), c_{V2G}\right]$$

The resulting new battery content is then calculated as follows

$$s_{V2G\text{-}Battery} := s_{V2G\text{-}Battery} - (e_{Inv} / \mu_{Inv})$$

Similar to the description for the hydropower energy storage, the above calculation is repeated until the storage content at the end is the same as at the beginning.

Step 9. The electricity storage is described in the model as a hydro storage consisting of the following components:

- Pump (converting electricity to potential energy) defined by a capacity and an efficiency
- Turbine (converting potential energy to electricity) defined by a capacity and an efficiency
- Storage (storing energy) defined by a capacity.

However, this hydro storage can be used for modelling any kind of electricity storage, for example batteries. The simulation of the storage is used solely to avoid critical excess electricity production. The storage facility is regulated in the following way:

The pump is used for charging the storage in the case of critical excess production, $e_{CEEP} > 0$. In this case, the available capacity in the storage ($S_{CAES} - s_{CAES}$) is calculated and the electricity demand of the pump (e_{Pump}) is identified as the minimum value of the following three values:

- e_{CEEP}, the critical excess production
- $(S_{CAES} - s_{CAES})/\alpha_{Pump}$ available storage capacity divided by the pump efficiency
- C_{Pump}, the maximum capacity of the pump.

If $e_{CEEP} > 0$ **then** $e_{Pump} := \min \left[e_{CEEP}, (S_{CAES} - s_{CAES}) / \alpha_{Pump}, C_{Pump} \right]$

$$s_{CAES} = s_{CAES} + e_{Pump} / \alpha_{Pump}$$

The turbine is used for discharging the storage, first by replacing import and then power plant production if $e_{PP} > 0$. In this case, the content of the storage (s_{CAES}) is identified and the electricity production of the turbine ($e_{Turbine}$) is identified as the minimum value of the following three parameters:

- e_{import}, e_{PP}, electricity import or electricity production of the power plant, respectively
- $s_{CAES} * \mu_{Turbine}$, storage content multiplied by turbine efficiency
- $C_{Turbine}$, the maximum capacity of the turbine.

If $e_{import} > 0$ **then** $e_{Turbine1} := \min \left[e_{import}, s_{CAES} * \mu_{Turbine}, C_{Turbine}\right]$

If $e_{PP} > 0$ **then** $e_{Turbine2} := \min \left[e_{PP}, s_{CAES} * \mu_{Turbine}, (C_{Turbine} - e_{Turbine1})\right]$

$$e_{Turbine} = e_{Turbine1} + e_{Turbine2}$$

$$s_{CAES} = s_{CAES} - e_{Turbine} / \mu_{Turbine}$$

Similar to the description for the hydropower and the V2G energy storage, the above calculation is repeated until the storage content at the end of the year is the same as at the beginning.

Step 10. As a final step, a number of measures to reduce Critical Excess Electricity Production, e_{CEEP}, are calculated depending on the input specification in which one can chose between:

1 Reducing renewable electricity productions from wind, photo voltaic, wave power, etc.
2 Reducing CHP production by replacing with peak load fuel-based boilers
3 Replacing fuel-based boiler production with electric heating
4 Increasing CO_2 hydrogenation
5 Part-loading nuclear power generation (otherwise nuclear is simulated following an exogenously given temporal distribution curve)

It is possible for the user to prioritise these measures.

3.3. Market economic simulation strategy

If market-economic simulation is chosen (see Fig. 6), EnergyPLAN distinguishes between business economy (including taxes) and socio-economy (*not* including taxes). Basically, EnergyPLAN seeks the least-cost solution of operating the system, assuming an electricity market in which all plant operators seek to optimise their business-economic profit. The market-economic modelling is based on the identification of the electricity market price at each hour resulting from the demand and supply of electricity. Moreover, the exact production level of the various units at which the resulting market price becomes equal to the marginal production price is identified. Similarly, marginal consumption prices are found for electricity-consuming units such as heat pumps and electrolysers. The net import is identified as the difference between the electricity demand, d_{Total}, and the supply, e_{Total}. The market price on the external market, p_X, is found as follows:

$$p_X = p_i + (p_i / p_o)* Fac_{depend} * d_{Net\text{-}Import}$$

where p_i is the system market price.

Fac_{depend} is the price elasticity (Currency/MWh/MW)
p_o is the basic price level for price elasticity (input),
$d_{Net\text{-}Import}$ is the trade on the market.

Import is calculated as positive and export as negative, resulting in an increase in the market price in the case of import and a decrease in the case of export.

The production level of a certain unit at which the resulting market price becomes equal to the marginal production price is identified as an integrated part of the procedure. Here, the calculation is illustrated by the example of the geothermal power plant.

First, the net-import, $d_{Net\text{-}Import}$, is calculated as well as the market price, p_X, when the electricity production of the geothermal power plant is zero. Then, the balance production is calculated as follows:

$$BalanceProduction_{Geothermal} = - [(VEPP_{Geothermal} - p_X) / (Fac_{depend} * p_X / p_o) - d_{Net\text{-}Import}]$$

where $VEEP_{Geothermal}$ is the marginal production cost of geothermal power production.

p_x is the market price before geothermal production
Fac_{depend} is the price elasticity (Currency/MWh/MW)
p_o is the basic price level for price elasticity (input)
$d_{Net\text{-}Import}$ is the trade on the market before geothermal production

The equation is typically subject to the limitations on power plant capacity.

The user may stipulate whether the transmission line capacity should limit dNet-Import or not. If EnergyPLAN is set to 'Transmission capacity limits the effect on the system price', then dNet-Import will be limited to the transmission line capacity of the system, in absolute values. If EnergyPLAN is set to "Transmission capacity does not limit the effect on the system price", then the transmission line capacity does not limit dNet-Import.

The simulation is done in the following steps as illustrated in Fig. 8:

Step 1. The hourly prices on an external electricity market is defined as an input. The fluctuations of the market prices are presented as an hourly distribution file for a year. The influence of import/export on the external market prices is given in terms of a dependence factor (price elasticity and a basic price level for the price elasticity). When the business-economic best operation strategy is identified for each plant in the following, the influence on the market price is taken into consideration.

Step 2. All marginal production costs are calculated on the basis of fuel costs, taxes, CO_2 costs and variable operational costs. For units connected to district heating plants (such as CHP and heat pumps), power stations and individual micro CHP, marginal costs are given in currency/MWh of electricity production/consumption. Currency can be chosen by the user, e.g. DKK or EUR. For storage units such as hydrogen CHP and pump storage systems, marginal costs are given according to a multiplication factor together with an addition factor. Basically, the simulation criterion is the following:

$$p_{sell} > p_{buy} * f_{MUL} + f_{ADD}$$

In which p_{sell} is the market electricity price when selling (Currency/MWh)

p_{buy} is the market electricity price when buying (Currency/MWh)
f_{MUL} is the multiplication factor (always higher than 1).
f_{ADD} is the addition factor (Currency/MWh)

Step 3. As a starting point for the simulation, the electricity system prices are calculated on the basis of:

- the electricity demand including flexible demand (calculated as described above)
- the production from RES

The production from RES is potentially affected by the "RES influence on system electricity price" setting, which has two options:

- "Zero bidding price (RES can stop)": When using this option, the Variable RES electricity production will be curtailed at negative system electricity market prices.
- "Negative bidding prices (RES cannot stop)": When using this option, the Variable RES will not be curtailed due to negative electricity market prices.

As a starting point, all district heating is defined as supplied by boilers. The sequence of optimising the individual plant type aggregation is then identified by the subsequent procedure.

Step 4. The least-cost solutions of buying the minimum amount of electricity needed to meet the following demands are identified, given the market price fluctuations and limitations on storage capacities, etc.:

- for producing hydrogen for transport
- for charging electric vehicles
- for producing hydrogen for micro-CHP systems

When identifying the least-cost solution for the hydrogen micro-CHP systems, the option of producing heat with a boiler using less hydrogen than the CHP unit is considered in situations of high electricity prices.

In the case of smart charge EV and V2G (Vehicle to Grid) possibilities, the optimal business-economic solutions of buying and selling are found on the basis of the multiplication and addition factors identified as an input.

Step 5. The following electricity-consuming options are sorted according to marginal consumption costs:

- replacing boiler with heat pumps in district heating Group 2
- replacing boiler with heat pumps in district heating Group 3
- replacing boiler with electrolysers in district heating Group 2
- replacing boiler with electrolysers in district heating Group 3
- replacing electric heating with heat pumps in individual houses
- replacing boiler with electric boiler in district heating Group 2
- replacing boiler with electric boiler in district heating Group 3
- producing steam for high-temperature thermal storage if the electricity price is lower than the cost of fuel for condensing-mode power generation and power generation at the extraction-mode CHP in DH Group 3 taking efficiencies into account.

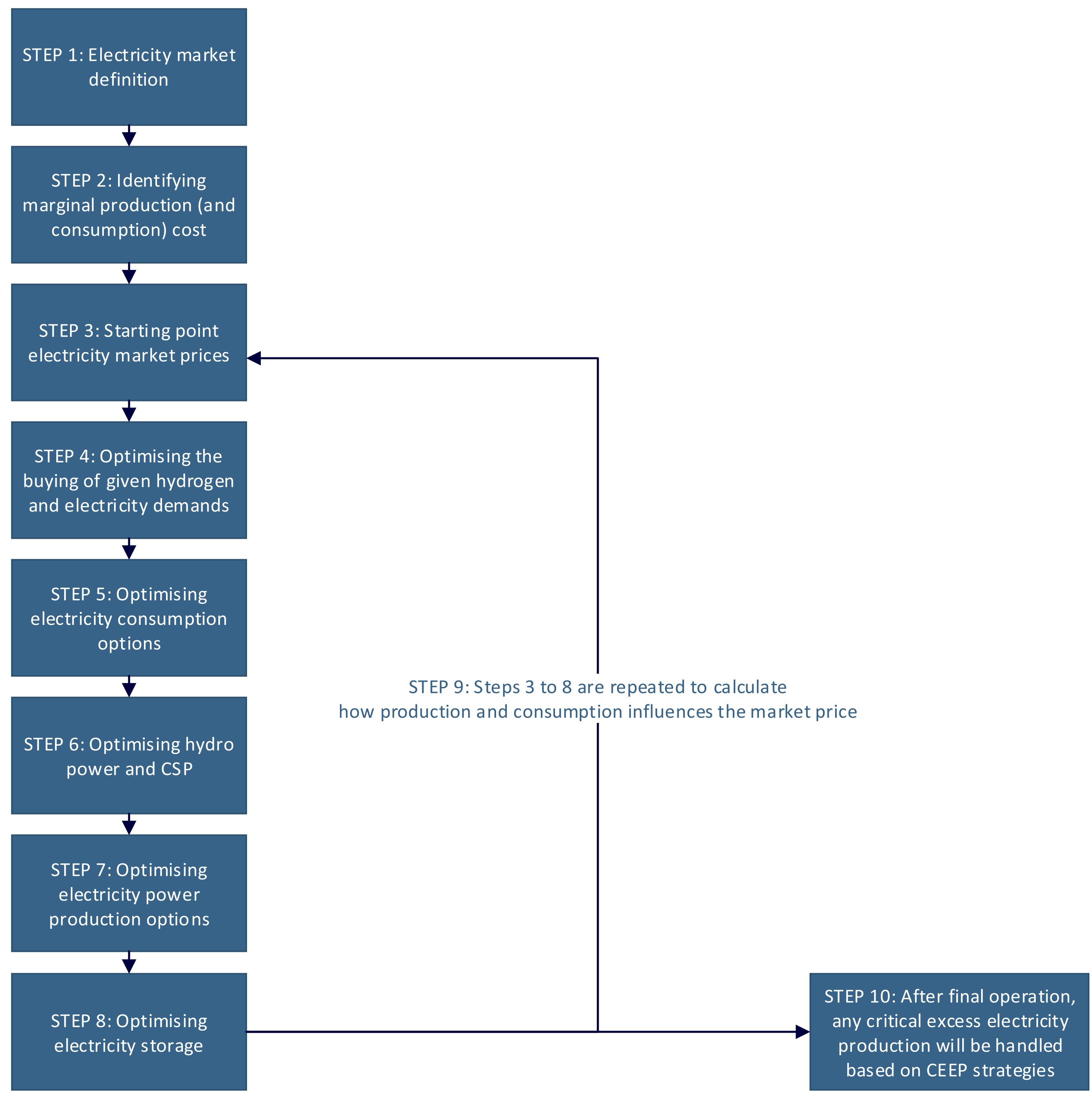

Fig. 8. Graphical representation of Stage 3B: Market-Economic Simulation Strategy in EnergyPLAN.

Each option is then optimised according to market electricity prices, by starting with the option with the highest marginal costs and taking into consideration the fact that each change in consumption influences the market price (increases the price).

Step 6. Then, the best business-economic production from concentrated solar power (CSP) is identified taking into consideration limitations on storage and generator capacities, and a similar calculation is done for hydropower. In the case of pumped hydro storage possibilities, the optimal business-economic solution of buying and selling is identified.

Step 7. The following electricity production options are then sorted according to the lowest marginal costs of production:

- Nuclear
- Geothermal
- Condensing-mode power plants

- Individual small-scale CHP units
- Individual biomass CHP
- CHP replacing boilers in district heating Group 2
- CHP replacing boilers in district heating Group 3
- CHP replacing heat pumps in district heating Group 2
- CHP replacing heat pumps in district heating Group 3
- CHP replacing electrolysers in district heating Group 2
- CHP replacing electrolysers in district heating Group 3

Each option is then optimised according to market electricity prices, starting with the option with the lowest marginal costs and taking into consideration the fact that each change in consumption influences the market price (decreases the market price). Limitations on transmission lines are taken into consideration by setting a limit on the production of each unit, so that the total export will not exceed the transmission capacity (if possible). Limitations on import are calculated with regard to the condensing power plants, which will simply be activated in the case that the import transmission capacity is exceeded.

Step 8. The optimal business-economic solution of buying and selling is identified on the basis of the above-mentioned multiplication and addition factors.

Step 9. In order to calculate the impact on the simulation of the consumption units after the market price is influenced by the production options, the procedure from Steps 3 to 8 is repeated.

Step 10. Any critical excess production is removed following the technical simulation procedure Step 10 as described in Section 3.2.

4. Summary and conclusion

In line with the objectives set out for the tool, EnergyPLAN enables the user to make consistent and comparative analyses of energy systems based on renewable energy, fossil fuels, and nuclear power. The tool considers all sectors of the energy system (electricity, heat, industry and transport) and includes a wide variety of technologies. Furthermore, EnergyPLAN makes it possible to quickly complete the modelling without losing coherence for a large variety of systems including current systems (which are based on fossil fuel production) as well as those with radical technological changes (such as 100% renewable energy systems).

EnergyPLAN is a freeware with a long record of active use. It involves independent add-ons and help tools and it may be executed from other platforms such as Excel or MATLAB, which enables multi-execution. In addition, it can calculate the hourly operation of an energy system to ensure that supply and demand are reliably matched, even with the introduction of intermittent renewable energy.

With EnergyPLAN, the modeller can also differentiate between a technical simulation, which ignores existing electricity market constructions and price levels, and a market-economic simulation, which can be adjusted using taxes. For both simulations, the tool can calculate the costs of the total system divided into investments costs, operation costs, fuel costs, CO_2 costs and other taxes. Hence, EnergyPLAN can create data for further analysis of socio-economic feasibility studies, such as the balance of payment and job creation. It is freely available for download along with detailed documentation about its operation, which enables its functionality and methodologies to be freely debated and improved.

Compared to other models, the main advantages of EnergyPLAN are the ability to model the entire system with all sectors, the aggregation of units into representative units limiting the data requirement, the ability to quickly simulate a user-defined scenario, the transparency in how scenarios are developed, the 1h temporal simulation step and the ability to simulate an entire year with seasonal variations.

The limitations of EnergyPLAN to some extent mirror the advantages. With a focus on the entire system and with the aggregation employed in EnergyPLAN, the detailed operation of individual units are not captured. Likewise, the exogenous and transparent system design (and resulting fast computational time) comes at the expense of larger requirements of the user; thus, some experience is required to identify favourable scenarios.

EnergyPLAN's appropriateness is dependent on the individual user's objectives. EnergyPLAN is particularly suitable if the main objective is to analyse the impact of long-term alternatives, particularly in relation to renewable energy, and where distinct scenarios are analysed without endogenous system optimisation. Other tools can often be used in combination with EnergyPLAN if there are additional objectives that need to be met when completing an energy system analysis.

Lastly, EnergyPLAN is undergoing continuous development to always be able to meet the modelling requirements of future energy systems. Currently, the model is being improved in its ability to identify suitable flexible use of electrolysers as well as in its ability to proper handle different assumptions on how variable renewable electricity productions influence negative electricity market prices.

Declaration of competing interestCOI

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] United Nations. Framework Convention on Climate change [UNFCCC]. Paris agreement. Paris, France: United Nations. 2015. FCCC/CP/2015/L.9.
[2] Dagoumas AS, Koltsaklis NE. Review of models for integrating renewable energy in the generation expansion planning. Appl Energy 2019;242: 1573–87. https://doi.org/10.1016/J.APENERGY.2019.03.194.
[3] Oberle S, Elsland R. Are open access models able to assess today's energy scenarios? Energy Strat Rev 2019;26:100396. https://doi.org/10.1016/j.esr.2019.100396.
[4] 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. https://doi.org/10.1016/j.apenergy.2009.09.026.
[5] 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. https://doi.org/10.1016/j.rser.2018.08.002.
[6] 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. https://doi.org/10.1016/j.rser.2018.07.045.
[7] Priesmann J, Nolting L, Praktiknjo A. Are complex energy system models more accurate? An intra-model comparison of power system optimization models. Appl Energy 2019;255:113783. https://doi.org/10.1016/J.APENERGY.2019.113783.
[8] Pilpola S, Lund PD. Analyzing the effects of uncertainties on the modelling of low-carbon energy system pathways. Energy 2020;201:117652. https://doi.org/10.1016/J.ENERGY.2020.117652.
[9] Tapia-Ahumada K, Octaviano C, Rausch S, Pérez-Arriaga I. Modeling intermittent renewable electricity technologies in general equilibrium models. Econ Model 2015;51:242–62. https://doi.org/10.1016/J.ECONMOD.2015.08.004.
[10] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator

applications in EnergyPLAN simulations. Appl Energy 2015;154:921–33. https://doi.org/10.1016/j.apenergy.2015.05.086.
[11] Liu W, Lund H, Mathiesen BV. Large-scale integration of wind power into the existing Chinese energy system. Energy 2011;36:4753–60. https://doi.org/10.1016/j.energy.2011.05.007.
[12] Connolly D, Mathiesen BV. A technical and economic analysis of one potential pathway to a 100% renewable energy system. Int J Sustain Energy Plan Manag 2014;1:7–28. https://doi.org/10.5278/ijsepm.2014.1.2.
[13] Connolly D, Lund H, Mathiesen BV, Leahy M. The first step towards a 100% renewable energy-system for Ireland. Appl Energy 2011;88:502–7. https://doi.org/10.1016/j.apenergy.2010.03.006.
[14] 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. https://doi.org/10.3390/en10070840.
[15] Lund H. Renew Energy Syst 2010. https://doi.org/10.1016/C2009-0-20259-5.
[16] Lund H. Renewable energy systems - a smart energy systems approach to the choice and modeling of 100% renewable solutions. second ed. Academic Press; 2014.
[17] Østergaard PA. Reviewing optimisation criteria for energy systems analyses of renewable energy integration. Energy 2009;34:1236–45. https://doi.org/10.1016/j.energy.2009.05.004.
[18] Lund H, Sorknæs P, Mathiesen BV, Hansen K. Beyond sensitivity analysis: a methodology to handle fuel and electricity prices when designing energy scenarios. Energy Res Soc Sci 2018. https://doi.org/10.1016/j.erss.2017.11.013.
[19] Hansen K, Mathiesen BV, Skov IR. Full energy system transition towards 100% renewable energy in Germany in 2050. Renew Sustain Energy Rev 2019;102:1–13. https://doi.org/10.1016/J.RSER.2018.11.038.
[20] Nielsen S, Sorknæs P, Østergaard PA. Electricity market auction settings in a future Danish electricity system with a high penetration of renewable energy sources – a comparison of marginal pricing and pay-as-bid. Energy 2011;36:4434–44. https://doi.org/10.1016/j.energy.2011.03.079.
[21] Sorknæs P, Djørup SR, Lund H, Thellufsen JZ. Quantifying the influence of wind power and photovoltaic on future electricity market prices. Energy Convers Manag 2019;180:312–24. https://doi.org/10.1016/J.ENCONMAN.2018.11.007.
[22] Askeland K, Bozhkova KN, Sorknæs P. Balancing Europe: can district heating affect the flexibility potential of Norwegian hydropower resources? Renew Energy 2019;141:646–56. https://doi.org/10.1016/J.RENENE.2019.03.137.
[23] Sáfián F. Modelling the Hungarian energy system - the first step towards sustainable energy planning. Energy 2014;69:58–66. https://doi.org/10.1016/j.energy.2014.02.067.
[24] Gota DI, Lund H, Miclea L. A Romanian energy system model and a nuclear reduction strategy. Energy 2011;36:6413–9. https://doi.org/10.1016/j.energy.2011.09.029.
[25] Fernandes L, Ferreira P. Renewable energy scenarios in the Portuguese electricity system. Energy 2014;69:51–7. https://doi.org/10.1016/j.energy.2014.02.098.
[26] Ali H, Sanjaya S, Suryadi B, Weller SR. Analysing CO2 emissions from Singapore's electricity generation sector: strategies for 2020 and beyond. Energy 2017;124:553–64. https://doi.org/10.1016/j.energy.2017.01.112.
[27] Ma T, Ostergaard PA, Lund H, Yang H, Lu L. An energy system model for Hong Kong in 2020. Energy 2014;68. https://doi.org/10.1016/j.energy.2014.02.096.
[28] Novosel T, Ćosić B, Krajačić G, Duić N, Pukšec T, Mohsen MS, et al. The influence of reverse osmosis desalination in a combination with pump storage on the penetration of wind and PV energy: a case study for Jordan. Energy 2014;76:73–81. https://doi.org/10.1016/j.energy.2014.03.088.
[29] 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 decarbonisation. J Clean Prod 2020:272.
[30] Xiong W, Wang Y, Mathiesen BV, Lund H, Zhang X. Heat roadmap China: new heat strategy to reduce energy consumption towards 2030. Energy 2015;81:274–85. https://doi.org/10.1016/j.energy.2014.12.039.
[31] Cabrera P, Lund H, Carta JA. Smart renewable energy penetration strategies on islands: the case of Gran Canaria. Energy 2018;162:421–43. https://doi.org/10.1016/j.energy.2018.08.020.
[32] Alves M, Segurado R, Costa M. On the road to 100% renewable energy systems in isolated islands. Energy 2020;198:117321. https://doi.org/10.1016/j.energy.2020.117321.
[33] Groppi D, Astiaso Garcia D, Lo Basso G, De Santoli L. Synergy between smart energy systems simulation tools for greening small Mediterranean islands. Renew Energy 2019;135:515–24. https://doi.org/10.1016/j.renene.2018.12.043.
[34] Thellufsen JZ, Lund H, Sorknæs P, Østergaard PA, Chang M, Drysdale D, et al. Smart energy cities in a 100% renewable energy context. Renew Sustain Energy Rev 2020;129. https://doi.org/10.1016/j.rser.2020.109922.
[35] Menapace A, Thellufsen JZ, Pernigotto G, Roberti F, Gasparella A, Righetti M, et al. The design of 100 % renewable smart urb an energy systems: the case of Bozen-Bolzano. Energy 2020. https://doi.org/10.1016/j.energy.2020.118198.
[36] Yuan M, Thellufsen JZ, Lund H, Liang Y. The first feasible step towards clean heating transition in urban agglomeration: a case study of Beijing-Tianjin-Hebei region. Energy Convers Manag 2020. https://doi.org/10.1016/j.enconman.2020.113282.
[37] Hagos DA, Gebremedhin A, Zethraeus B. Towards a flexible energy system – a case study for Inland Norway. Appl Energy 2014;130:41–50. https://doi.org/10.1016/j.apenergy.2014.05.022.
[38] Connolly D, Lund H, Mathiesen BV. 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. https://doi.org/10.1016/j.rser.2016.02.025.
[39] Lund H, Salgi G. The role of compressed air energy storage (CAES) in future sustainable energy systems. Energy Convers Manag 2009;50:1172–9.
[40] Kwon PS, Østergaard PA. Priority order in using biomass resources - energy systems analyses of future scenarios for Denmark. Energy 2013;63. https://doi.org/10.1016/j.energy.2013.10.005.
[41] Lund R, Mathiesen BV. Large combined heat and power plants in sustainable energy systems. Appl Energy 2015;142:389–95. https://doi.org/10.1016/j.apenergy.2015.01.013.
[42] Thellufsen JZ, Nielsen S, Lund H. Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland. J Clean Prod 2019. https://doi.org/10.1016/j.jclepro.2018.12.303.
[43] Lund H. Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach. Energy 2018;151. https://doi.org/10.1016/j.energy.2018.03.010.
[44] Hedegaard K, Mathiesen BV, Lund H, Heiselberg P. Wind power integration using individual heat pumps - analysis of different heat storage options. Energy 2012;47. https://doi.org/10.1016/j.energy.2012.09.030.
[45] Lund H, Kempton W. Integration of renewable energy into the transport and electricity sectors through V2G. Energy Pol 2008;36:3578–87. https://doi.org/10.1016/j.enpol.2008.06.007.
[46] Kwon PSPS, Østergaard P. Assessment and evaluation of flexible demand in a Danish future energy scenario. Appl Energy 2014;134:309–20. https://doi.org/10.1016/j.apenergy.2014.08.044.
[47] Djørup S, Thellufsen JZ, Sorknæs P. The electricity market in a renewable energy system. Energy 2018;162:148–57. https://doi.org/10.1016/J.ENERGY.2018.07.100.
[48] Sorknæs P, Lund H, Skov IR, Djørup S, Skytte K, Morthorst PE, et al. Smart Energy Markets - future electricity, gas and heating markets. Renew Sustain Energy Rev 2020;119. https://doi.org/10.1016/j.rser.2019.109655.
[49] Nielsen S, Sorknæs P, Østergaard PA. Electricity market auction settings in a future Danish electricity system with a high penetration of renewable energy sources - a comparison of marginal pricing and pay-as-bid. Energy 2011;36. https://doi.org/10.1016/j.energy.2011.03.079.
[50] Drysdale D, Mathiesen BV, Paardekooper S. Transitioning to a 100% renewable energy system in Denmark by 2050: assessing the impact from expanding the building stock at the same time. Energy Effic 2019. https://doi.org/10.1007/s12053-018-9649-1.
[51] Lund H, Thellufsen JZ, Aggerholm S, Wichtten KB, Nielsen S, Mathiesen BV, et al. Heat saving strategies in sustainable smart energy systems. Int J Sustain Energy Plan Manag 2014:3–16. https://doi.org/10.5278/ijsepm.2014.4.2. 04.
[52] Bačeković I, Østergaard PA. A smart energy system approach vs a non-integrated renewable energy system approach to designing a future energy system in Zagreb. Energy 2018;155. https://doi.org/10.1016/j.energy.2018.05.075.
[53] Bacekovic I, Østergaard PA. Local smart energy systems and cross-system integration. Energy 2018;151:812–25. https://doi.org/10.1016/j.energy.2018.03.098.
[54] Hansen K, Breyer C, Lund H. Status and perspectives on 100% renewable energy systems. Energy 2019;175:471–80. https://doi.org/10.1016/j.energy.2019.03.092.
[55] Mahbub MS, Cozzini M, Østergaard PA, Alberti F. Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design. Appl Energy 2016;164:140–51. https://doi.org/10.1016/j.apenergy.2015.11.042.
[56] Viesi D, Crema L, Mahbub MS, Verones S, Brunelli R, Baggio P, et al. Integrated and dynamic energy modelling of a regional system: a cost-optimized approach in the deep decarbonisation of the Province of Trento (Italy). Energy 2020:209. https://doi.org/10.1016/j.energy.2020.118378.
[57] Prina MG, Cozzini M, Garegnani G, Moser D, Oberegger UF, Vaccaro R, et al. Smart energy systems applied at urban level: the case of the municipality of Bressanone-Brixen. Int J Sustain Energy Plan Manag 2016;10:33–52. https://doi.org/10.5278/ijsepm.2016.10.4.
[58] Prina MG, Cozzini M, Garegnani G, Manzolini G, Moser D, Filippi Oberegger U, et al. Multi-objective optimization algorithm coupled to EnergyPLAN software: the EPLANopt model. Energy 2018;149:213–21. https://doi.org/10.1016/J.ENERGY.2018.02.050.
[59] Prina MG, Moser D, Vaccaro R, Sparber W. EPLANopt optimization model based on EnergyPLAN applied at regional level: the future competition on excess electricity production from renewables. Int J Sustain Energy Plan Manag 2020;27. https://doi.org/10.5278/ijsepm.3504.
[60] Prina MG, Lionetti M, Manzolini G, Sparber W, Moser D. Transition pathways optimization methodology through EnergyPLAN software for long-term energy planning. Appl Energy 2019;235:356–68. https://doi.org/10.1016/j.apenergy.2018.10.099.
[61] Cabrera P, Lund H, Thellufsen JZ, Sorknæs P. The MATLAB Toolbox for EnergyPLAN: a tool to extend energy planning studies. Sci Comput Program 2020;191:102405. https://doi.org/10.1016/j.scico.2020.102405.
[62] Pillai JR, Heussen K, Østergaard PA. Comparative analysis of hourly and dynamic power balancing models for validating future energy scenarios. Energy 2011;36. https://doi.org/10.1016/j.energy.2011.03.014.
[63] Østergaard PA. Ancillary services and the integration of substantial quantities of wind power. Appl Energy 2006;83. https://doi.org/10.1016/j.apenergy.2005.04.007.

[64] Mathiesen BV, 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. https://doi.org/10.1016/j.apenergy.2015.01.075.

[65] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems - a market operation based approach and understanding. Energy 2012;42:96–102. https://doi.org/10.1016/j.energy.2012.04.003.

[66] Lund H, Mathiesen BV, Connolly D, Østergaard PA, Vad Mathiesen B, Connolly D. Renewable energy systems - a smart energy systems approach to the choice and modelling of 100 % renewable solutions. Chem Eng Trans 2014;39:1–6. https://doi.org/10.3303/CET1439001.

[67] Lund H, Thellufsen JZ. EnergyPLAN - advanced energy systems analysis computer model. 2020. https://doi.org/10.5281/zenodo.4017214. Version 15.1.

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Early decarbonisation of the European energy system pays off

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For a given carbon budget over several decades, different transformation rates for the energy system yield starkly different results. Here we consider a budget of 33 $GtCO_2$ for the cumulative carbon dioxide emissions from the European electricity, heating, and transport sectors between 2020 and 2050, which represents Europe's contribution to the Paris Agreement. We have found that following an early and steady path in which emissions are strongly reduced in the first decade is more cost-effective than following a late and rapid path in which low initial reduction targets quickly deplete the carbon budget and require a sharp reduction later. We show that solar photovoltaic, onshore and offshore wind can become the cornerstone of a fully decarbonised energy system and that installation rates similar to historical maxima are required to achieve timely decarbonisation. Key to those results is a proper representation of existing balancing strategies through an open, hourly-resolved, networked model of the sector-coupled European energy system.

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Achieving a climate-neutral European Union in 2050[1] requires meeting the milestones in between. Although carbon emissions will most likely sink by 20% in 2020 relative to 1990[2], it is unclear whether the 40% objective settled for 2030 will be met. The national energy plans for the coming decade submitted by member states do not add up the necessary reduction to meet the target[3], while in the context of a European Green Deal a more ambitious reduction of 55% is under discussion in 2020[4].

A remaining global carbon budget of 800 Gigatons (Gt) of CO_2 can be emitted from 2018 onwards to limit the anthropogenic warming to 1.75 °C relative to the preindustrial period with a probability of >66%[5]. This is compatible with holding the temperature increase well below 2 °C as stated in the Paris Agreement. Different sharing principles can be used to split the global carbon budget into regions and countries[6]. Subtracting the CO_2 emissions in 2018 and 2019, and considering an equal per-capita distribution translates into a quota of 48 $GtCO_2$ for Europe. An approach that took into account historical emissions would lead to more ambitious targets for Europe than other regions[7]. Assuming that sectoral distribution of emissions within Europe remains at present values, the carbon budget for the generation of electricity and provision of heating in the residential and services sectors accounts for ~21 $GtCO_2$,[8] and Supplementary Note 1. The budget increases to 33 $GtCO_2$ when the transport sector is included.

Electricity generation is expected to spearhead the transition spurred by the dramatic cost reduction of wind energy[9] and solar photovoltaics (PV)[10,11]. A vast body of literature shows that a power system based on wind, solar and hydro generation can supply hourly electricity demand in Europe as long as proper balancing is provided[12–15]. This can be done by reinforcing interconnections among neighbouring countries[16] to smooth renewable fluctuations by regional aggregation or through temporal balancing using local storage[17–19]. Moreover, coupling the power system with other sectors could provide additional flexibilities facilitating the system operation and simultaneously helping to abate emissions in those sectors[20–22].

CO_2 emissions from heating in the residential and services sectors show a more modest historical reduction trend compared to electricity generation (Fig. 1). Nordic countries have been particularly successful in reducing carbon emissions from the heating sector by using sector-coupling strategies, Supplementary Figs. 2 and 3. Denmark, where more than half of the households are connected to district heating systems[23], has shifted the fuel used in Combined Heat and Power (CHP) units from coal to biomass and urban waste incineration[24]. Sweden encouraged a large-scale switch from electric resistance heaters to heat pumps[23] which are now supported by high CO_2 prices[25] and low electricity taxes.

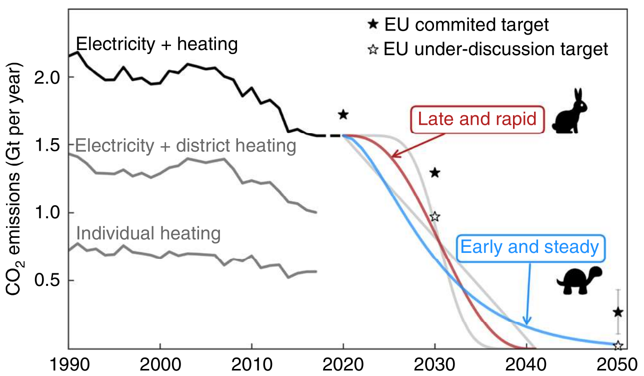

Fig. 1 Historical CO_2 emissions from the European power system and heating supply in the residential and services sectors. Data from EEA[8]. The various future transition paths shown in the figure have the same cumulative CO_2 emissions, which correspond to the remaining 21 $GtCO_2$ budget to avoid human-induced warming above 1.75 °C with a probability of >66%, assuming current sectoral distribution for Europe, and equity sharing principle among regions. Black stars indicate committed EU reduction targets, while white stars mark targets under discussion in 2020. See also Supplementary Fig. 1.

Energy models assuming greenfield optimisation, that is, building the European energy system from scratch without considering current capacities, shows that sector-coupling decreases the system cost and reduces the need for extending transmission lines due to the additional local flexibility brought by the heating and transport sectors[21]. Sector-coupling allows large CO_2 reductions before large capacities of storage become necessary, providing more time to further develop storage technologies[19]. Greenfield optimisation is useful to investigate the optimal configuration of the fully decarbonised system, but it does not provide insights on how to transition towards it. Today's generation fleet and decisions taken in intermediate steps will shape the final configuration.

Transition paths for the European power system have been analysed using myopic optimisation, i.e., without full foresight over the investment horizon[26–29]. Myopic optimisation results in higher cumulative system cost than optimising the entire transition period with perfect foresight because the former leads to stranded investments[28,30]. However, the myopic approach is less sensitive to the assumed discount rate and can capture better short-sighted behaviour of political actors and investors[28,29].

Transition paths under stringent carbon budgets have been mainly investigated using Integrated Assessment Models (IAMs), which represent a broader approach including other sectors, globe, land and climate models[10,31–33]. However, the low temporal resolution and outdated cost assumptions for wind and solar PV[10,34] in IAMs could hinder the role that renewable technologies could play in decarbonising the energy sector.

In this work, we use an hourly resolved sector-coupled networked model of the European energy system and myopic optimisation in 5 years steps from 2020 to 2050 to investigate the impact of different CO_2 reduction paths with the same carbon budget. In every time step, the expansion of generation, storage and interconnection capacities in every country is allowed if it is cost-effective under the corresponding global emissions constraint. We show that up-to-date costs for wind and solar, that take into account recent capacity additions and technological learning, together with proper representation of balancing strategies make a fully decarbonised system based on those technologies cost-effective. Furthermore, we find that a transition path with more ambitious short-term CO_2 targets reduces the cumulative system cost and requires a smoother increase of the CO_2 price and more stable build rates. Our research includes the coupling with heating and transport sectors, which is absent in transition path analyses for the European power system[27–29], incorporates the notion of carbon budget to the analysis, and captures relevant weather-driven variability due to hourly and non-interrupted time stepping. Moreover, we use an open model, which ensures transparency and reproducibility of the results[35].

Results

First, we investigate the consequences of following two alternative transition paths for the electricity and heating coupled system. The transport sector is added at the end of this section. The baseline analysis assumes that district heating penetration remains constant at present values, annual heat demand is constant throughout the transition paths, and power transmission

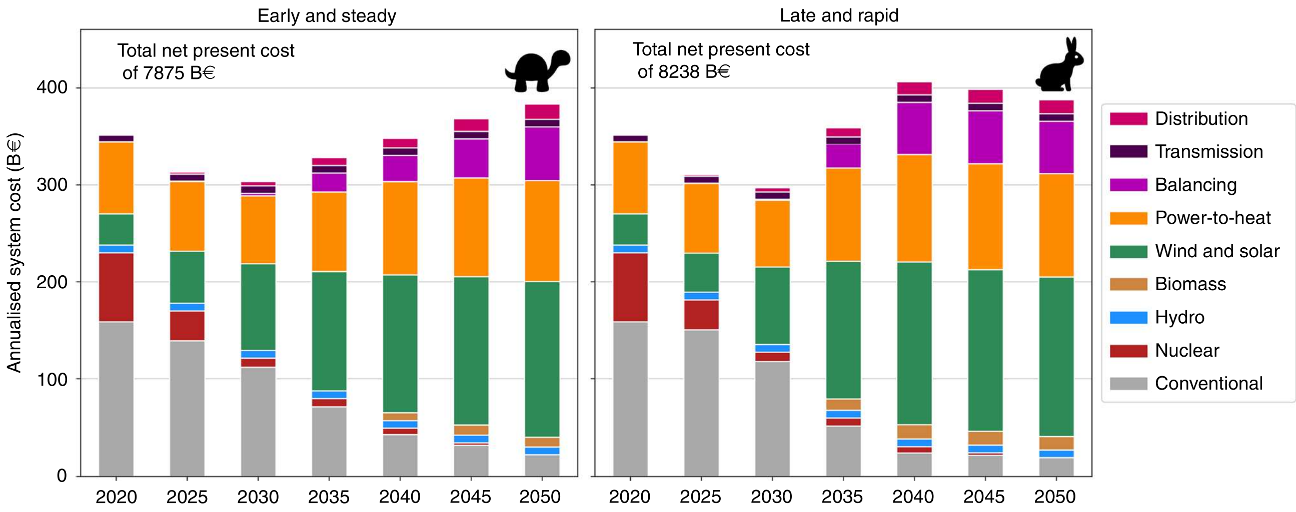

Fig. 2 Annualised system cost for the European electricity and heating system throughout transition paths Early and Steady and Late and Rapid shown in Fig. 1. Conventional includes costs associated with coal, lignite and gas power plants producing electricity as well as costs for fossil-fuelled boilers and CHP units. Power-to-heat includes costs associated with heat pumps and heat resistors. Balancing includes costs of electric batteries, H_2 storage and methanation.

capacities are expanded as planned in the TYNDP[36] up to 2030 and fixed after that year. The impacts of these assumptions are assessed later. The Early and Steady path represents a cautious approach in which significant emissions reductions are attained in the early years. In the Late and Rapid path, the low initial reduction targets quickly deplete the carbon budget, requiring a sharp reduction later. As in Aesop's fable "The Tortoise and the Hare", the tortoise wins the race by making steady progress, whereas following the hare and delaying climate action requires a late acceleration that will be more expensive.

Cumulative costs and system configuration. The two alternative paths arrive at a similar system configuration in 2050, Fig. 2. Towards the end of the period, under heavy CO_2 restriction, balancing technologies appear in the system. They include large storage capacities comprising electric batteries and hydrogen storage, and production of synthetic methane. Cumulative system cost for the Early and Steady path represents 7875 billion euros (B €), while the Late and Rapid path accounts for 8238 B€. It is worth remarking that the cumulative cost remains lower for the Early and Steady path provided that social discount rates <15% are assumed. In 2050, the cost per unit of delivered energy (including electricity and thermal energy) is ~59 €/MWh. The newly built conventional capacity for electricity generation is very modest in both cases, Fig. 3 and Supplementary Fig. 5. No new lignite, coal or nuclear capacity is installed. Thus, at the end of both paths, conventional technologies include only gas-fuelled power plants, CHP and boilers. Biomass contributes to balancing renewable power but plays a minor role.

Decarbonising the power system has proven to be cheaper than the heating sector[37]. Consequently, although CO_2 allowances differ, the electricity sector gets quickly decarbonised in both paths and more notable differences appear in new conventional heating capacities, Fig. 4. In both paths, yearly costs initially decrease as the power system takes advantage of the low costs of wind and solar. Removing the final emissions in heating causes total costs to rise again towards 2050. The main reason behind the higher cumulative system cost for the Late and Rapid strategy is that the earlier depletion of carbon budget forces it to reach zero emissions by 2040 when renewable generation and balancing technologies are more expensive than in 2050.

Stranded assets. Part of the already existing conventional capacities become stranded assets, in particular, coal, lignite, CCGT (which was heavily deployed in the early 2000s, Fig. 3) and gas boilers. As renewable capacities deploy, utilisation factors for conventional power plants decline and they do not recover their total expenditure via market revenues, Supplementary Figs. 11–14. Up to 2035, operational expenditure for gas-fuelled technologies are lower than market revenues so they are expected to remain in operation. Contrary to what was expected, the sum of expenditures not recovered via market revenues is similar for both paths. In the Late and Rapid path, the high CO_2 price resulting from the zero-emissions constraint, justify producing up to 220 TWh/a of synthetic methane already in 2040, Supplementary Fig. 10. This enables CCGT and gas boilers to keep operating allowing them to recover part of their capital expenditure, but the consequence is a higher cumulative system cost, as previously discussed. Stranded costs, that is the sum of expenditures not recovered via market revenues, represent ~12% of the total cumulative system cost in both paths. Although closing plants early might be seen as an unnecessary contribution to a higher cost of energy, it must be remarked that the early retirement of electricity infrastructure has been identified as one of the most cost-effective actions to reduce committed emissions and enable a 2 °C-compatible future evolution of global emissions[38].

Transition smoothness. Wind and solar PV supply most of the electricity demand in 2050, complemented by hydro and with a minor biomass contribution. Previously, most IAMs have emphasised the importance of bioenergy or carbon capture and storage and failed to identify the key role of solar PV due to their unrealistically high-cost assumptions for this technology, see refs. [10,34] and Supplementary Note 4.2. The paths described here require a massive deployment of wind and solar PV during the next 30 years. In the past, Germany and Italy have shown record installation rates for solar PV of 8 and 10 GW/a, Supplementary Fig. 4. Since those countries account for 16% and 10% of electricity demand in Europe, those rates would be equivalent to 50 and 100 GW/a at a European level. Decarbonising the electricity and heating sectors through the Early and Steady path requires similar installation rates, Fig. 3. Consequently, attaining higher build rates to also decarbonise transport and industry sectors seems challenging yet possible.

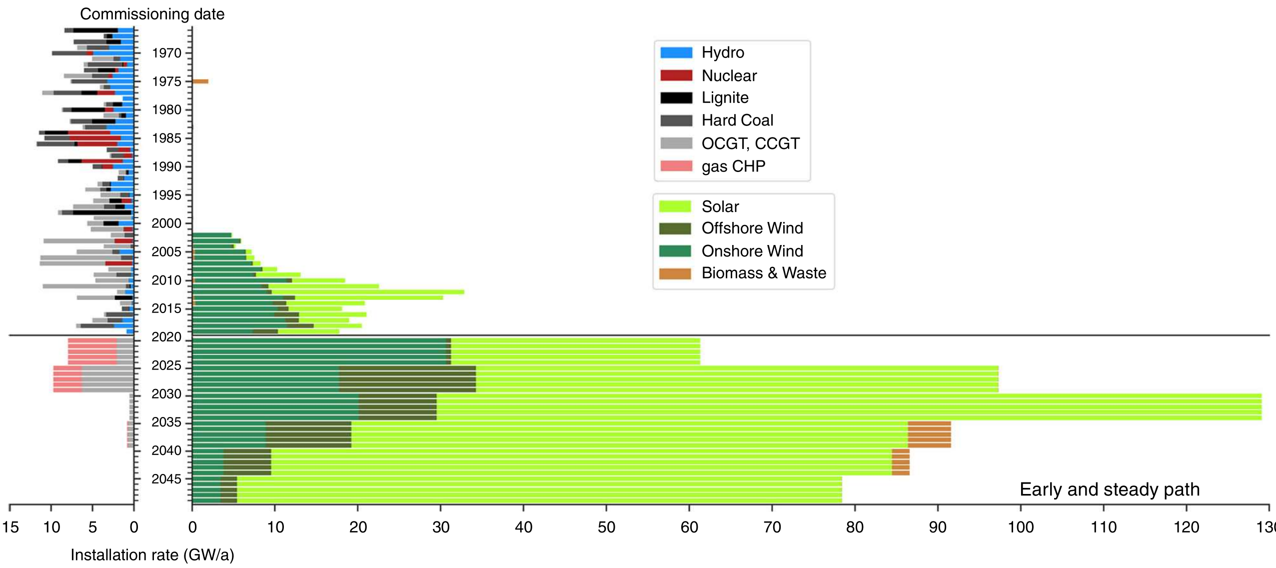

Fig. 3 Age distribution of European power plants in operation and required annual installation throughout the Early and Steady path. Historical data from refs. [53,67], see also Supplementary Figs. 5–10.

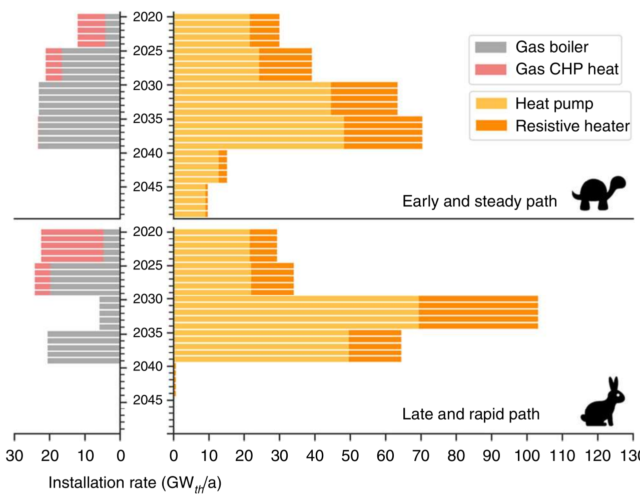

Fig. 4 Required expansion of heating capacities in both paths. Maximum heating capacities are shown for CHP plants.

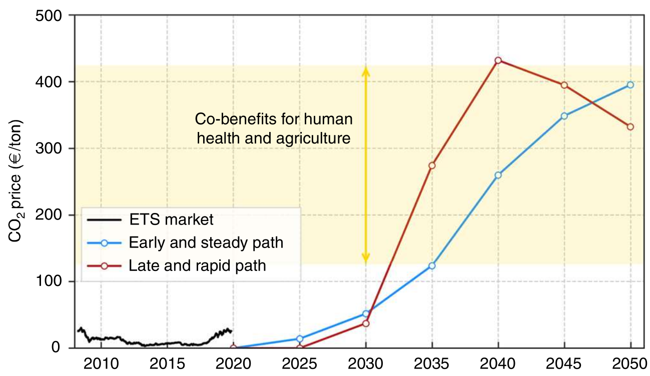

Fig. 5 Historical evolution of CO_2 price in the EU Emissions Trading System[68] and required CO_2 price obtained from the model throughout transition paths shown in Fig. 1. Co-benefits of reducing CO_2 emissions in Europe due to avoided premature mortality, reduced lost workdays and increased crop yields are estimated in the range of 125–425 €/ton CO_2[43].

During the past decade, several European countries have shown sudden increments in the annual build rate for solar PV, followed by equivalent decrements one or two years later, Supplementary Fig. 4. Italy, Germany, UK and Spain show clear peaks due to the combination of a fast cost decrease of the technology and unstable regulatory frameworks whose details are country-specific[39–41]. These peaks can have negative consequences for local businesses. The sudden shrinkage of annual build capacity might result in companies bankruptcy and lost jobs. The Early and Steady path requires a smoother evolution of build rates which could better accommodate the cultural, political, and social aspects of the transition[42], and Supplementary Fig. 15. The mild evolution could also facilitate reaching a stationary situation in which build rates offset decommissioning.

The required CO_2 price at every 5-years time step, Fig. 5, is an outcome of the model, i.e., it is the Lagrange/KKT multiplier associated with the maximum CO_2 constraint. The fact that results indicate zero CO_2 price in 2020 means that the constraint is not binding, that is, the cost of renewable technologies makes the system cost-effective without the constraint. As the CO_2 emissions are restricted, a higher CO_2 price is needed to remain below the CO_2 limit. Towards the end of the transition, CO_2 prices much higher than those historically attained in the ETS market are needed. The Early and Steady path requires a smoother evolution of CO_2 price, which might be preferred by investors. Two remarks should be made. First, reducing CO_2 emissions implies significant co-benefits in Europe associated with avoided premature mortality, reduced lost workdays and increased crop yields. Those cost benefits are estimated at 125–425 €/ton CO_2[43], which is similar to the required CO_2 prices at the end of the path. On top of that, economic benefits of mitigating climate change impacts have also been estimated in hundreds of €/ton CO_2. Second, CO_2 price is mainly an indicator of the price gap between polluting and clean technologies and several policies can be established to fill that gap. Among others, sector-specific CO_2 taxes[25], direct support for renewables that reduce investor risk, and consequently the cost of capital and LCOE of the technology[44], or regulatory frameworks that incentivise the required technologies such those promoting rooftop PV installations or ensuring the competitiveness of district heating systems.

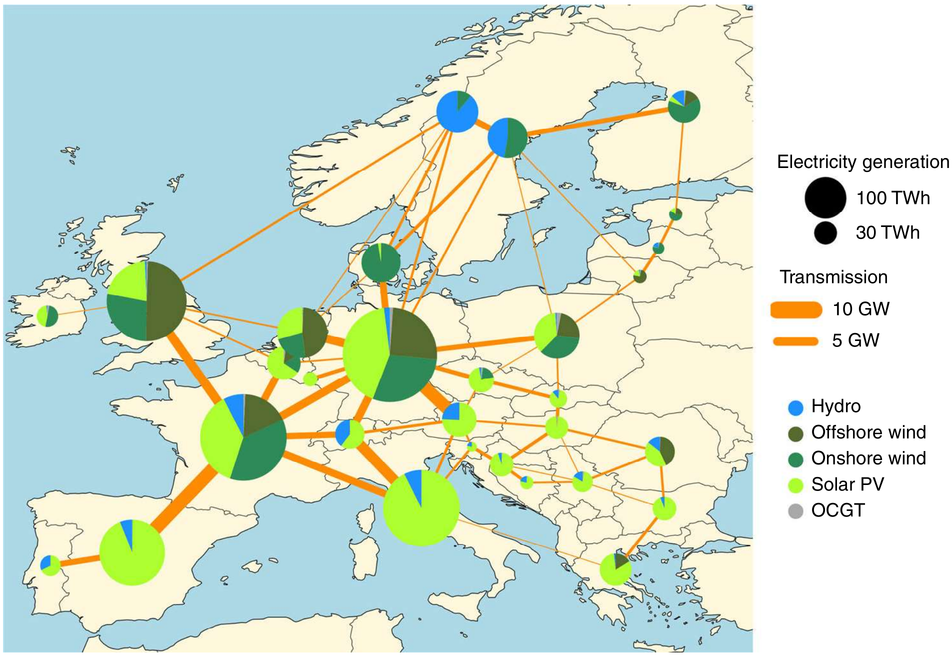

Fig. 6 Electricity generation in 2050 in the Early and Steady path. Evolution of the electricity mix throughout the transition and country-specific results are included in Supplementary Fig. 16.

Country and hourly resolved results. Figure 6 depicts the electricity mix at the end of the Early and Steady path. As expected, southern countries exploit solar resource while northern countries rely mostly on offshore and onshore wind. At every time step, the optimal renewable mix in every country depends on the local resources and the already existing capacities, see Supplementary Figs. 16 and 17. Nevertheless, the analysis of near-optimal solutions has recently shown that country-specific mixes can vary significantly while keeping the total system cost only slightly higher than the minimum[45].

Modelling an entire year with hourly resolution unveils the strong links between renewable generation technologies and balancing strategies. For countries and years in which large solar PV capacities are deployed, it is also cost-effective to install large battery capacities to smooth the strong daily solar generation pattern. Conversely, onshore and offshore wind capacities require hydrogen storage and reinforced interconnections to balance wind synoptic fluctuations[13,17,19]. This can also be appreciated by looking at the dominant dispatch frequencies of the Europe-aggregated time series in 2050, Fig. 7 and Supplementary Fig. 18.

IAMs and partial equilibrium models with similar spatial resolution have also been used to investigate the sector-coupled decarbonisation of Europe[1,10,46]. However, those models typically use a much lower time resolution, e.g., using a few time slices to represent a full year[29,46–49] or considering the residual load duration curve[10,50], and some IAMs assume very high integration costs for renewables[51]. The hourly and non-interrupted time stepping in our model reveals several effects that are critical to the operation of highly renewable systems. First, solar and wind power generation is variable but correlated. The grid can effectively contribute to its smoothing by regional integration and storage technologies with different dispatch frequencies required to balance solar and wind fluctuations, Fig. 7. Second, long-term storage plays a key role in balancing seasonal variation and ease the system operation during cold spells, i.e., a cold week with low wind and solar generation[21].

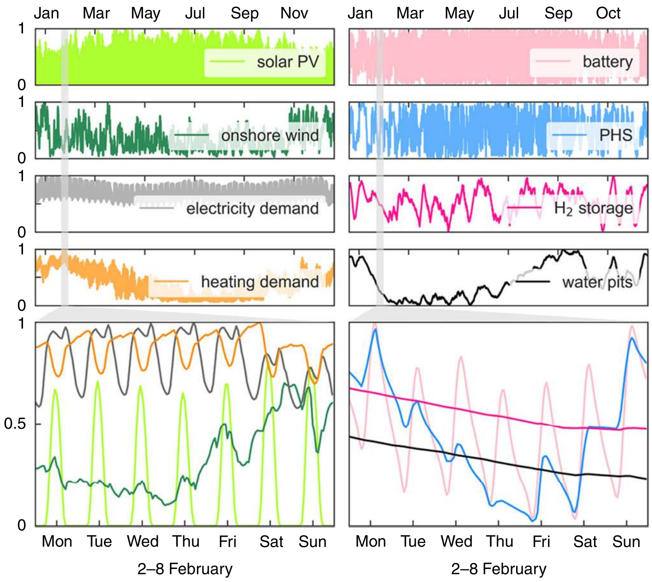

Fig. 7 Time series for the Europe-aggregated demand, generation and storage technologies dispatch for the Early and Steady path in 2050. The bottom figures depicts the system operation throughout one of the most critical weeks of the year (comprising high heating demand, low wind and solar generation). Hydrogen storage discharges and fuel cells help to cover the electricity deficit, hot water pits in district heating systems discharge stored thermal energy to supply heat demand.

Results robust under different scenarios. In Nordic countries, district heating (DH) has proven to be useful to decarbonise the heating sector, Supplementary Fig. 2. It allows lower cost large-scale technologies such as heat pumps and CHP units, enables a faster conversion because it is easier to substitute one central heating unit than a myriad of individual domestic systems, and facilitates long-term thermal energy storage, via cheap large water pits, Fig. 7, that help to balance the large seasonal variation of heating demand, Supplementary Fig. 24. So far, we have assumed

Table 1 Cumulative system costs (B€) for additional analyses.

Analysis	Early and Steady path	Late and Rapid path	Difference	Change relative to Baseline (Early and Steady) (%)
Baseline	7875	8238	363	
District heating expansion	7688	8003	315	−187 (−2.4)
Space heat savings due to building renovation	6989	7319	330	−886 (−11.3)
Transmission expansion after 2030	7771	8081	310	−104 (−1.3)
Including road and rail transport	8303	8753	450	+428 (+5.4)

that DH penetration remains constant at 2015 values. When DH is assumed to expand linearly so that in 2050 it supplies the entire urban heating demand in every country, cumulative system cost for the Early and Steady path reduces by 2.4%. This roughly offsets the cost of extending and maintaining the DH networks and avoids the additional expansion of gas distribution networks, Supplementary Note 4.5.

We now look at the impact of efficiency measurements by modifying the constant heat demand assumption. When a 2% reduction of space heating demand per year is assumed due to renovations of the building stock, while demand for hot water is kept constant and rebound effects are neglected, cumulative system cost decreases by 11.3%, significantly offsetting costs of renovations, Supplementary Note 4.6.

When the model is allowed to optimise transmission capacities after 2030, together with the generation and storage assets, the optimal configuration at the end of the paths includes a transmission volume approximately three times higher than that of 2030. The reinforced interconnections contribute to the spatial smoothing of wind fluctuations, increasing the optimal onshore and offshore wind capacities at the end of the path. The required energy capacity for hydrogen storage is reduced due to the contribution of interconnections to balancing wind generation. Although the cumulative system cost is 1.3% lower, it is unclear to what extent it compensates the social acceptance issues associated with extending transmission capacities.

Neither of the paths installs new nuclear capacity. This technology is only part of the optimal system in 2050 when nuclear costs are lower by 15% compared to the reference cost and no transmission capacity expansion is allowed. In all the previous scenarios, the difference in cumulative system cost for the Early and Steady and the Late and Rapid path is roughly the same, Table 1.

Adding the transport sector. Finally, both paths are re-run including the coupling of road and rail transport. The number of Battery Electric Vehicles (BEVs) is not an outcome of the optimisation but an exogenous input parameter. This assumes that people's decision to shifts to BEVs is mainly dictated by their mobility needs and not by the optimal operation of the energy system. The cost of BEVs and their batteries are not included in the results. For every time step, the percentage of road and rail transport that is electrified is assumed to follow the path of CO_2 emissions reduction in the electricity and heating sectors. In this way, emissions in transport sink roughly parallel to those of heating and electricity sectors. Road and rail transport is modelled as a lumped demand in every country. The details of the model for this sector are described in Supplementary Note 3.5. At every time step, half of the passenger car BEVs present in the model are assumed to allow demand-side management and a quarter of the available BEVs are assumed to provide vehicle-to-grid (V2G) services. The possible use of hydrogen in the transport sector is not considered.

For the Early and Steady path, cumulative system cost increase by 5.4%. The system cost increase was expected, since, when fully electrified, road and rail transport increase electricity demand by 1102 TWh_{el}/a. However, the evolution of LCOE remains similar throughout the transition, Supplementary Figs. 6 and 20. The additional flexibility provided by BEVs reduces the need for stationary batteries and incentivises a higher solar PV penetration, as previously observed[19,21]. The impacts of the percentage of BEVs allowing smart charging and V2G services were analysed in detail in Brown et al.[21] where it is shown that the initial 25% of vehicles doing V2G captures the highest cost reductions.

Discussion

In this section, we briefly compare our results with other relevant decarbonisation pathways for Europe and indicate the main limitations of this study.

The analysis accompanying the EU *Clean Planet for All* strategy[1] comprises 8 scenarios, three of which are compatible with limiting temperature increase at the end of the century to 1.5 °C. All of them include a nuclear capacity >85 GW in 2050. Most probably this is a result of the lower cost assumed for nuclear in ref. [1]. Scenario 1.5Life in ref. [1] assumes significant changes in lifestyle and consumer choices, while Scenario 1.5Tech relies on bioenergy with carbon capture and storage (BECCS). In ENTSO-E scenario report[36], biomass accounts for >30% of the electricity mix in 2050. Using cost-optimisation we have shown that a decarbonised European electricity mix based mainly on wind and solar is cost-effective. It can also avoid the concerns associated with nuclear, biomass and BECCS. A proper evaluation of feasibility requires a multidimensional approach which on top of the land availability, technological and economical aspects considered here, includes also social acceptance, institutions and politics. Although that evaluation is out of the scope of this work, the gradual transition described in the Early and Steady path could potentially be beneficial when those aspects are taken into consideration.

A recent analysis of the globally cost-effective emission pathways for the emissions cap in the EU ETS showed that increasing the linear reduction factor for 2021–2030 from the current value of 2.2 to 4% is cost-effective[52]. This is supported by the increase in renewable penetration and efficiency targets for 2030 and the coal phase-out plans of several European countries. For the ETS sectors, failing to reduce emissions in the next decade would require a drastic reduction after 2030 that implies higher cumulative costs[52]. The results in this paper, which include also non-ETS sectors such as transport and domestic heating supply, support this recommendation.

The database of existing power plants was described and validated in a separate publication[53]. The power system model PyPSA-Eur including load, generation and a detail transmission network, was validated in Hörsch et al.[54], while the interplay of generation and network with regards historical curtailment levels was examined in Frysztacki et al.[55]. Data on the existing heating was taken from ref. [56].

Our model uses hourly resolution, but as renewable penetration increases, adaptation will also be required to ensure system stability at shorter time scales. Several strategies are being developed and implemented to ensure sufficient power system inertia and the provision of reserve requirements and ancillary services[15,57]. Synchronous compensators to provide reactive power and inertia are already used in Denmark[58] and conventional power plants can be retrofitted to become such synchronous compensators. Grid-forming inverters in batteries and non-synchronous generators can regulate the system frequency and voltage[57,59]. Solar and wind generation can contribute to downward regulation by curtailing and to upward regulation when operating at reduced capacity as well as storage and demand response from new electrified loads like electric vehicles and heat pumps[57]. The existing literature[15,57] and historical field experience do not indicate any major limitation to ensure the feasibility of highly renewable power system at short time scales.

This study uses one single year of weather data. The system cost for a highly decarbonised European power system was found to be robust to different weather years[60], but more analysis is needed on the impact of inter-annual weather variability for the sector-coupled energy system. Climate change will have a twofold impact. On the generation side, correlation lengths for wind energy are predicted to increase in Europe, reducing the efficacy of transmission grids for balancing[61]. Minor changes in solar generation[62], and significant variations on the hydro inflow seasonal patterns are expected[61]. On the demand side, the increase in cooling demand in southern European countries, and more relevant, the reduction of heating demand in northern countries are expected to reduce the system cost[63].

Low social acceptance for onshore wind and utility-scale solar may limit expansion of these technologies in some countries. Reducing onshore wind installable potentials was shown in Schlachtberger et al.[60] to cause a larger expansion of offshore wind and have a limited impact on total system costs. In our model, hydrogen is assumed to be produced and consumed within the same country and transport of hydrogen is not included. The possible future retrofitting of existing nuclear power plants or the deployment of coal power plants with carbon capture and storage (CCS) are not included in the model. The aforementioned limitations could impact the model results but they are not expected to modify the main conclusions obtained in this study. Finally, this study focuses on the European energy system because the European Union has a shared decarbonisation strategy and a common commitment via the Paris agreement. Moreover, the power systems of member states are already interconnected. Neglecting the interconnection of Europe with other regions and their mutual interdependence is a limitation of the analysis.

In conclusions, when comparing alternative transition paths for the European energy system with the same carbon budget, we find that a transition including an early and steady CO_2 reduction is consistently ~350 B€UR cheaper than a path where low targets in the initial period demand a sharper reduction later. Our results support the proposal to increase the ambition in the EU CO_2 reduction target for 2030 under discussion in 2020[4]. We found that up-to-date costs for wind and solar and the inclusion of highly resolved time series for balancing allows a fully decarbonised system relying on those technologies together with hydropower and minor contribution from biomass. The required renewable build rates to decarbonise the electricity and heating sectors correspond to the highest historical values, making the transition challenging yet possible. We have shown that early action not only allows room for decision-making later but it also pays off.

Methods

The system configuration is optimised by minimising annualised system cost in every time step (one every 5 years), under the global CO_2 emissions cap imposed by the transition path under analysis (Fig. 1). This can be considered a myopic approach since the optimisation has no information about the future. The cumulative CO_2 emissions for the transition paths is equal to a carbon budget of 21 $GtCO_2$ when only the electricity and heating sectors are included. It represents 33 $GtCO_2$ when the transport sector is included. In every time step, generation, storage and transmission capacities in every country are optimised assuming perfect competition and foresight as well as a long-term market equilibrium. Besides the global CO_2 emission cap, other constraints such as the demand-supply balance at every node, and capacity limitations are imposed to ensure the feasibility of the solution, see Supplementary Note 2.

We use a one-node-per-country network, including 30 countries corresponding to the 28 European Union member states as of 2018 excluding Malta and Cyprus but including Norway, Switzerland, Bosnia-Herzegovina and Serbia, see Fig. 6. Countries are connected by High Voltage Direct Current (HVDC) links whose capacities can be expanded if it is cost-effective. Figure 8 provides an overview of

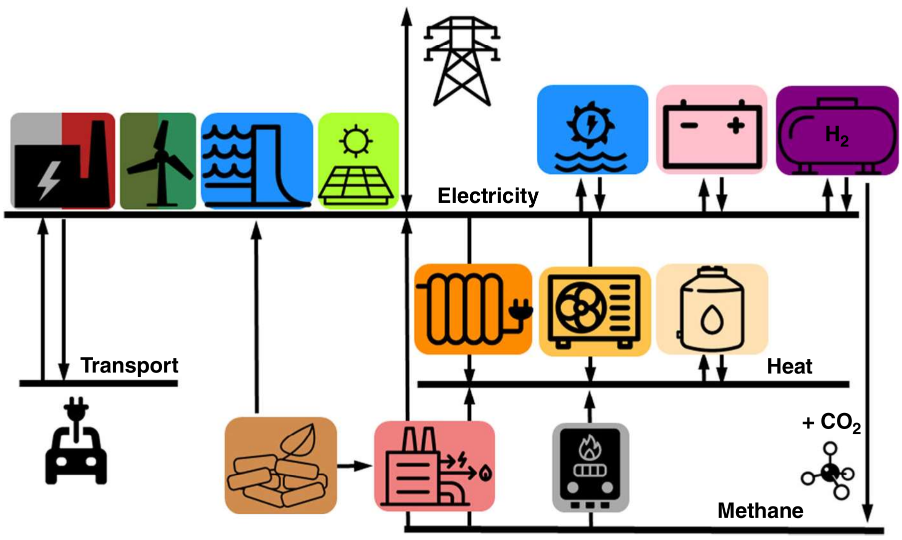

Fig. 8 Model diagram representing the main generation and storage technologies in every country. Electricity can be produced with conventional power plants (nuclear, coal, lignite and gas), reservoir and run-of-river hydro, as well as solar PV, onshore and offshore wind. It can be stored in pumped hydro storage, battery and hydrogen storage. Heating can be supplied via heat resistors, heat pumps and gas boilers. It can be stored in thermal energy storage. Combined heat and power (CHP) can use methane and biomass. Electrolytic hydrogen can be combined with direct air capture CO_2 to produce synthetic methane. When the transport sector is included, half of the battery electric vehicles allow smart charging and a quarter provide vehicle-to-grid services.

the technologies included in the model. In the power sector, electricity can be supplied by onshore and offshore wind, solar photovoltaics (PV), hydroelectricity, Open Cycle Gas Turbines (OCGT), Combined Cycle Gas Turbines (CCGT), Coal, Lignite, and Nuclear power plants and Combined Heat and Power (CHP) units using gas, coal or biomass. Electricity can be stored using Pumped Hydro Storage (PHS), stationary electric batteries and hydrogen storage. Hydrogen is produced via electrolysers and converted back into electricity using fuel cells. Methane can be produced by combining Direct Air Capture (DAC) CO_2 and electrolytic-H_2 in the Sabatier reaction. Heating demand is split into urban heating demand, corresponding to regions whose population density allows district heating, and rural heating demand where only individual solutions are allowed. Heating can be supplied via large-scale heat pumps, heat resistors, gas boilers, solar collectors and CHP units for urban regions, while only individual heat pumps, electric boilers and gas boilers can be used in rural areas. Thermal energy storage can be installed both in district heating networks and in individual homes. A detailed description of all the sectors is provided in Supplementary Note 3.

Costs assumed for the different technologies depend on time (Supplementary Note 4) but not on the cumulative installed capacity since we assume that they will be influenced by the predicted global installation rates and learning curves. The financial discount rate applied to annualise costs is equal to 7% for every technology and country. Although it can be strongly impacted by the maturity of a technology, including the country-specific experience with the technology, and the credit rating of a country[64], we assumed European countries to be similar enough to use a constant discount rate. For decentral solutions, such as rooftop PV or small water tanks, a discount rate equal to 4% is considered based on the assumption that individuals have lower expectations for return on capital[65]. The already installed capacities, i.e., existing capacities in 2020 or capacities installed in a previous year whose lifetime has not concluded, are exogenously included in the model. For every time step, the total system cost includes annualised and running cost for newly installed assets and for exogenously fixed capacities. For those fossil fuel generators that were installed in a previous year and are not used due to the stringent CO_2 emissions constraint, their annualised costs are included in the total system cost (see Fig. 2 in the Results section) as long as the end of their assumed technical lifetime is not reached.

To estimate the cumulative cost of every transition path, the annualised cost for all years are added up assuming a social discount rate of 2%. This rate represents how society compares investments in far-future years with investments in the present, and is chosen by comparison with the average growth rate of 1.6% over the past 20 years in the European Union. The CO_2 price is not an input to the model, but a result that is obtained via the Lagrange/Karush-Kuhn-Tucker multiplier associated with the global CO_2 constraint, see Supplementary Note 2.

Data availability

The datasets used as input as well as the data generated by the model are available in a public repository 10.5281/zenodo.4010643.

Code availability

The model is implemented in the open-source framework Python for Power System Analysis (PyPSA)[66]. The model instance used in this paper can be retrieved from the open repository 10.5281/zenodo.4014807.

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References

1. In-depth analysis in support of the Comission Communication COM (2018) 773 A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. (2018) https://ec.europa.eu/knowledge4policy/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en.
2. EEA, Total greenhouse gas emissions, trends and projections. https://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends-6/assessment-3.
3. EU comission appraisal on national energy and climate plans. (2019) https://ec.europa.eu/commission/presscorner/detail/546%20en/IP_19_2993.
4. The European Green Deal. Comunication from the Commission to the European Parliment. (2019) https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf.
5. IPCC. Global Warming of 1.5 °C, Intergovernmental Panel on Climate Change. (2018) https://www.ipcc.ch/sr15/.
6. Raupach, M. R. et al. Sharing a quota on cumulative carbon emissions. *Nat. Clim. Change* **4**, 873–879 (2014).
7. Matthews, H. D. Quantifying historical carbon and climate debts among nations. *Nat. Clim. Change* **6**, 60–64 (2016).
8. EEA. National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism. https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16
9. Lantz, E., Wiser, R. & Hand, M. The past and future cost of wind energy. NREL (2012) https://www.nrel.gov/docs/fy12osti/53510.pdf.
10. Creutzig, F. et al. The underestimated potential of solar energy to mitigate climate change. *Nat. Energy* **2**,17140 (2017).
11. Haegel, N. M. et al. Terawatt-scale photovoltaics: transform global energy. *Science* **364**, 836–838 (2019).
12. Eriksen, E. H., Schwenk-Nebbe, L. J., Tranberg, B., Brown, T. & Greiner, M. Optimal heterogeneity in a simplified highly renewable European electricity system. *Energy* **133**, 913–928 (2017).
13. Schlachtberger, D. P., Brown, T., Schramm, S. & Greiner, M. The benefits of cooperation in a highly renewable European electricity network. *Energy* **134**, 469–481 (2017).
14. Gils, H. C., Scholz, Y., Pregger, T., de Tena, D. L. & Heide, D. Integrated modelling of variable renewable energy-based power supply in Europe. *Energy* **123**, 173–188 (2017).
15. Brown, T. W. et al. Response to Burden of proof: a comprehensive review of the feasibility of 100% renewable-electricity systems'. *Renew. Sustain. Energy Rev.* **92**, 834–847 (2018).
16. Rodríguez, R. A., Becker, S., Andresen, G. B., Heide, D. & Greiner, M. Transmission needs across a fully renewable European power system. *Renew. Energy* **63**, 467–476 (2014).
17. Rasmussen, M. G., Andresen, G. B. & Greiner, M. Storage and balancing synergies in a fully or highly renewable pan-European power system. *Energy Policy* **51**, 642 – 651 (2012).
18. Cebulla, F., Naegler, T. & Pohl, M. Electrical energy storage in highly renewable European energy systems: capacity requirements, spatial distribution, and storage dispatch. *J. Energy Storage* **14**, 211–223 (2017).
19. Victoria, M., Zhu, K., Brown, T., Andresen, G. B. & Greiner, M. The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system. *Energy Convers. Manag.* **201**, 111977 (2019).
20. 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.* **60**, 1634–1653 (2016).
21. 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* **160**, 720–739 (2018).
22. Child, M., Kemfert, C., Bogdanov, D. & Breyer, C. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. *Renew. Energy* **139**, 80–101 (2019).
23. Gross, R. & Hanna, R. Path dependency in provision of domestic heating. *Nat. Energy* **4**, 358–364 (2019).
24. Danish Energy Agency. Regulation and planning of district heating in Denmark. (2015) https://ens.dk/sites/ens.dk/files/contents/material/file/regulation_and_planning_of_district_heating_in_denmark.pdf.
25. World Bank Group. State and Trends of Carbon Pricing 2019. (2019) https://openknowledge.worldbank.org/handle/10986/31755.
26. Bogdanov, D. et al. Radical transformation pathway towards sustainable electricity via evolutionary steps. *Nat. Commun.* **10**, 1–16 (2019).
27. Pleßmann, G. & Blechinger, P. How to meet EU GHG emission reduction targets? A model based decarbonization pathway for Europe's electricity supply system until 2050. *Energy Strategy Rev.* **15**, 19–32 (2017).
28. Gerbaulet, C., von Hirschhausen, C., Kemfert, C., Lorenz, C. & Oei, P. Y. European electricity sector decarbonization under different levels of foresight. *Renew. Energy* **141**, 973–987 (2019).
29. Poncelet, K., Delarue, E., Six, D. & D'haeseleer, W. Myopic optimization models for simulation of investment decisions in the electric power sector. In *13th International Conference on the European Energy Market (EEM)*, 1–9 (IEEE, 2016).
30. Heuberger, C. F., Staffell, I., Shah, N. & Dowell, N. M. Impact of myopic decision-making and disruptive events in power systems planning. *Nat. Energy* **3**, 634–640 (2019).
31. Rogelj, J. et al. Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nat. Clim. Change* **8**, 325–332 (2018).
32. van Vuuren, D. P. et al. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat. Clim. Change* **8**, 391–397 (2018).
33. Grubler, A. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515–527 (2018).
34. Krey, V. et al. Looking under the hood: a comparison of techno-economic assumptions across national and global integrated assessment models. *Energy* **172**, 1254–1267 (2019).
35. Pfenninger, S. Energy scientists must show their workings. *Nature* **542**, 393 (2017).

36. ENTSOE TYNDP. Ten Years Network Development Plan 2020, Scenario Report (2019).
37. Zhu, K., Victoria, M., Brown, T., Andresen, G. B. & Greiner, M. Impact of CO2 prices on the design of a highly decarbonised coupled electricity and heating system in Europe. *Appl. Energy* **236**, 622–634 https://doi.org/10.1016/j.apenergy.2018.12.016 (2019).
38. Tong, D. et al. Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. *Nature* **572**, 373–377 (2019).
39. Chase, J. *Solar Power Finance Without the Jargon*. (World Scientific, Singapore, 2019).
40. Photovoltaics Report. Fraunhofer ISE (2019).
41. Victoria, M., Gallego, C., Anton, I. & Sala, G. Past, Present and Future of Feed-in Tariffs in Spain: What are their Real Costs? *27th European Photovoltaic Solar Energy Conference and Exhibition*. 4612–4616 https://doi.org/10.4229/27thEUPVSEC2012-6CV.3.49 (2012).
42. Geels, F. W., Sovacool, B. K., Schwanen, T. & Sorrell, S. Sociotechnical transitions for deep decarbonization. *Science* **357**, 1242–1244 (2017).
43. Vandyck, T. et al. Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. *Nat. Commun.* **9**, 1–11 (2018).
44. Vartiainen, E., Masson, G., Breyer, C., Moser, D. & Medina, E. R. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. *Progress in Photovoltaics: Research and Applications* (John Wiley & Sons Ltd, 2017) https://doi.org/10.1002/pip.3189.
45. Neumann, F. & Brown, T. The near-optimal feasible space of a renewable power system model. *Electr. Power Syst. Res.* **190**, 106690 (2021).
46. Simoes, S. et al. *The JRC-EU-TIMES Model, Assessing The Long-term Role Of The Set Plan Energy Technologies* (Publications Office of the European Union, 2013).
47. Löffler, K., Burandt, T., Hainsch, K. & Oei, P.-Y. Modeling the low-carbon transition of the European energy system - a quantitative assessment of the stranded assets problem. *Energy Strat. Rev.* **26**, 100422 (2019).
48. McGlade, C. & Ekins, P. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature* **517**, 187–190 (2015).
49. Babrowski, S., Heffels, T., Jochem, P. & Fichtner, W. Reducing computing time of energy system models by a myopic approach. *Energy Syst.* **5**, 65–83 (2014).
50. Ueckerdt, F. et al. Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model. *Energy Econ.* **64**, 665–684 (2017).
51. Pietzcker, R. C., Stetter, D., Manger, S. & Luderer, G. Using the sun to decarbonize the power sector: The economic potential of photovoltaics and concentrating solar power. *Appl. Energy* **135**, 704–720 (2014).
52. Zaklan, A. et al. EU ETS cap must and can be reduced more quickly. *DIW Wkly. Rep.* **10**, 293–300 (2020).
53. Gotzens, F., Heinrichs, H., Hrsch, J. & Hofmann, F. Performing energy modelling exercises in a transparent way - The issue of data quality in power plant databases. *Energy Strategy Rev.* **23**, 1–12 (2019).
54. Hörsch, J., Hofmann, F., Schlachtberger, D. & Brown, T. PyPSA-Eur: An open optimisation model of the European transmission system. *Energy Strat. Rev.* **22**, 207–215 (2018).
55. Frysztacki, M. & Brown, T. Modeling curtailment in germany: how spatial resolution impacts line congestion. Preprint at http://arxiv.org/abs/2009.03801 (2020).
56. European Commission. Mapping and analyses of the current and future (2020–2030) heating/cooling fuel deployment (fossil/renewables).
57. Kroposki, B. et al. Achieving a 100% renewable grid: operating electric power systems with extremely high levels of variable renewable energy. *IEEE Power Energy Mag.* **15**, 61–73 (2017).
58. Orths, A. & Eriksen, P. The future has come: the 100% RES driven power system is reality. *Revue de l´Electricité et de l´Electronique* **5** (2016).
59. Rojas, E. G., Sadri, H. & Krueger, W. Case study of MW-sized power generation at St. Eustatius island combining photovoltaics, battery storage, and gensets. *Prog. Photovolt. Res. Appl.* **28**, 562–568 https://doi.org/10.1002/pip.3222 (2020).
60. Schlachtberger, D. P., Brown, T., Schfer, M., Schramm, S. & Greiner, M. Cost optimal scenarios of a future highly renewable European electricity system: exploring the influence of weather data, cost parameters and policy constraints. *Energy* **163**, 100–114 (2018).
61. 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* **230**, 1645–1659 (2018).
62. Jerez, S. et al. The impact of climate change on photovoltaic power generation in Europe. *Nat. Commun.* **6**, 10014 (2015).
63. Zhu, K., Victoria, M., Andresen, G. B. & Greiner, M. Impact of climatic, technical and economic uncertainties on the optimal design of a coupled fossil-free electricity, heating and cooling system in Europe. *Appl. Energy* **262**, 114500 (2020).
64. Egli, F., Steffen, B. & Schmidt, T. S. Bias in energy system models with uniform cost of capital assumption. *Nat. Commun.* **10**, 1–3 (2019).
65. Fraunhofer ISE. Stromgestehungskosten Erneuerbare energien (2018).
66. Brown, T., Hörsch, J. & Schlachtberger, D. PyPSA: Python for Power System Analysis. *J. Open Res. Softw.* **6**, 4 (2018).
67. IRENA. Renewable Capacity Statistics 2019.
68. Carbon price viewer. https://sandbag.org.uk/carbon-price-viewer/.

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Author contributions

M.V. designed the analysis, drafted the manuscript and contributed to the data acquisition, analysis and interpretation of data. K.Z. contributed to the data acquisition, modelling, analysis and interpretation of data. T.B., G.B.A. and M.G. contributed to the initial idea and made substantial revisions of the manuscript.

Competing interests

The authors declare no competing interests.

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Trends in tools and approaches for modelling the energy transition

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HIGHLIGHTS

- Survey of current trends and challenges in energy system modelling tools (N = 54).
- Tool features, linkages, user accessibility and policy application were reviewed.
- Growing coverage of cross-sectoral synergies, open access, and improved temporal detail.
- Challenges in representing high resolution energy demand in all sectors.
- Key issues remain in understanding tool coupling, accessibility & perceived policy-relevance.

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ABSTRACT

Energy system models are crucial to plan energy transition pathways and understand their impacts. A vast range of energy system modelling tools is available, providing modelling practitioners, planners, and decision-makers with multiple alternatives to represent the energy system according to different technical and methodological considerations. To better understand this landscape, here we identify current trends in the field of energy system modelling. First, we survey previous review studies, identifying their distinct focus areas and review methodologies. Second, we gather information about 54 energy system modelling tools directly from model developers and users. Unlike previous questionnaire-based studies solely focusing on technical descriptions, we include application aspects of the modelling tools, such as perceived policy-relevance, user accessibility, and model linkages. We find that, to assess the possible applications and to build a common understanding of the capabilities of these modelling tools, it is necessary to engage in dialogue with developers and users. We identify three main trends of increasing modelling of cross-sectoral synergies, growing focus on open access, and improved temporal detail to deal with planning future scenarios with high levels of variable renewable energy sources. However, key challenges remain in terms of representing high resolution energy demand in all sectors, understanding how tools are coupled together, openness and accessibility, and the level of engagement between tool developers and policy/decision-makers.

1. Introduction

The transition towards a decarbonized and sustainable energy system is expected to play a crucial role in halting the effects of global warming while furthering human wellbeing, security, and sustainable development [1]. Energy system models - mathematical representations of energy systems - are often needed to quantify the impacts of this transition, and plan potential pathways [2,3] due to increasing complexity. Numerous energy system modelling tools[1] are available, providing energy modelling practitioners and planners with a wide range of alternatives to represent energy systems according to different technical and methodological considerations, which can help inform policy- and decision-makers in their planning processes and policy recommendations [4,5]. These tools are in continuous development in

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[1] We refer to modelling tools as computational software, or modelling frameworks, that generate energy system models.

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response to the emerging challenges in the energy transition and new technological breakthroughs [3,5]. For this reason, multiple efforts have been made in the energy modelling community to review the ever-changing pool of tools available to energy modellers, to classify their features, outline their applications, and point at the issues that these aim to tackle [4,6–8].

In this paper, we survey how these reviews have been conducted and what issues they address. Moreover, we show current trends found in energy system modelling tools by gathering some of their key features and applications, including their apparent role in decision-making support. To do this effectively, we have gathered inputs from tool developers to better assess some of the key considerations and to gather information that is not necessarily readily available from written academic sources or tool documentation.

The work presented here is divided into four parts. Section 2 gives an overview of different reviews and surveys of energy system models and tools, outlining how these reviews were conducted, their respective focus areas, and existing gaps in the literature. The purpose of this review is to not only identify emerging trends, but to also identify how some of the lessons learned in past reviews are captured. In Section 3, we detail the analytical approach followed in our survey of energy system modelling tools. In Section 4 we present the results from this survey and identify the key features and trends in tool developments. In Section 5, we put into perspective some of the emerging challenges and discuss potential ways forward.

2. Literature review

This section presents an overview of different reviews and surveys of energy system models and tools found in the literature. These are then categorized according to their respective focus areas and their review approach, to show existing gaps in the literature.

2.1. Background

Energy system modelling tools are used for assisting energy policy making and assessing different energy pathways [9]. The range of available energy modelling tools is significant and continuously expanding. Several studies have investigated the developments of the above with a focus on different aspects of these models and reported different challenges faced in the field of energy systems analysis. For instance, Connolly et al. [4] present an overview of computational modelling tools capable of analyzing the integration of renewable energy sources (RES) in energy systems at large, looking into survey responses from 37 model developers.

In Foley et al. [10], a literature review of system models with a focus only on the electricity sector is presented. Similarly, Després et al. [11] conduct a review of modelling tools focusing on the integration of variable renewable energy (VRE) mainly in the power sector. Mahmud and Town [12] reviewed modelling tools with a focus on the integration of electric vehicles in the energy system. More recently, in a study by Ringkjøb et al. [6], a thorough review of 75 energy and electricity system modelling tools is presented, assessing modelling scopes, characteristics and limitations, and validating most inputs with tool developers.

In addition to these broader overviews of energy system modelling tools, a relevant body of work exists about the underlying implications that models 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 planning exercise.

Different classifications of energy system modelling tools have been discussed by a number of studies, which reflect upon the characteristics and challenges of bottom-up applications [8], the suitability of tools for decision support in local planning [13], as well as their applicability worldwide [14], their general effectiveness for energy planning purposes [15], their level of technical complexity [16], and the classification of modelling approaches with direct feedback from modelling tool developers [17].

Another critical consideration examined in the literature is the applicability of models in specific context-areas. This has been the case, for instance, in reviewing and narrowing down the applicability of various energy system modelling tools and their limitations for analyzing the energy transition in a European context [18], in a regional Nordic perspective [19], on a country-specific level [20,21], in developing world countries [22,23], in energy systems of urban scale [24–29], and standalone and grid-connected hybrid energy systems [30,31].

Over the past years, a number of studies have shifted the spotlight from a pure overview of modelling tools towards the study of emerging issues for energy system modellers and planners, as developers and users of such tools, under the context of climate change and the transition towards sustainable energy systems. For example, Pfenninger et al. [5] outline different modelling paradigms and emerging methodological challenges faced in the energy system modelling arena, highlighting the way current modelling methods could be revised by benefiting from cross-discipline and cross-sectoral synergies.

Similarly, Lund et al. [32] put into perspective the theoretical positioning with regards to selecting a modelling approach and how these should be considered when addressing and debating different future energy system scenarios based on sector integration.

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 [33–35], as the focus towards more cross-sectoral integration [12,36–38] and socio-technical considerations becomes more apparent [39–43].

Meanwhile, Savvidis et al. [7] review and discuss the gaps between energy policy questions and modelling capabilities found in a selected sample of modelling tools. In addition to these, the openness of energy data and models have been discussed in a number of studies [44–48] and by expert groups. These include the *Open Energy Modelling Initiative* [45,49], which collects information on a growing number of open-source energy system models and frameworks in addition to open energy data; and combined efforts in the modelling community like the Energy Modelling Platform for Europe and other energy system modelling related projects [50–55].

However, some key gaps remain present. As pointed out by Hall and Buckley [20], the lack of clarity found in the literature about models' characteristics can hinder side-to-side comparisons. Moreover, the target audience and the main area of application of these modelling tools are not always explicit in the literature, often leaving these aspects open to interpretation [25]. Furthermore, potential misinterpretations or misrepresentations while reviewing modelling tools can arise if no form of dialogue with developers take place. Taking as an example the EnergyPLAN tool as portrayed in recent literature review studies, the tool is described as having an optimization methodology [56], geographical coverage [8] and being developed in a programming language [21] which do not necessarily correspond to the tool as described by its developers [57]. Thus, having open lines of dialogue, such as surveys and personal communication, can be a valuable approach when reviewing and validating the technical characteristics of modelling tools, as has been shown in past studies [4,6,16,17].

Nonetheless, this more direct review approach has had limited use when probing aspects such as the policy relevance of the tools, the ability to couple multiple modelling tools to answer complex research questions, or the level of accessibility of the tools with a perspective on not only the licensing but also on the user interaction. This becomes especially crucial as the value of modelling tools and scenarios for decision support is not always fully appreciated by energy planning practitioners and decision-makers [58], despite the intent of models and tools to be relevant for decision-support [59].

2.2. Classification of energy system modelling reviews

As described in the previous section, the current landscape of reviews assessing energy system modelling tools is quite vast. To better understand how these studies have been conducted and their focus areas, we have put forth a classification scheme of these reviews. This classification scheme also has the purpose of outlining new potential focus areas to survey modelling tools, and potential areas of actionable research. At the same time, it provides a useful view into past research that has listed some existing modelling tools, including their attributes and applications.

For this, we have used a modified and expanded categorization scheme compared to that initially proposed by Savvidis et al. [7], where the reviews were catalogued into four groups based on their underlying purpose.

In the present study, we reformulate the four original categories with additional details and propose three new additional categories based on recurring themes found in previous literature but not explicitly mentioned in the previous categorization effort. Namely, these new categories cover reviews that examine real-life policy application of the tools, model linking, and the transparency, accessibility and usability of the tools. In addition to this, we contextualize these studies in terms of their review approach, as well as their area of application and delimiting scope. This allows identifying existing trends and new potential study areas while putting in perspective how modelling lessons are gathered, and how future review exercises can potentially be conducted.

In this paper, the categories considered are divided as follows, considering their corresponding purpose(s):

- Category 1 [Descriptive overview]: Provide descriptive overviews of the technical features of modelling tools, such as their methodological approach, mathematical formulation, and resolution (spatial, temporal, techno-economic, sectoral).
- Category 2 [Classification]: Provide a new classification scheme, and/or focus on grouping modelling tools to provide an overview of existing modelling typologies (based on their technical attributes or modelling approaches).
- Category 3 [Practical application]: Identify the use of energy system modelling tools based on previous applied studies, and to identify areas of suitability for addressing current and future issues based on the tools' modelling capabilites.
- Category 4 [Inter-comparison & suitability]: Compare modelling features side-by-side in order to identify the suitability for a particular application.
- Category 5 [Transparency, accessibility & usability]: Identify transparency and licensing/accessibility of the modelling tool, outlining issues such as result reproducibility, validation and testing, and open source code, and the user interaction with the tool.
- Category 6 [Policy relevance]: Identify policy-relevance of modelling tools based on real-world applications and policy-making case studies[2].
- Category 7 [Model linking]: Identify combined capabilities of modelling approaches through the linking of modelling frameworks.

It is apparent that these categories are not mutually exclusive. In fact, most reviews fell into more than one single category. It is also important to note that there is a degree of overlap between the categories, where some elements of one category could be sub-categorized within another due to some of the studies having more general purposes. However, a degree of differentiation is needed to zero in on the key issues and insights contributed by the reviewed literature. For instance, when considering reviews of the modelling tools' practical application (category 3), an overlap with potentially reviewing their suitability to access policy applications. However, the latter warrants deeper analysis to determine actionable research and real-life application of the reviewed tools, as conveyed by Category 6.

In addition to these categories, we have categorized the reviews by their focus area and delimitating scope, by outlining whether the reviews focused on – for example – urban scale modelling tools, power sector models, bottom-up tools, socio-technical energy transition (STET) models, etc. Similarly, the review approach was also outlined. Here, we noted three distinct approaches: literature reviews, reviews with developer/user inputs (from survey questionnaires, presentations, or review validation with tool developers), and web searches. Concretely for the last approach, the review paper by Markovic et al. [24], presented results without further procedural description and solely referencing websites.

A summary of the categorization, focus and approach of the reviews is seen in Table 1.

As observed in Table 1, several purposes can be identified in previous review studies of energy system models and tools. This survey shows that a clear majority of the studies provide some type of descriptive overview (Category 1) of the features found in models and tools, while also providing classification schemes (Category 2) or prescriptive narrowed-down lists of tools suitable to address a specific issue or scope of analyses. In general, these reviews are useful at mapping the technical aspects and considerations for modellers to select a tool and to pinpoint issues within specific modelling approaches. This is especially the case when these tools are assessed in tandem with applied case studies, where their application provides further insight into how the tools are able to tackle questions about the energy system and different energy policy scenarios.

Although dialogue with tools developers is often suggested by a number of reviews to improve clarity on modelling purpose and scope, assumptions and categorizations; the reviews are not always conducted in such ways. Instead, as seen in Table 1, most of these studies rely on reviewing the existing literature to formulate their interpretation of modelling features or to assess the applicability of models or their policy-relevance.

In more recent years, the issues of transparency and model accessibility have come into focus, being key issues covered by a growing number of studies. This often refers to having open access to a model or to a modelling framework's underlying mathematical formulation - i.e. making the underlying software code in some tools being open source. However, the broader accessibility of the tools in terms of the readiness with which end-users can use tools to construct an energy system model and generate energy system scenarios is not commonly evaluated in previous studies.

Moreover, from this survey we have seen that the policy relevance of the modelling tools is often evaluated in terms of the tool's capabilities to assess the impacts of current policy and potential future developments in academic studies. Given the technical features found in the current landscape of modelling tools, evaluating techno-economic aspects of policy implementations could be routinely performed. However, the focus has been more limited in terms of reviewing the tools used for official policy-making – including both whether the tools have been used directly or as a reference to support official policy choices and their subsequent impact on official planning and decision-making processes. Finding out about these types of applications requires going beyond the tools' technical documentation, and sometimes even beyond written academic outlets. While, this information might be available in official documents, it becomes increasingly complicated to compile when considering the multitude of national, regional and local official plans (often only published in their local language) documenting the use of

[2] While the technical features of some energy modelling tools enable the analysis of policy relevant questions, the actual use of these to support official policy is more limited. Here, we refer to reviews that follow up on whether the modelling tools have been used to support official (government) policy, rather than their ability to technically evaluate policy and generate insights solely on an academic level.

Table 1
Overview of the 42 review articles surveyed with their corresponding classification and review method, sorted by year of publication.

Source	Category 1	2	3	4	5	6	7	Focus topic	Spatial/Technical/Access delimitation	Review method	Year published
Van Beeck [13]	X	X		X				Classification of tools for local energy planning	Local	Literature review	1999
Jebaraj and Iniyan [14]	X		X					Review of energy models' applications	Global	Literature review	2006
Connolly et al. [4]	X			X				Suitability of tools for modelling integration of renewables	Local/National/Regional	Survey questionnaire	2010
Bhattacharyya and Timilsina [22]	X			X				Comparison of suitable tools for developing countries	Developing countries	Literature review	2010
Mundaca et al. [60]	X		X			X		Review of tools for evaluating energy efficiency policies	Bottom/up energy economic models	Literature review	2010
Foley et al. [10]	X		X					Overview of tools for electricity system modelling	Electricity sector models	Literature review	2010
Unger et al. [19]	X	X	X				X	Coordinated use of modelling tools	National/Regional	User inputs, Literature review	2010
Mendes et al. [61]	X		X	X				Review of integrated community energy system tools	Local (district/ community)	Literature review	2011
Markovic et al. [24]	X			X				Tools suitable for modelling urban energy systems	Local (urban/district)	Web searches	2011
Manfren et al. [62]	X	X		X				Tools for distributed generation projects	Local (urban/district)	Literature review	2011
Keirstead et al. [25]		X	X					Review of urban energy system models approaches	Local (urban/district)	Literature review	2012
DeCarolis et al. [63]	X		X		X			Modelling results transparency and reproducibility	Energy economic optimization	Literature review	2012
Mirakyan and De Guio [64]	X		X	X				Tools & methods for integrated energy planning in cities	Local (urban/district)	Literature review	2013
Pfenninger et al. [5]	X	X	X			X		Modelling categories and outline emergingchallenges	National	Literature review	2014
Allegrini et al.[26]	X		X	X				Modelling approaches and tools for district-scale systems	Local (urban/district)	Literature review	2015
Huang et al. [65]	X	X	X	X				Modelling approaches and tools for community systems	Local (urban/district)	Literature review	2015
Van Beuzekom et al. [27]	X		X	X				Suitable optimization tools for urban development	Local (urban/district)	Literature review	2015
Li et al. [39]	X		X					Review of socio-technical energy transition models	STET models	Literature review	2015
Despres et al. [11]	X	X	X					Energy modelling tool typologies for renewable integration	Power sector	Literature review	2015
Hall and Buckley [20]	X	X	X					Systematic review of energy models and classification	National (UK)	Literature review	2016
Olsthoorn et al. [36]	X	X						District heating systems and integrated storage	Local (urban/district)	Literature review	2016
Mahmud and Town [12]	X		X					EV modelling	EV modelling included	Literature review	2016
Lund et al. [66]		X	X			X		Modelling approaches and planning support	Simulation/optimization	Literature review	2017
Ringkjøb et al. [6]	X	X	X	X	X			Renewable energy integration	Active models (2012<)	Lit. review, developer inputs	2018
Lopion et al. [21]			X					Historical trends in energy system models' development	National	Literature review	2018
Müller et al. [17]		X				X		Discussion of approaches and categories of energy	EU developed models	Developers' presentations	2018
Crespo del Granado et al. [33]		X	X					Review of nexus between energy and economic models	Economic/bottom up models	Literature review	2018
Lyden et al. [67]	X		X	X				Community-scale energy systems with storage & DMS	Local (district/ community)	Literature review	2018
Morrison [46]					X			Modelling transparency, reproducibility and openness	Open modelling projects	Literature review	2019
Oberle and Elsland [47]	X	X	X		X			Suitability and application of open access models	Open access models	Literature review	2019
Ferrari et al. [28]	X		X	X				Suitability of tools for urban energy planning	Local (urban/district)	Literature review	2019
Scheller and Bruckner [29]	X	X		X				Optimization models & approaches for municipal systems	Local (urban/district), ESOMs	Literature review	2019
Savvidis et al. [7]				X		X		Suitability of models to answer policy questions	Active, policy relevant models	Literature & expert review	2019
Groissböck [48]	X		X	X	X			Review of tools for power system modelling	Open access tools	Literature review	2019
Abbasabadi and Ashsayeri [68]	X	X	X					Outlook of modelling approaches in urban energy systems	Local (urban/district)	Literature review	2020
Hirt et al. [34]	X		X				X	Applied cases of linking energy system and STET models	STET models	Literature review	2020
Prina et al. [8]	X	X		X				Classification of bottom-up energy models	Bottom-up models	Literature review	2020
Ridha et al. [16]		X		X				Profiles and categorization based on modelling complexity	Available data in MODEX database	Survey questionnaire	2020

(continued on next page)

Table 1 (*continued*)

Source	Category							Focus topic	Spatial/Technical/Access delimitation	Review method	Year published
	1	2	3	4	5	6	7				
Weinand et al. [31]			X	X				Suitability of modelling autonomous systems	Local (district/ community)	Literature review	2020
Musonye et al. [23]	X		X	X				Suitability of modelling in Sub-Saharan African context	National/Regional (Sub-Saharan Africa)	Literature review	2020
Fattahi et al. [35]	X	X	X				X	Linking of modelling approaches	National	Literature review	2020
Klemm and Vennemann [56]	X		X	X				Suitability of tools for modelling district energy system	Local (urban/district)	Literature review	2021

energy system modelling tools.

Finally, another recurring area suggested in the surveyed review articles is the application of interdisciplinary approaches, and model coordination and integration. However, few reviews try to map how tools have been coupled together beyond a specific set of modelling traditions [34]. This opens questions as to how model coupling is done, with which tools, and to what extent coupling approaches are used to answer specific energy planning questions.

2.3. Observed trends and findings in past energy system modelling reviews

Looking beyond the scope and methodologies of past reviews listed in Table 1, several trends and findings emerge from the literature over the past 10 years. In Connolly et al. [4], the typical application of different modelling tools is provided. While this study has a comparative nature, it outlines that – at the time – only seven energy system modelling tools were identified capable of modelling 100% renewable energy systems, four considering hourly time-steps and different sector coverage, and three with coarser (annual) temporal resolutions but with multi-year perspectives.

From there, several suitability studies have looked further into the technical descriptions of different energy modelling tools, having as main outcome shortlists of applicable tools that could address specific research cases. This has been predominantly the case of reviews looking into the suitability of energy system modelling tools to represent local scale energy systems (ie. Urban, district, community scale), though similar cases apply for other geographical scales. As early examples, Mendes et al. [61] identify a handful of tools highlighting the importance of hourly modelling and spatial scale flexibility to conduct their assessment; while Allegrini et al. [26] call for adequate representation of district heating, renewable energy and adequate integration of the urban microclimate and resulting effects on building demands when conducting energy system analyses. By contrast, studies conducted over the past 5 years incorporate into their model-finding exercises far more comprehensive criteria about high modelling details such as multiple sector representation, high spatial and temporal resolutions, uncertainty analysis, storage and demand side management representation [29,36,67]; but also user-friendliness [28] and openness of these tools [56]. Meanwhile, other studies point at a lack of representation of additional dimensions, like increased social aspects in energy system modelling tools [31].

Similar to Connolly et al. a decade ago, Foley et al. [10] also raised the issue of modelling renewable energy, finding that electricity system models were ill suited to properly consider energy storages, flexibility services and variable renewable energy sources. More recently, Ringkjøb et al. [6] found that several studies address the effects of integrating variable renewable energy sources to varying degrees, with models capable of representing grid expansion, storages and demand-side management technologies. However, representing the variability of these sources in long-term energy models was found as a challenge due to the coarser time-step of these modelling tools. Likewise, the integration of energy sectors was also found as an outstanding challenge to be address in model development. Prina et al. [8] also makes this point, after identifying the current status of bottom-up models in their spatial, temporal, techno-economic and sectoral resolutions. In their study, bottom-up modelling tools are found uncapable of addressing these four dimensions fully.

Similarly, in Lopion et al. [21], key trends are also examined around the development of energy system models over the last decades. In this review, they found new developments around increasing spatial and temporal flexibility of energy system models and state the need to have modelling efforts align to answering energy policy questions. This is also touched upon by Savvidis et al. [7], when reviewing gaps between modelling capabilities and technology-specific policies. From this study, the representation of the distribution grids, endogenous demands, the systems technical flexibility and policy constraints were found as areas of improvement for energy system models.

Other key areas found among recent reviews, include the prospect of expanding modelling dimensions to increase realism in addressing energy and climate challenges, and increasing modelling transparency. In the case of the former, linking energy system modelling tools with socio-technical energy transition approaches [34] or macro-economic models [33] has been found as a potential avenue for inter-disciplinarity and better representation of the energy system. Fattahi et al. [35], also highlights this potential, after noting the shortcoming of energy system modelling tools in generating insight about micro- and macro-economic aspects of the energy transition.

On the issue of transparency, much has been said in recent years. For instance, Morrison [46] and Pfenninger et al. [45] find that energy system models are lagging behind in adopting best practices for transparency, such as those found in the open modelling community, pointing out the need to enhance transparency of modelling analysis and reproducibility. Following from this, Oberle and Elsland [47] look into the current landscape of open access tools to outline their features, finding them technically suitable to address research questions regarding a variety of energy scenarios.

3. Methods

In this paper, we opted to review the features and applicability of energy system modelling tools by gathering inputs directly from tool development teams and key users. As seen in the literature review, some aspects of the tools and their applications can be overlooked, are rather difficult to come by from only analyzing publications or are altogether misinterpreted due to a lack of a common language found in the existing literature describing modelling tools. This becomes increasingly relevant when considering the application of some modelling tools outside the realms of academia, where modelling outputs can translate into local or national policy discussion in white or green papers (sometimes in their original language), while being less accessible to external inspection or by reviewing traditional sources and model documentation.

By establishing some line of dialogue, in this case through a survey questionnaire, we try to bridge this methodological gap and establish a common language to describe the tools and their applications from the developers and users own perspectives.

In this process, 137 different modelling tools were identified from the existing literature and survey studies referenced in the previous section. The conceptualization of the questionnaire took the work presented in Connolly et al. [4] as a starting point of inspiration, with several reconsiderations and new aspects added to the questionnaire presented in that study corresponding to new developments and considerations in the practice of energy system modelling and tool development.

A web-based questionnaire was designed on the SurveyXact platform, which then was sent to the developers of each tool identified.

From this survey, 54 complete responses where gathered, plus an additional six partially completed entries. Although, additional tools and model descriptions can be found in the literature, these are not considered in the following result interpretation in order to preserve the consistency of the analysis. It must be noted that the overall survey results, while not necessarily providing a comprehensive sample of all existing tools, are still indicative of general trends found in the energy system modelling field. The tools covered in the analysis ranged from commercially available software, to in-house proprietary developments, and open access, widely used modelling tools. In addition, a deliberate choice was made to only include one modelling tool in cases where multiple branch-out versions exist; for example, in the case of MARKAL-TIMES [69], and its family of models [70–74], or similarly in the case of OSeMOSYS [75] and GENeSYS-MOD [76]. The list of tools surveyed is presented in Table 2.

The survey questionnaire covered questions regarding the tools' access and licensing, user interface, methodological approach, mathematical formulation, spatio-temporal resolutions, sectoral representation, technical attributes and technology detail, and area of past application, including use for official policy-support. In addition to this, data regarding typical application of tools and descriptions from the respondents was also gathered.

An overview of the questionnaire is provided in Appendix A, while a summary of the inputs for the 54 modelling tools is provided in Appendix B as a supplementary data repository.

Table 2
List of the 54 modelling tools surveyed where full responses were gathered.

Modelling tools surveyed (completed questionnaire responses)
Balmorel [77]
Calliope [78]
COMPOSE [79]
DER-CAM [80]
DIETER [81]
Dispa-SET [82]
E2M2 - European Electricity Market Model [83]
EMLab-Generation [84]
EMMA [85]
EMPIRE[86]
Enerallt [87]
Energy Transition Model [88]
EnergyPLAN [57]
energyPRO [89]
energyRt [90]
EnergyScope [91]
Enertile [92]
ENTIGRIS [93]
ESO-XEL [94]
EUCAD [95]
EUPowerDispatch [96]
Global Energy System Model (GENeSYS-MOD) [76]
GridCal [97]
Homer Grid [98]
iHOGA [99]
IMAGE [100]
IMAKUS [101]
Integrated Whole-Energy System (IWES) model [102]
INVERT/EE-Lab [103]
LIBEMOD [104]
LIMES-EU [105]
LOADMATCH [106,107]
LUSYM [108]
Maon [109]
MESSAGEix [110]
National Energy Modeling system (NEMS) [111]
OpenDSS [112]
OptEnGrid [113]
POLES-JRC [114]
POTEnCIA [115]
PRIMES [116]
PSR – SDDP [117]
Pymedeas [118]
PyPSA[119]
RamsesR [120]
Regional Energy Deployment System (ReEDS) [121]
REMIND [122]
Sifre [123]
System Advisor Model [124]
TIMES [69]
TransiEnt Library [125]
UniSyD5.0 [126]
WEGDYN [127]
WITCH [128]

4. Features and trends in energy modelling tools

In this section, the results from the tool survey are presented with a focus on approach, scope, coverage, access, policy relevance and model coupling.

4.1. Approaches and formulation of the objective

As identified in the literature, several schemes exist to classify modelling tools according to their methodological approach and mathematical formulation [13,17,20,129]. In this study we examined the modelling tools under three broad categories according to their analytical approach: Simulation, Optimization and Equilibrium models. In the case of the latter, further subcategorizations were defined by model developers about their modelling tools, namely to clarify if these are computable general equilibrium (CGE) or partial equilibrium. In addition to the above, some simulation tools made further specifications to describe the novelty of their underlying methodology; for instance, by elaborating on their operation and iterative simulation approach [107].

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

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 can serve multiple purposes with their underlying formulation. Overall, we observed that most modelling tools can use multiple assessment criteria in their studies depending on the specific case and the underlying context, resulting in a wide range of choices as highlighted in [31,130].

4.2. Modelling scope: temporal, spatial, and technical resolution

4.2.1. Temporal resolution

The integration of high levels of variable renewable energy sources (VRES) poses a challenge for energy planning, which calls for models capable of representing the corresponding variability. Similarly, 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 on capturing the actual dynamics of a modelled system and adequately balancing supply and demand. This is illustrated, for example, by Poncelet et al. [131] when assessing the impact of temporal resolution in systems with high uptake of renewables, concluding that low temporal resolution can potentially underestimate operational costs and overestimate generation capacity.

Similarly, Deane et al. [132] determined that higher temporal resolutions are better able to capture system loads, the inflexibility of large thermal power units, and renewable energy generation; thereby assessing more accurately the corresponding system costs. Nonetheless, increasing the time resolution can be computationally expensive. Thus, temporal resolution should be selected with caution, especially when considering resolutions coarser than 1-hour to represent renewable generation fluctuations [133].

In the modelling tools sampled for this study, the 1-hour modelling time-step was the most frequently observed, as seen in Fig. 1. Other time-steps observed, although to a lesser extent, were the yearly and multi-year resolutions, as well as seasonal time-slices. In the "Other" category, the modelling tools were reported capable of adjusting their modelling time-step to even higher levels like minutes, seconds, or having user-defined steps, as well as having lower resolutions e.g. daily, using representative hours and hour-blocks and weekly resolutions. In addition, some tools had higher (hourly) resolutions in certain aspects of their system representation while using coarser (annual) resolutions for others.

Interestingly, modelling tool developers also highlighted that the capabilities of their models not always correspond to their typical application. For example, some tools although technically capable of operating with an hourly resolution, are typically used with other modelling time-steps, such as using a time-slice representation [69] or with a reduced yearly time-series produced from aggregation algorithms [76]. For some tools, this can be explained by the fact that high modelling resolutions and temporal detail can translate to higher computational effort and calculation times [5]. However, the choice of lower time resolutions can also driven by a lack of empirical high resolution data for future time horizons, or from the use coarser temporal detail of the energy demands represented in energy system modelling tools [134].

An additional temporal aspect considered is the time horizon of the modelled outputs, as seen in Fig. 1. This shows that a large majority of the modelling tools can provide more than just a single snapshot of the energy system, but rather have the capability to outline multiple stages of the energy transition by providing multi-year outlooks, with some being capable of having more than one fixed time horizon. This modelling capability is reflective of the intent to outline the pathways of policy scenarios and sequential decision-making [135], as seen – for example – for capacity expansion at a country level [136], to formulate energy policy at the EU level [137–139], or to assess regional and global decarbonization pathways [140].

On the other hand, a smaller yet significant share of the modelling tools surveyed can also use a 1-year modelling time horizon or even shorter-term horizons. This comes with the potential advantage of lower computational effort and less uncertainty due to the number of assumptions and data inputs going into the modelling. While less detailed in outlining potential energy transition pathways, the application of a 1-year time horizon can still outline end- and mid-point snapshots of technical developments or policy scenarios at selected years. This can provide high levels of detail of an energy system redesign to strive for, as illustrated in studies about urban energy transitions [141,142], national energy system redesigns [143–146], and regional studies [147–149]; in turn, acting as potential points for policy backcasting [150–153].

Putting these results into perspective, we can see that over the past decade advances have been made in how time is represented in modelling tools. Taking the study by Connolly et al. (2010) as an example, we can see that now a larger share of energy system modelling tools are capable of using hourly time-steps, compared to roughly half capable of such identified at the time for the 37 tools surveyed in that study [4]. In terms of the modelling time horizon, the results found in this survey are to an extent similar to those presented by Connolly et al. [4], which shows that most models surveyed then were already capable of handling multi-year time horizons, as well as yearly, and to a lesser extent coarser resolutions.

Similarly, Pfenninger et al. [5] raises the issue of higher temporal detail as a pending challenge in energy system modelling development. As seen today, increased development has been given to capture high temporal detail in the modelling tools surveyed.

4.2.2. Spatial and technical resolution

Across the surveyed modelling tools, a levelled distribution was observed between tools working with aggregate technical specifications and those capable of representing individual plants or energy system components. Out of the 54 tools surveyed, 31 reported using individual plant details, while 23 reported using aggregate technical details. 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 (and in some cases even at the urban level), where aggregate operational detail provides adequate representation of the energy system [154,155], having an overall less significant impact than the temporal resolution [131].

On the other hand, some of the tools working with finer operational detail are tuned based on the purpose and scope; for instance, to flexibly represent project-specific components [156,157] or set up to represent specific dispatchable units or plants [158,159].

Interestingly, the survey pointed that even if some of these tools are capable of representing individual plants and conversion units, the standard modelling representation for larger spatial scopes – like on a national scale – would still rely on aggregated values. This raises an interesting point when considering the features and intended flexibility of use, with the standard practical use of the tools.

4.3. Cross-sector coverage

As the global focus shifts towards higher penetration of renewable energy sources to decarbonize the energy system and to halt global warming, more effort has been put towards coupling the main energy sectors to benefit from their potential synergies. A vast range of reviews identify the challenges of integrating more renewable energy, mainly considering electricity sector [5,10,11]. However, as identified by Lund et al. [37], cross-sector integration can also be a pivotal aspect to incorporate larger shares of renewables, by facilitating additional flexibility in the energy system. This has been the subject of a number of studies (e.g. [149,159–162]), which have analyzed 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. This is shown in Fig. 2 and Table 3, and outlined in further detail in Appendix B.

As seen in Fig. 2 and Table 3, the inclusion of the electricity sector is shared across almost all the tools examined. For roughly half of these tools, it is furthermore possible to explicitly model both the transport sector and heating (including individual and district heating). However, it must be noted that when considering tools representing only the electricity vector, non-explicit approaches to represent scenarios where heating and transport are electrified can arise and, thus be partialy covered. Additional sector coverage is seen to a varying degree when looking at industry or cooling applications, and it is much less prominent considering biofuel production, being modelled by only one-third of the tools examined.

The common theme of the electricity sector is key to sectoral integration, since thermal, transport, and industry sectors are considered in the context of electrification in a smart energy system [163]. Indeed, it is

Fig. 1. Modelling time-step by time horizon of the 54 surveyed tools. Note that the sum exceeds 54 as some tools can operate with different user-defined time resolutions.

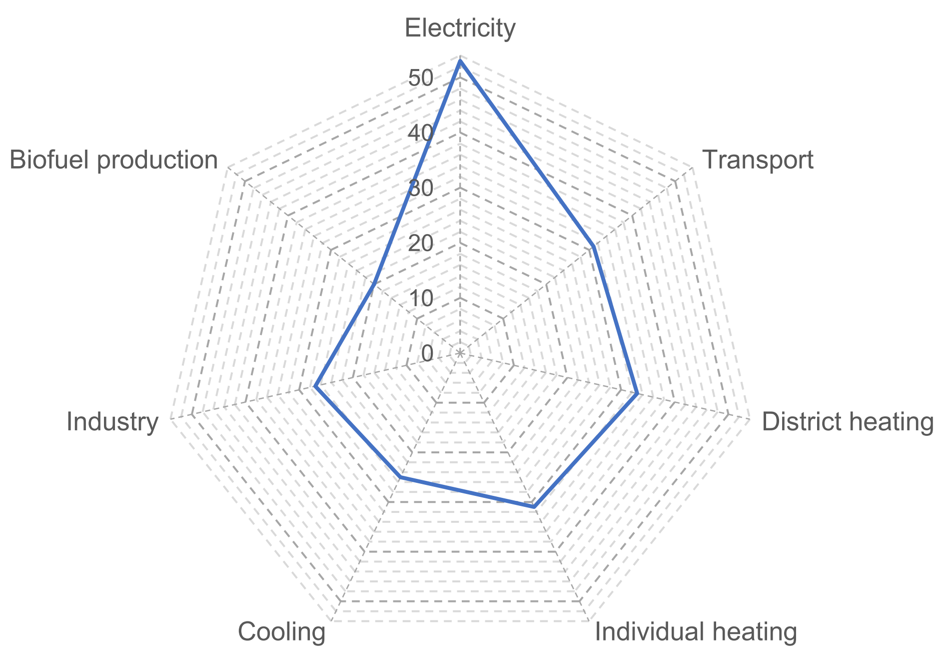

Fig. 2. Sector & end-use coverage in the 54 surveyed modelling tools.

expected that when incorporating these demands, the total electricity demand will markedly increase [160]. More importantly, however, these sectors can act as sources of demand response, having promising prospects to provide flexibility and improve the efficiency of the energy system [164]. This has been shown in prior studies when analyzing the potentials to shift industrial [165], thermal [166], and electric transport loads [167]. This flexibility can also be reaped within the electricity sector, by considering flexible demands responsive to the costs of generation dispatch, which could cover second priority loads. This can be done by covering these lower-priority demands in off-peak hours, or in the presence of excess electricity from fluctuating renewable sources when generation costs are lower [164,168,169]. In our survey, about 23 of the 54 models were capable of representing elastic demands responsive to supply costs (Fig. 3).

4.4. Demand representation

Common across all energy system models is the need to balance energy supply and demand. As seen in Fig. 3, energy demand is rarely a modelling outcome, but rather an exogenous input assumption, either as

Table 3
Sector coverage overlap by number of tools in the 54 surveyed modelling tools.

No. of sectors/ end-uses covered	Number of modelling tools	Sectors/end-uses excluded by number of tools
7	15	n/a (ie. all sectors covered)
6	5	biofuel production (3 tools), industry (1), cooling (1)
5	4	biofuel production (4), cooling (1), industry (1), district heating (1), transport (1)
4	7	cooling (5), biofuel production (4), individual heating (4), industry (4), transport (3), district heating (1)
3	3	biofuel production (3), cooling (3), industry (2), district heating (2), individual heating (1), transport (1)
2	8	biofuel production (8), cooling (7), industry (7), individual heating (6), transport (6), district heating (5), electricity (1)[a]
1	12	All but electricity generation (12)

[a] Partially covers electricity as contributions for heating purposes.

a static demand or with some elasticity. This requires that modellers represent energy demand for the variety of aforementioned sectors at the relevant temporal and spatial resolution of their modelling tool.

Focusing in on specific studies undertaken by some of the surveyed modelling tools, we see that the same data sources are often used, or that the hurdles to data acquisition are dealt with in similar ways.

In the European context, hourly electricity demands are readily available from the European Network of Transmission System Operators for Electricity (ENTSO-E) [170]. ENTSO-E data is used in several national scope studies [81,147,171–174], although others source data directly from relevant national bodies [133,166,175–177] or as a synthesis of ENTSO-E and national statistics, via the Open Power System database [178]. When data is unavailable for countries, or subnational regions are being modelled, scaling factors are applied based on aggregated demand statistics [147,179], relative population magnitudes [133,142,177], or additional economic parameters and weighting ratios [180]; in all such cases, it is not possible to verify validity.

The inclusion of additional sectors beyond electricity poses additional difficulties, since high resolution measured data is not readily available outside the electricity sector. Instead, national statistics are usually mapped to representative profiles of demand [161,175]. In the case of thermal demand, heating degree days or hours are used in this process, whereby the deviation of outdoor temperature from a reference temperature indicates a requirement for heating or cooling. Several projects have endeavored to simulate thermal demand using both bottom-up and top-down approaches [169–171], but their incorporation by energy modelling tools is currently limited.

Although sources exist to understand historical demand at some resolution, future demand is understandably unknown. Frequently, historical demand is used directly when modelling a scenario of a future energy system, without altering its magnitude or shape [172,175,181]. 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 [133]. Yet, it is clear that demand changes over time. Roadmaps for energy systems, such as the EIA international energy outlook [182], include estimations of the increase in demand and have been used to scale the magnitude of model input profiles accordingly [166,183]. However, the magnitude of demand is not the only element that will change, the profile shape is also variable. Indeed, at the high (one hour) temporal resolution we see to be increasingly important to modellers, the dynamics of demand are as important as variable renewables; the two may even be coupled [184,185]. As with thermal demand, reliance on demand modelling tools is key to understanding future profile shapes, but is underutilized. An example of how they could be used is shown in [171], where the DeSTINEE [186] simulation tool is used to estimate electricity demand in Italy for the year 2050, considering full electrification of heat and transport sectors.

4.5. Cross-platform modelling integration: Model coupling

With the expanding number of energy modelling tools available, and with these 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 or to complement their methodological approach and coverage. This has been the case in studies looking into combining the capabilities of energy system modelling tools and demand modelling [187], energy system modelling tools with different technological and temporal resolution [188], and linking bottom-up and top-down modelling approaches [189].

Based on the survey of energy tools, the most common linking approach is the so-called "soft-linking" of tools: 33 of the 54 tools have been run with other tools, by applying an external workflow or a linking 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 to operate automatically

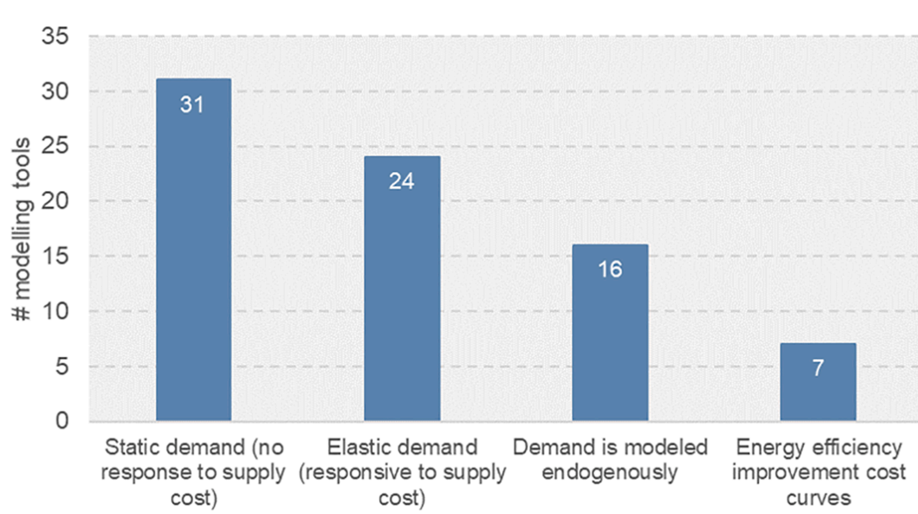

Fig. 3. Overview of how energy demands are handled across the 54 surveyed modelling tools. Note that the sum exceeds 54 as some tools can represent different energy demands in multiple ways.

together. An example of soft-linking could be the energy scenario of one tool modelled in another energy system tool that can capture a finer temporal resolution and sectoral or technological details.

If two or more tools are linked through their source code, we specify that as hard-linked tools. An example of this would be if the code of two or more energy system optimization tools are linked together in such a manner that they can be solved as a single, yet complex, optimization problem. Three of the tools in the survey have been hard linked to other tools. Five of the tools have been integrated into other tools, making new merged tools. The difference between an integrated tool and a hard-linked tool is as follows. In principle, with hard-linking, two separate tools still exist but linked to each other to exchange input/output data automatically. However, when two tools are fully integrated, the linked tools evolved into a new tool with a common set of input and output data. So, in total nine tools have been integrated with specific coding between tools. Out of all tools examined, 11 have not been linked to other tools, and for one the linking status was unknown for the tool developer. Further information regarding the type of tools connected between each other was not collected in the survey.

These results hint at a growing trend where complementary methodological approaches are used in tandem to leverage their capabilities and potential for additional insight. Fattahi et al. [35] present an example of this by reviewing the features and gaps of current energy system models and proposing a conceptual framework of how model coupling can take place between energy system modelling tools and regional models presenting infrastructure and resource constraints, electricity market, and macroeconomic modelling tools. Otherwise, more focused coupling efforts can also be found in the literature, including cases coupling top-down and bottom-up energy system modelling tools to gain insight about appropriateness of technology choices in the energy system and wider macroeconomic and welfare effects [189–191], linkages between technology-rich modelling tools and long-term planning ones to get more nuanced representations of the systems' sector coupling and flexibility options [159,192–194], coupling tools forecasting fuel and transport demands with energy system simulation tools [195], or even combined efforts linking spatial analysis [146,196], and behavioral aspects of end-user transport demands [197,198] with energy system modelling tools. Likewise, linking socio-technical transition aspects with energy system tools can prove beneficial to capture more realism in modelling [34].

In all, the coordinated use of modelling tools and different approaches opens a world of possibilities to capture greater detail of the real-world and its dynamics with the energy system. Moreover, this could help in tackling modelling uncertainty, as a better representation could be captured by linking approaches. However, increasing modelling realism should not trump the functionality of modelling tools. While it is certainly impossible and impractical to create and all-encompassing model [19], the added complexity of model coupling could also be detrimental for uptake by relevant users, or for an eventual use of modelling outcomes which are perceived as being too-complex [58]. At its core, the interpretability of modelling outcomes will be rooted in a clear understanding of the underlying modelling assumptions and formulations rather than the increase realism of integrated modelling tools [3]. Thus, a balance between modelling complexity and interpretability and usability is necessary when considering tool coupling exercises.

4.6. Tool usage: accessibility and transparency

There is a current trend and focus on openness of energy system modelling tools [44,46,47,199,200], which, as gathered by Oberle & Elsland [47], are well suited technically to model current challenges in the energy transition. As mentioned in Section 2, this open development is also one of the drivers behind the *Open Energy Modelling Initiative* [45,49], which gathers a growing number of open-source energy system models and frameworks. While this openness generates a natural exchange of knowledge between researchers and modellers and allows for a transparent modelling framework for modellers and users, it is essential to focus on user accessibility and third-party replicability [63].

As explored in other fields of study, prospective users of open access tools still require adequate levels of guidance to learn how to use these, and enable subsequent model implementations [201]. In some cases, this can be facilitated by dedicated graphical interfaces as opposed to direct manipulation of the source code, especially when considering occasional users[3] of a tool [202]. However, the selection of interface should accommodate the specific user-needs [203]. This is especially relevant as the uptake of energy system models as tools for decision-support can be hindered by the functionalities and complicatedness of use perceived by target users [28,58].

Therefore, we compare the tool openness with the tool's user interface. In Fig. 4, the same tool might appear more than once, but in total, 36 of the 54 models and tools surveyed can be free for other users. Of those, 22 are open source, and eight of these require additional commercial software or solvers to run. Only two freeware applications were reported which were not also open source, while 11 tools commercial (paid) software were identified. In addition, 11 tools were observed to be in-house tools that are not sold or provided to outside users. Moreover, 11 tools report being free under special conditions, or being available under request for academic purposes, and overlapping with some of the previous categories otherwise.

The open-source category, as well as most of the other categories, are to a large extent 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 more easily handle the code of some tools' code. In addition, under the "other" category for user-interface we identify that some tools can be used in diverse ways via other external applications such as Excel, Jupyter Notebooks, via bash controls, etc.

Within the non-open source tools, whether they are free or commercial, the share of tools with a dedicated graphical user interface is more significant, while there is a lower number of tools with web-based interfaces.

Many energy tools are dependent on mathematical solvers to operate and find solutions. Talking about the accessibility of free tools, it is important if a tool can operate on open-source/free solvers. Of the 37 tools that indicated they use a solver, 23 are dependent on commercial software while only 8 of these are reported as being open source. This potentially also limits the accessibility of such open and/or free tools, especially looking outside of academic settings with special educational licensing agreements to access some of these solvers.

4.7. Perceived policy-relevance

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 [5,32,204]. Although it is commonly understood that energy policies are political decisions, the use of energy system modelling studies is important to inform and substantiate the policy-making process [7].

In the survey, we attempt to quantify the number of tools that have made some policy contributions. We differentiate between those that have been used directly by an official governmental or public institution for guidance in official policy and indirectly by contributing to the discussion or used as a reference to contrast and/or validate official policies. An outline of this can be seen in Table 4.

Many of the surveyed tools have been used for policy support, both directly (e.g. PRIMES [205]) and indirectly, with some overlapping

[3] Casual or occasional users refers to those who are using a tool intermittently rather than having constant interactions, regardless of their level of expertise in the field of study for which the tool is applied.

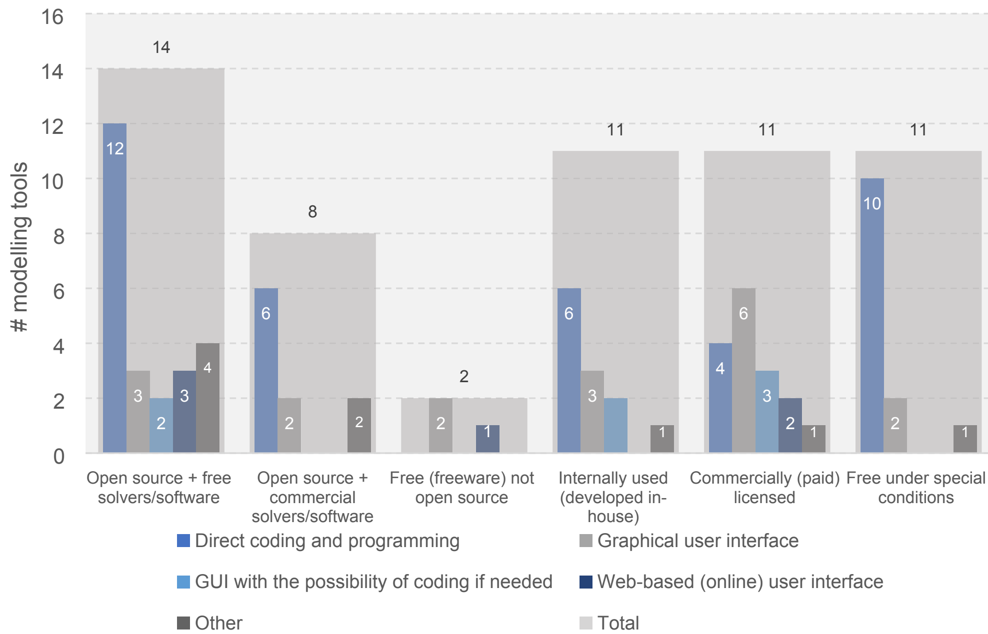

Fig. 4. Comparison of tool types with user-interface among the 54 surveyed tools. Note that the sum of each bar and the total exceed 54 as some tools can fall under multiple licensing/availability and user interface categories.

Table 4
Modelling tools and policy support status among the 54 surveyed tools. Note that the sum exceeds 54 as some tools have had more than a single policy-support application.

Use for policy-making and/or support	# of tools
No	8
Not known	16
Yes, directly	16
Yes, indirectly referred in a relevant official document	17

usage between these two categories (e.g. EnergyPLAN [206,207]). On the other hand, over a third of the models did not have any identifiable policy contribution. This could correspond to the fact that some of these tools are rather new in-house developments used within academic research, or they have been used for a limited scope of projects.

While this certainly shows a gap between modelling and policy, it does not reflect on the modelling potential of such tools to answer policy-related questions. It does however raise a question regarding awareness of modelling tool application beyond initial development, and the involvement of policy-makers in discussions about modelling features and results. Such an involvement could enrich the end-use of energy system models, particularly to produce scenarios answering policy-related questions [7,17]. Ultimately, having this interaction with policy-makers and putting the models to use in decision-support also serve as form of legitimacy and could be viewed as a real-world validation of the energy system model in question [59].

For this reason, it is important to understand the characteristics of the tools used for policy support applications. The attributes of these tools vary in terms of technical modelling characteristics, but also in their accessibility, target user-base and interfasing. In Fig. 5, an overview is presented of the different attributes found in those tools. From the results shown in Fig. 5, a few clear trends can be observed.

First, the tools used for policy-support tend to have high temporal resolution, relying mostly on hourly modelling. This has been specially the case for those tools reported to have direct policy applications, which responds to the need to model the energy system's dynamics when considering fluctuating demands and supply sources, as well as energy balancing. For the tools with indirect application, the hourly time resolution is apparently used as much as yearly resolutions. To a lesser extend, some tools also consider seasonal time-slices or multi-year resolutions to conduct their modelling.

In terms of modelling time-horizon, a multi-year outlook is seen to be most predominant among the surveyed tools with policy applications, while yearly horizons are less used. The ability to represent multiple years facilitates outlining long-term policy pathways, making it a valuable attribute when modelling transition scenarios for the energy system. On the other hand, 1-year horizons, while not explicitly modelling transition pathways, can still aptly model different end- and mid- point scenarios for the enegy system, making them equally valid tools for policy analysis and support.

As seen in Fig. 5, the ability to represent multiple energy sectors and end-uses is widely considered in the tools with policy applications. Here, the electricity sector seems to be slightly more well represented, however other key sectors and end-uses are also considered to an almost equal extent. Interestingly, those tools used indirectly for policy support report having higher representation of some of these sectors, with a slight edge on modelling transport, industry and cooling. By contrast, the overall number of tools surveyed, shown prior in Fig. 2, show a gap between modelling the electricity and other sectors and end-uses.

The energy demand representation in the tools used for policy support falls mostly under static demand representations, with elastic demands also being represented. On the other hand, endonegous demand modelling does not seem to be a common feature present in these models. This aligns with the discussion in Section 4.4. However, endogenous demand representations is slightly more predominant in the tools used for indirect policy support. On the other hand, we see that most of the energy system modelling tools with policy applications rely on connections with other tools, likely to supplement their modelling capabilities.

Finaly, regarding the access and use of the tool, it is possible to see some clear cut distinctions between the tools used directly and indirectly for policy support. For instance, while open source access seems to be a prefereed attribute in the observed tools, the use of commercial and non-open source freeware seems more prevalent in direct policy applications. Similarly, tools used for direct policy-support seem more likely to provide graphical user interfaces, in contrast with direct coding, mostly found in those modelling tools used indirectly for policy support

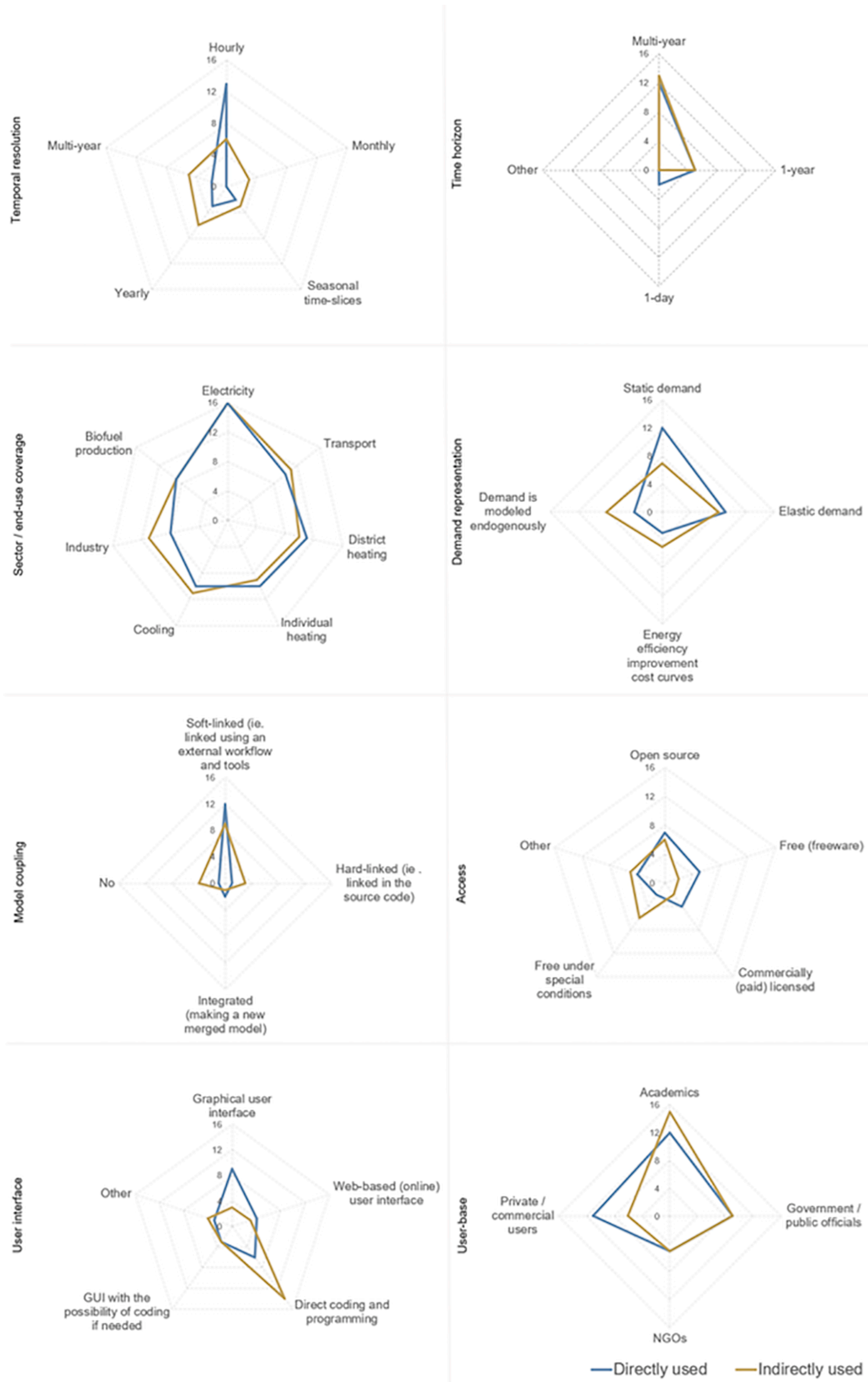

Fig. 5. Characteristics of the tools reported to be used directly (in blue) and indirectly (yellow) for policy support represented as radar plots of temporal resolutions, time horizons, sectoral coverage, demand representations, model coupling applications, access/licensing, type of user interface and user-base of the tools. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

applications. Ultimately, this could potentially be associated to the target user-base of the modelling tools as seen in Fig. 5, where we see that for direct policy support the main user-base consists of private/commercial users, as well as academics and government/public officials; while, academic users make up the main user-base of those tools used for indirect policy-support.

5. Summary and discussion

This study reviews recent trends in energy system modelling tools by surveying the existing literature and gathering inputs directly from tool developers about the features and applications of their modelling tools. Unlike previous review studies found in the literature, this contribution establishes a direct communication with modellers and developers of the tools through a questionnaire, to reflect the way these developers understand their tool under a common terminology, while also addressing issues that previous survey-based studies have not put much focus on, such as the factual policy-relevance of studies conducted by an energy system modelling tool, the accessibility, openness and usability of the tool, and possible model coupling applications. This reduces the risk of misinterpretation or biased assessment of different tools by relying on their published information, although with a limited sample of tools surveyed. Moreover, the survey offers an avenue to gather information about the real-world application of the tools directly from their developers.

This, of course, does not come free of downsides, like the potential exclusion in the current survey of some well-documented modelling tools, in cases where no responses were gathered for the questionnaire, or by considering representative 'members' from a family of models which might have different technical attributes to their source. Moreover, potential biases in the survey can arise as the majority of the past reviews, and the models survey stem from European research, which could hint at a focus on modelling specific aspect of European energy transition paradigms. Nonetheless, we recommend this line of dialogue with tool developers when conducting future review exercises in order to gather insight about the modelling applications of a particular tool or for validation purposes, and more generally to identify trends in the field of energy system modelling. From this, the following points appeared to be evident after the process of conducting the survey, including both literature reviews and modelling tools.

First, it is challenging to agree on a specific vocabulary that all tool developers reach consensus in the same way. For instance, multiple studies have focused on proposing new classification schemes and to categorize different modelling approaches or methodologies. While some of these categories are unambiguous, other descriptive labels assigned to tools might fall within an overlapping spectrum which is harder to define. This is not surprising as an overlap between modelling methodologies does exist; it highlights, however, the importance of communication between modellers when discussing different modelling methods and would be relevant when interpreting the tools application or when working on linking different tools. Similarly, expanding this dialogue can also provide a better understanding of a tool's intended design versus its inferred potential applications obtained from only reviewing modelling features, as seen in Section 4.2. regarding the typical modelling time-step used by some tools and the clarifications from tool developers, or in Section 4.6 regarding their policy-related applications. However, it is important to point out that surveying can only be fully effective if there is a common understanding of terminology and a clear framing of survey questions. As a case in point, a survey question like "How is energy demand modelled in the tool?" can be understood in many ways, such as in terms of energy carriers (e.g. a country's demand for oil) or in terms of end-uses (e.g. demand for energy from households). In turn, this could lead to potential misunderstandings on whether the demand is modelled endogenously or exogenously depending on how the respondent interprets demand in the first place.

Second, modelling tools rely on exogenous demand datasets. Yet, there is still a lack of accessible data for modellers to understand projected and uncertain changes in demand, and to model high spatial and temporal resolution systems. Where available, standard input datasets are relied upon in energy system models, irrespective of their research focus, representing the frontier of data availability. The modelling of cross-sectoral decarbonization will open new challenges, including the integration of sectors for which ever more data is required and the need to specify demand that is matched to the weather conditions influencing the increasing prevalence of variable renewable generation. For this, coupling with demand modelling tools is necessary, but nascent. In addition to issues of data availability, greater energy system complexity and reliance on non-dispatchable technologies exposes the inadequacy of exogenous demand. Instead, modelling tools must embrace elastic and endogenous demand to develop highly interconnected energy systems.

Third, when investigating many tools that can do different things in terms of modelling energy transitions, it becomes clear that it is impossible to build a tool that can do it all. Most of the tools have been developed to fulfil a specific task within a defined scope or according to specific user-needs. It might have received updates and an increased number of capabilities, but the underlying general architecture, technology, and terminology remains the same. We would argue that efforts should be targeted towards linking these different tools to each other, utilizing the many capabilities that are already present. Individual tool development is obviously still required and necessary, but there is a trade-off between the details and granularity of a model and computational resources. In line with this, future review efforts could also study in more detail model coupling exercises and identify more specifically which tools are coupled together, which specific typologies exist and the trade-offs of coupling approaches. For instance, this could be done by examining the coupling of energy system modelling tools with demand models, socio-technical energy transition models, etc.

Finally, the transparency and policy-relevant applications of energy system modelling tools should be put into a real-world perspective. For example, the complexity of linking modelling tools should not jeopardize the interpretability of the underlying modelling assumptions and outcomes, as this would detract modellers and output consumers (e.g. decision/policy-makers). In line with this, model development should be conducted in such a way that it leads to actionable research, and in which policy and decision support takes center stage. In this regard, further research could be conducted to identify how user-needs and policy-making processes mark the development of modelling tools actually used for decision-support, and which features these have and need.

In line with this, modelling interpretability goes beyond the access to open code and the perceived transparency that this provides. While open development and open source development is laudable and a recommended practice, the "out-of-the-box" usability of a tool also needs to be accounted for as an additional dimension of accessibility. Doing so could enhance the application of energy modelling tools and allow for a more active engagement with a wider multiplicity of actors that can actively contribute and enrich the energy policy debate by using modelling outcomes, while also validating the appropriateness of energy system modelling tools in the real-world arena.

CRediT authorship contribution statement

Miguel Chang: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Jakob Zink Thellufsen:** Conceptualization, Methodology, Writing - original draft, Supervision, Project administration. **Behnam Zakeri:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Bryn Pickering:** Conceptualization, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Stefan Pfenninger:** Conceptualization, Writing - review & editing. **Henrik Lund:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Poul Alberg Østergaard:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Survey questionnaire structure

1. General information
Name of the modelling tool
2. Modelling specifications
2.1. Modelling method
Simulation//Optimization//Equlibrium (specify)//Other (specify)
2.2. Purpose of the model's mathematical formulation
Investment cost minimization//Dispatch cost minimization//Electricity import/export minimization//Social welfare maximization//Fuel minimization//Multi-criteria analysis//Agent-based analysis//Other (specify)
2.3. User interface:
Graphical user interface//Web-based (online) user interface//Direct coding and programming//GUI with the possibility of coding if needed//Other (specify)
2.4. Accessibility of modelling tool:
Open source//Free (freeware)//Commercially (paid) licensed//Free under special conditions//Other (specify)
2.5. Additional modules or solvers needed to run the model
Yes/No
2.5.1. Based on the above, are the additional module/solver: (check all that apply)
Open source//Free (freeware)//Commercially (paid) licensed//Free under special conditions//Other (specify)
2.7. Possibility to add equations/sectors/technologies/add-ons or other details to the structure of the model
Yes//No//Specific parts (specify)
2.8. Derivative/branch-out versions based on the original modelling tool
Yes//No//Not known
3. Application
3.1. Previous case studies
(Specify)
3.2. Previous linkeages with other modelling tools
Yes, soft-linked (ie. linked using an external workflow and tools//Yes, hard-linked (ie . linked in the source code)//Yes, integrated (making a new merged model)//No//Not known
3.3. Main user-base
Academics//Government/public officials//NGOs//Private/commercial users//Not known//Others (specify)
3.4. Previous use for policy-making
Yes, directly (reference below)//Yes, indirectly referred in a relevant official document (reference below)//No//Not known
3.4.1. Policy-relevant reference
(Specify)
4. Modelling resolution
4.1. Geographical resolutions represented in the modelling tool (multiple choice)
Global//Regional//National//Local//Project-specific resolution//Other (specify)
4.2. Minimum level of granularity to represent a technology (multiple choice)
Aggregated values//Individual plant/component(s) inputs//Other (specify)
4.3. Typical scale of technology representation in national level modeling
(Specify)
4.4. Sectors represented in the model (multiple choice)
Electricity generation//Individual heating//District heating//Cooling//Transport//Industry//Biofuel production//Other (please specify)
4.5. Temporal resolution (multiple choice)
Hourly//Monthly//Seasonal time-slices//Yearly//Multi-year//Other (specify)
4.6. Time horizon of modeled outputs (multiple choice)
1-day//1-year//Multi-year (specify) //Other (specify)
5. Key inputs
5.1. Represention of demand
Static demand (no response to supply cost)//Elastic demand (responsive to supply cost)//Energy efficiency improvement cost curves//Demand is modeled endogenously//Others (specify)
5.2. Demand-side flexibility to integrate variable renewable energy
Yes, electricity and heat//Yes, only electricity//No//Other (specify)
5.3. Electricity generation technologies considered (multiple choice)
Power plants (Thermo electric)//CHP plants//Nuclear//Hydro power (dam)//Run-of-river hydro//Wind//Photovoltaic//Solar Thermal//Geothermal//Wave and/or Tidal//Other (specify) //Any (user-defined)
5.4. Heat supply technologies considered (multiple choice)
Heat pumps//Fuel-based boilers//Electric boilers//Solar thermal//CHP plants//Geothermal//Industrial excess heat//Other (specify) //Any (user defined)
5.4. Storage technologies considered (multiple choice)
Pumped hydroelectric energy storage //Battery electric storage//Compressed-air energy storage//Rockbed storage//Hydrogen production i.e. *electrolysis//Power to gas//Power to liuid//Power to heat (electric heat pump and heat storage)//Liquid & Gas fuel storage//Smart charging of electric vehicles//Other (specify) //Any (user-defined)*
5.5. Transport technologies and sub-sectors considered (multiple choice)
Internal combustion vehicles//Battery electric vehicles//Intelligent battery electric vehicles//Hybrid vehicles//Rail//Aviation//Other (specify) //Any (user-defined)
5.6. Representation of electricity transmission and bottlenecks in the grid
Yes, as a transshipment network//Yes, as a DC or AC load flow network//Yes, a point-to-pool network (no explicit bilateral trade)//No//Other (please specify)
6. Additional information
6.1. Overview of the modelling tool (developers' description)
(Specify)
6.2. Specific modelling focus on a technology or group of technologies listed in the previous sections (ie. if the modelling tool has more level of detail on a specific technology)
Yes (specify)/No
6.3. Public availability of tool's documentation
Yes (please provide source)/No
6.4. Format of modelling tool documentation
Documentation file available online//Documentation file published//Online documentation//Online documentation linked to the mathematical model//Other (specify)

Appendix B. Supplementary data – Survey inputs

The following is the supplementary data to this article: [208].

References

[1] IEA. World Energy Outlook 2018; 2018. https://doi.org/10.1787/weo-2018-en.

[2] 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. https://doi.org/10.1186/s13705-017-0107-2.
[3] Ellenbeck S, Lilliestam J. How modelers construct energy costs: Discursive elements in Energy System and Integrated Assessment Models. Energy Res Soc Sci 2019;47:69–77. https://doi.org/10.1016/j.erss.2018.08.021.
[4] 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. https://doi.org/10.1016/j.apenergy.2009.09.026.
[5] Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first century energy challenges. Renew Sustain Energy Rev 2014;33:74–86. https://doi.org/10.1016/j.rser.2014.02.003.
[6] A review of modelling tools for energy and electricity systems with large shares of variable renewables.pdf n.d.
[7] Savvidis G, Siala K, Weissbart C, Schmidt L, Borggrefe F, Kumar S, et al. The gap between energy policy challenges and model capabilities. Energy Policy 2019;125:503–20. https://doi.org/10.1016/j.enpol.2018.10.033.
[8] Prina MG, Manzolini G, Moser D, Nastasi B, Sparber W. Classification and challenges of bottom-up energy system models - A review. Renew Sustain Energy Rev 2020;129:109917. https://doi.org/10.1016/j.rser.2020.109917.
[9] Grunwald A. Energy futures: Diversity and the need for assessment. Futur Evol Psychol 2011;43:820–30. https://doi.org/10.1016/j.futures.2011.05.024.
[10] Foley AM, Gallachóir BPÓ, Hur J, Baldick R, McKeogh EJ. A strategic review of electricity systems models. Energy 2010;35:4522–30. https://doi.org/10.1016/j.energy.2010.03.057.
[11] 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. https://doi.org/10.1016/j.energy.2014.12.005.
[12] Mahmud K, Town GE. A review of computer tools for modeling electric vehicle energy requirements and their impact on power distribution networks. Appl Energy 2016;172:337–59. https://doi.org/10.1016/j.apenergy.2016.03.100.
[13] Van Beeck NMJ. Classification of energy models. FEW Res Memo 1999.
[14] Jebaraj S, Iniyan S. A review of energy models. Renew Sustain Energy Rev 2006;10:281–311.
[15] Mougouei FR, Mortazavi MS. Effective approaches to energy planning and classification of energy systems models. Int J Energy Econ Policy 2017;7:127–31.
[16] Ridha E, Nolting L, Praktiknjo A. Complexity profiles: A large-scale review of energy system models in terms of complexity. Energy Strateg Rev 2020;30:100515. https://doi.org/10.1016/j.esr.2020.100515.
[17] 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. https://doi.org/10.1016/j.esr.2018.03.006.
[18] Pilavachi PA, Dalamaga T, Rossetti di Valdalbero D, Guilmot JF. Ex-post evaluation of European energy models. Energy Policy 2008;36:1726–35.
[19] Unger T, Springfeldt PE, Ravn H, Niemi J, Fritz P, Rydén B, et al. Coordinated use of energy system models in energy and climate policy analysis - Lessons learned from the Nordic Energy Perspectives Project; 2010.
[20] Hall LMH, Buckley AR. A review of energy systems models in the UK: Prevalent usage and categorisation. Appl Energy 2016;169:607–28. https://doi.org/10.1016/j.apenergy.2016.02.044.
[21] 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. https://doi.org/10.1016/j.rser.2018.07.045.
[22] Bhattacharyya SC, Timilsina GR. A review of energy system models. Int J Energy Sect Manag 2010;4:494–518. https://doi.org/10.1108/17506221011092742.
[23] Musonye XS, Davíðsdóttir B, Kristjánsson R, Ásgeirsson EI, Stefánsson H. Integrated energy systems' modeling studies for sub-Saharan Africa: A scoping review. Renew Sustain Energy Rev 2020:128. https://doi.org/10.1016/j.rser.2020.109915.
[24] Markovic D, Cvetkovic D, Masic B. Survey of software tools for energy efficiency in a community. Renew Sustain Energy Rev 2011;15:4897–903. https://doi.org/10.1016/j.rser.2011.06.014.
[25] 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. https://doi.org/10.1016/j.rser.2012.02.047.
[26] 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. https://doi.org/10.1016/j.rser.2015.07.123.
[27] Van Beuzekom I, Gibescu M, Slootweg JG. A review of multi-energy system planning and optimization tools for sustainable urban development. In: 2015 IEEE Eindhoven PowerTech, PowerTech 2015; 2015. p. 1–7. https://doi.org/10.1109/PTC.2015.7232360.
[28] Ferrari S, Zagarella F, Caputo P, Bonomolo M. Assessment of tools for urban energy planning. Energy 2019;176:544–51. https://doi.org/10.1016/j.energy.2019.04.054.
[29] Scheller F, Bruckner T. Energy system optimization at the municipal level: An analysis of modeling approaches and challenges. Renew Sustain Energy Rev 2019;105:444–61. https://doi.org/10.1016/j.rser.2019.02.005.
[30] 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. https://doi.org/10.1016/j.rser.2015.05.040.
[31] Weinand JM, Scheller F, McKenna R. Reviewing energy system modelling of decentralized energy autonomy. Energy 2020;203:117817. https://doi.org/10.1016/j.energy.2020.117817.
[32] 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. https://doi.org/10.3390/en10070840.
[33] Crespo del Granado P, van Nieuwkoop RH, Kardakos EG, Schaffner C. Modelling the energy transition: A nexus of energy system and economic models. In: Energy Strateg Rev, 20; 2018. p. 229–35. https://doi.org/10.1016/j.esr.2018.03.004.
[34] Hirt LF, Schell G, Sahakian M, Trutnevyte E. A review of linking models and socio-technical transitions theories for energy and climate solutions. Environ Innov Soc Transitions 2020;35:162–79. https://doi.org/10.1016/j.eist.2020.03.002.
[35] Fattahi A, Sijm J, Faaij A. A systemic approach to analyze integrated energy system modeling tools, a review of national models. Renew Sustain Energy Rev 2020;133:110195. https://doi.org/10.1016/j.rser.2020.110195.
[36] Olsthoorn D, Haghighat F, Mirzaei PA. Integration of storage and renewable energy into district heating systems: A review of modelling and optimization. Sol Energy 2016;136:49–64. https://doi.org/10.1016/j.solener.2016.06.054.
[37] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. https://doi.org/10.1016/j.energy.2017.05.123.
[38] Thellufsen JZ, Lund H. Cross-border versus cross-sector interconnectivity in renewable energy systems. Energy 2017;124:492–501. https://doi.org/10.1016/j.energy.2017.02.112.
[39] Li FGN, Trutnevyte E, Strachan N. A review of socio-technical energy transition (STET) models. Technol Forecast Soc Change 2015;100:290–305. https://doi.org/10.1016/j.techfore.2015.07.017.
[40] Li FGN, Strachan N. Take me to your leader: Using socio-technical energy transitions (STET) modelling to explore the role of actors in decarbonisation pathways. Energy Res Soc Sci 2019;51:67–81. https://doi.org/10.1016/j.erss.2018.12.010.
[41] Trutnevyte E, Hirt LF, Bauer N, Cherp A, Hawkes A, Edelenbosch OY, et al. Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. One Earth 2019;1:423–33. https://doi.org/10.1016/j.oneear.2019.12.002.
[42] Bolwig S, Bazbauers G, Klitkou A, Lund PD, Blumberga A, Gravelsins A, et al. Review of modelling energy transitions pathways with application to energy system fl exibility. Renew Sustain Energy Rev 2019;101:440–52. https://doi.org/10.1016/j.rser.2018.11.019.
[43] Bolwig S, Folsland T, Klitkou A, Lund PD, Bergaentzlé C, Borch K, et al. Energy Research & Social Science Climate-friendly but socially rejected energy-transition pathways : The integration of techno-economic and socio-technical approaches in the Nordic-Baltic region. Energy Res Soc Sci 2020;67:101559. https://doi.org/10.1016/j.erss.2020.101559.
[44] 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. https://doi.org/10.1016/j.enpol.2012.06.032.
[45] 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. https://doi.org/10.1016/j.esr.2017.12.002.
[46] Morrison R. Energy system modeling: Public transparency, scientific reproducibility, and open development. Energy Strateg Rev 2018;20:49–63. https://doi.org/10.1016/j.esr.2017.12.010.
[47] Oberle S, Elsland R. Are open access models able to assess today's energy scenarios? Energy Strateg Rev 2019;26:100396. https://doi.org/10.1016/j.esr.2019.100396.
[48] Groissböck M. Are open source energy system optimization tools mature enough for serious use? Renew Sustain Energy Rev 2019;102:234–48. https://doi.org/10.1016/j.rser.2018.11.020.
[49] openmod. Open Energy Modelling Initiative; 2020. https://openmod-initiative.org/[accessed February 23, 2020].
[50] 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.
[51] MEDEAS. Modelling the Energy Development under Environmental and Socioeconomic Contraints;2018; n.d. http://www.medeas.eu/[accessed February 24, 2020].
[52] SET-nav. Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation 2018. http://www.set-nav.eu/[accessed February 24, 2020].
[53] REFLEX. Analysis of the European Energy System under the Aspects of Flexibility and Technological Progress 2018. http://reflex-project.eu/.
[54] openENTRANCE. Open Energy Transition Analyses for a low-Carbon Economy 2019. https://openentrance.eu/[accessed February 24, 2020].
[55] SENTINEL. Sustainable Energy Transitions Laboratory 2019. https://sentinel.energy/[accessed February 24, 2020].
[56] Klemm C, Vennemann P. Modeling and optimization of multi-energy systems in mixed-use districts: A review of existing methods and approaches. Renew Sustain Energy Rev 2021;135:110206. https://doi.org/10.1016/j.rser.2020.110206.
[57] Lund H, Thellufsen JZ. EnergyPLAN - Advance Energy Systems Anaysis Computer Model (Version 15.1) 2020. https://doi.org/10.5281/zenodo.4001540.
[58] Ben Amer S, Gregg JS, Sperling K, Drysdale D. Too complicated and impractical? An exploratory study on the role of energy system models in municipal decision-making processes in Denmark. Energy Res Soc Sci 2020;70:101673. https://doi.org/10.1016/j.erss.2020.101673.

[59] Silvast A, Laes E, Abram S, Bombaerts G. What do energy modellers know? An ethnography of epistemic values and knowledge models. Energy Res Soc Sci 2020;66:101495. https://doi.org/10.1016/j.erss.2020.101495.
[60] Mundaca L, Neij L, Worrell E, McNeil M. Evaluating energy efficiency policies with energy-economy models. Annu Rev Environ Resour 2010;35:305–44. https://doi.org/10.1146/annurev-environ-052810-164840.
[61] Mendes G, Ioakimidis C, Ferrão P. On the planning and analysis of Integrated Community Energy Systems: A review and survey of available tools. Renew Sustain Energy Rev 2011;15:4836–54. https://doi.org/10.1016/j.rser.2011.07.067.
[62] Manfren M, Caputo P, Costa G. Paradigm shift in urban energy systems through distributed generation: Methods and models. Appl Energy 2011;88:1032–48. https://doi.org/10.1016/j.apenergy.2010.10.018.
[63] DeCarolis JF, Hunter K, Sreepathi S. The case for repeatable analysis with energy economy optimization models. Energy Econ 2012;34:1845–53. https://doi.org/10.1016/j.eneco.2012.07.004.
[64] Mirakyan A, De Guio R. Integrated energy planning in cities and territories: A review of methods and tools. Renew Sustain Energy Rev 2013;22:289–97. https://doi.org/10.1016/j.rser.2013.01.033.
[65] Huang Z, Yu H, Peng Z, Zhao M. Methods and tools for community energy planning: A review. Renew Sustain Energy Rev 2015;42:1335–48. https://doi.org/10.1016/j.rser.2014.11.042.
[66] Lund H, Arler F, Østergaard P, Hvelplund F, Connolly D, Mathiesen B, et al. Simulation versus Optimisation: Theoretical Positions in Energy System Modelling. Energies 2017;10:840. https://doi.org/10.3390/en10070840.
[67] Lyden A, Pepper R, Tuohy PG. A modelling tool selection process for planning of community scale energy systems including storage and demand side management. Sustain Cities Soc 2018;39:674–88. https://doi.org/10.1016/j.scs.2018.02.003.
[68] Abbasabadi N, Mehdi Ashayeri JK. Urban energy use modeling methods and tools: A review and an outlook. Build Environ 2019;161:106270. https://doi.org/10.1016/j.buildenv.2019.106270.
[69] Loulou R, Remme U, Anudia A, Lettila A, Goldstein G. Documentation for the TIMES Model - PART I; 2005.
[70] Yang C, Yeh S, Zakerinia S, Ramea K, McCollum D. Achieving California's 80% greenhouse gas reduction target in 2050: Technology, policy and scenario analysis using CA-TIMES energy economic systems model. Energy Policy 2015; 77:118–30. https://doi.org/10.1016/j.enpol.2014.12.006.
[71] Shi J, Chen W, Yin X. Modelling building's decarbonization with application of China TIMES model. Appl Energy 2016;162:1303–12. https://doi.org/10.1016/j.apenergy.2015.06.056.
[72] Salvucci R, Gargiulo M, Karlsson K. The role of modal shift in decarbonising the Scandinavian transport sector: Applying substitution elasticities in TIMES-Nordic. Appl Energy 2019;253:113593. https://doi.org/10.1016/j.apenergy.2019.113593.
[73] Di Leo S, Caramuta P, Curci P, Cosmi C. Regression analysis for energy demand projection: An application to TIMES-Basilicata and TIMES-Italy energy models. Energy 2020;196:117058. https://doi.org/10.1016/j.energy.2020.117058.
[74] Nijs W, Simoes S, Sgobbi A, Ruiz-Castello P, Thiel C, Giannakidis G, et al. Improved Representation of the European Power Grid in Long Term Energy System Models: Case Study of JRC-EU-TIMES. In: Giannakidis G, Labriet M, Ó Gallachóir B, Tosato G, editors. Informing Energy Clim. Policies Using Energy Syst. Model. Insights from Scenar. Anal. Increasing Evid. Base, Cham: Springer International Publishing; 2015. p. 201–22. https://doi.org/10.1007/978-3-319-16540-0_12.
[75] Howells M, Rogner H, Strachan N, Heaps C, Huntington H, Kypreos S, et al. OSeMOSYS: The Open Source Energy Modeling System. An introduction to its ethos, structure and development. Energy Policy 2011;39:5850–70. https://doi.org/10.1016/j.enpol.2011.06.033.
[76] Löffler K, Hainsch K, Burandt T, Oei PY, Kemfert C. Von Hirschhausen C. Designing a model for the global energy system-GENeSYS-MOD: An application of the Open-Source Energy Modeling System (OSeMOSYS). Energies 2017;10. https://doi.org/10.3390/en10101468.
[77] Wiese F, Bramstoft R, Koduvere H, Pizarro Alonso A, Balyk O, Kirkerud JG, et al. Balmorel open source energy system model. Energy Strateg Rev 2018;20:26–34. https://doi.org/10.1016/j.esr.2018.01.003.
[78] Pfenninger S, Pickering B. Calliope: a multi-scale energy systems modelling framework. J Open Source Softw 2018;3:825. https://doi.org/10.21105/joss.00825.
[79] Energianalyse. COMPOSE n.d. http://www.energianalyse.dk/index.php/software [accessed September 17, 2020].
[80] Berkeley Lab. DER-CAM n.d. https://gridintegration.lbl.gov/der-cam [accessed September 17, 2020].
[81] Zerrahn A, Schill WP. Long-run power storage requirements for high shares of renewables: review and a new model. Renew Sustain Energy Rev 2017;79: 1518–34. https://doi.org/10.1016/j.rser.2016.11.098.
[82] Quoilin S, Hidalgo Ganzalez I, Zucker A. Modelling Future EU Power Systems Under High Shares of Renewables The Dispa-SET 2.1 open-source model; 2017. https://doi.org/10.2760/25400.
[83] Sun N. Model-based investigation of the electricity market: unit commitment and power plant investments; 2013.
[84] Chappin EJL, de Vries LJ, Richstein JC, Bhagwat P, Iychettira K, Khan S. Simulating climate and energy policy with agent-based modelling: The Energy Modelling Laboratory (EMLab). Environ Model Softw 2017;96:421–31. https://doi.org/10.1016/j.envsoft.2017.07.009.
[85] Hirth L. The European electricity market model EMMA 2014:12.
[86] Skar C, Doorman GL, Pérez-Valdés GA, Tomasgard A. A multi-horizon stochastic programming model for the European power system; 2016.
[87] Zakeri B, Virasjoki V, Syri S, Connolly D, Mathiesen BV, Welsch M. Impact of Germany's energy transition on the Nordic power market – A market-based multi-region energy system model. Energy 2016;115:1640–62. https://doi.org/10.1016/j.energy.2016.07.083.
[88] Quintel Intelligence. Energy Transition Model n.d. https://docs.energytransitionmodel.com/main/intro/[accessed September 17, 2020].
[89] EMD International A/S. energyPRO n.d. https://www.emd.dk/energypro/support/tutorials-guides/[accessed September 17, 2020].
[90] Lugovoy O, Potashnikov V. energyRt n.d. https://energyrt.org/[accessed September 17, 2020].
[91] Limpens G, Moret S, Jeanmart H, Maréchal F. EnergyScope TD: A novel open-source model for regional energy systems. Appl Energy 2019;255:113729. https://doi.org/10.1016/j.apenergy.2019.113729.
[92] Fraunhofer ISI. Enertile n.d. https://www.enertile.eu/enertile-en/publication.php [accessed September 17, 2020].
[93] Fraunhofer ISE. ENTIGRIS n.d. https://www.ise.fraunhofer.de/en/business-areas/power-electronics-grids-and-smart-systems/energy-system-analysis/energy-system-models-at-fraunhofer-ise/entigris.html [accessed September 17, 2020].
[94] Heuberger CF. Electricity Systems Optimisation with capacity eXpansion and Endogenous technology Learning (ESO-XEL) 2017. https://doi.org/10.5281/zenodo.1048942.
[95] Despres J. Development of a dispatch model of the European power system for coupling with a long-term foresight energy model. Cah Rech EDDEN 2015;37.
[96] JRC - Smart Electricity Systems and Interoperability. EUPowerDispatch n.d. https://ses.jrc.ec.europa.eu/eupowerdispatch-model [accessed September 17, 2020].
[97] Peñate Vera S. GridCal n.d. https://gridcal.readthedocs.io/en/latest/# [accessed September 17, 2020].
[98] Homer Energy. Homer Grid n.d. https://www.homerenergy.com/products/grid/index.html [accessed July 19, 2020].
[99] Dufo López R. iHOGA n.d. https://ihoga.unizar.es/en/[accessed September 17, 2020].
[100] Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., et al. Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications; 2014.
[101] Kuhn P. Iteratives Modell zur Optimierung von Speicherausbau und -betrieb in einem Stromsystem mit zunehmend fluktuierender Erzeugung; 2012.
[102] Strbac G, Pudjianto D, Sansom R, Djapic P, Ameli H, Shah N, et al. Analysis of Alternative UK Heat Decarbonisation Pathways 2018:159.
[103] EEG. Invert-EELab n.d. https://www.invert.at/.
[104] Aune FR, Golombek R, Kittelsen SAC, Rosendahl KE. Liberalizing European Energy MarketsAn Economic Analysis. Cheltenham, UK: Edward Elgar Publishing; 2008.
[105] Osorio S, Pietzcker R, Tietjen O. Documentation of LIMES-EU - A long-term electricity system model for Europe 2020.
[106] Jacobson MZ, Delucchi MA, Cameron MA, Mathiesen BV. Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. Renew Energy 2018;123:236–48. https://doi.org/10.1016/j.renene.2018.02.009.
[107] Jacobson MZ, Delucchi MA, Cameron MA, Coughlin SJ, Hay CA, Manogaran IP, et al. Impacts of Green New Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries. One Earth 2019;1:449–63. https://doi.org/10.1016/j.oneear.2019.12.003.
[108] Van Den Bergh K, Bruninx K, Delarue E, D'haeseleer W. LUSYM: a Unit Commitment Model formulated as a Mixed-Integer Linear Program 2016.
[109] Maon GmbH. Maon n.d. https://cloud.maon.eu/handbook [accessed September 17, 2020].
[110] Huppmann D, Gidden M, Fricko O, Kolp P, Orthofer C, Pimmer M, et al. The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. Environ Model Softw 2019;112: 143–56. https://doi.org/10.1016/j.envsoft.2018.11.012.
[111] Energy Information Administration. The National Energy Modeling System: An Overview 2018; 2019.
[112] EPRI. OpenDSS n.d. https://sourceforge.net/projects/electricdss/[accessed July 17, 2020].
[113] FFG. OptEnGrid n.d. https://projekte.ffg.at/projekt/1822013 [accessed September 17, 2020].
[114] Després J, Keramidas K, Schmitz A, Kitous A, Schade B, Diaz Vasquez A, et al. POLES-JRC model documentation. Publications Office of the European Union; 2018. https://doi.org/10.2760/814959.
[115] Mantzos L, Wiesenthal T. POTEnCIA model description: Version 0.9. vol. JRC100638; 2016. https://doi.org/10.2791/416465.
[116] E3MLab. Primes Model version 2018: detailed model description 2018.
[117] PSR. SDDP User Mannual Version 16.0 2019.
[118] Capellán-Pérez I, De Blas I, Nieto J, De Castro C, Miguel LJ, Carpintero Ó, et al. MEDEAS: A new modeling framework integrating global biophysical and socioeconomic constraints. Energy Environ Sci 2020;13:986–1017. https://doi.org/10.1039/c9ee02627d.
[119] Brown T, Hörsch J, Schlachtberger D. PyPSA Python for power system analysis. J Open Res Softw 2018;6. https://doi.org/10.5334/jors.188.
[120] Energistyrelsen. RamsesR 2018:1–38.

[121] Cohen S, Becker J, Bielen D, Brown M, Cole W, Eurek K, et al. Regional Energy Deployment System (ReEDS) Model Documentation: Version 2018. Natl Renew Energy Lab 2019. https://doi.org/NREL/TP-6A20-67067.

[122] Aboumahboub T, Auer C, Bauer N, Baumstark L, Bertram C, Bi S, et al. REMIND - REgional Model of INvestments and Development - Version 2.1.0 2020.

[123] Energinet. SIFRE: Simulation of Flexible and Renewable Energy sources 2015: 1–34.

[124] Blair N, Diorio N, Freeman J, Gilman P, Janzou S, Neises TW, et al. System Advisor Model (SAM) General Description (Version 2017.9.5) 2018.

[125] TUHH. TransiEnt Library n.d. https://www.tuhh.de/transient-ee/en/news.html [accessed September 17, 2020].

[126] Leaver JD, Gillingham KT, Leaver LHT. Assessment of primary impacts of a hydrogen economy in New Zealand using UniSyD. Int J Hydrogen Energy 2009; 34:2855–65.

[127] Mayer J, Bachner G, Steininger KW. Macroeconomic implications of switching to process-emission-free iron and steel production in Europe. J Clean Prod 2019; 210:1517–33. https://doi.org/10.1016/j.jclepro.2018.11.118.

[128] RFF-CMCC-EIEE. WITCH Model n.d. https://www.witchmodel.org/documentation/[accessed September 17, 2020].

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

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

[131] 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. https://doi.org/10.1016/j.apenergy.2015.10.100.

[132] 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. https://doi.org/10.1016/j.apenergy.2013.07.027.

[133] 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. https://doi.org/10.1016/j.apenergy.2017.03.051.

[134] McCallum P, Jenkins DP, Peacock AD, Patidar S, Andoni M, Flynn D, et al. A multi-sectoral approach to modelling community energy demand of the built environment. Energy Policy 2019;132:865–75. https://doi.org/10.1016/j.enpol.2019.06.041.

[135] Keppo I, Strubegger M. Short term decisions for long term problems - The effect of foresight on model based energy systems analysis. Energy 2010;35:2033–42. https://doi.org/10.1016/j.energy.2010.01.019.

[136] Prina MG, Lionetti M, Manzolini G, Sparber W, Moser D. Transition pathways optimization methodology through EnergyPLAN software for long-term energy planning. Appl Energy 2019:356–68. https://doi.org/10.1016/j.apenergy.2018.10.099.

[137] Capros P, De Vita A, Tasios N, Siskos P, Kannavou M, Petropoulos A, et al. EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050. European Commission; 2016.

[138] Capros P, Kannavou M, Evangelopoulou S, Petropoulos A, Siskos P, Tasios N, et al. Outlook of the EU energy system up to 2050: The case of scenarios prepared for European Commission ' s " clean energy for all Europeans " package using the PRIMES model. Energy Strateg Rev 2018;22:255–63. https://doi.org/10.1016/j.esr.2018.06.009.

[139] Capros P, Zazias G, Evangelopoulou S, Kannavou M, Fotiou T, Siskos P, et al. Energy-system modelling of the EU strategy towards climate-neutrality ☆. Energy Policy 2019;134:110960. https://doi.org/10.1016/j.enpol.2019.110960.

[140] Solé J, Samsó R, García-Ladona E, García-Olivares A, Ballabrera-Poy J, Madurell T, et al. Modelling the renewable transition: Scenarios and pathways for a decarbonized future using pymedeas, a new open-source energy systems model. Renew Sustain Energy Rev 2020;132:37–49. https://doi.org/10.1016/j.rser.2020.110105.

[141] Bacekovic I, Østergaard PA. Local smart energy systems and cross-system integration. Energy 2018. https://doi.org/10.1016/j.energy.2018.03.098.

[142] Thellufsen JZ, Lund H, Sorknæs P, Østergaard PA, Chang M, Drysdale D, et al. Smart energy cities in a 100% renewable energy context. Renew Sustain Energy Rev 2020;129. https://doi.org/10.1016/j.rser.2020.109922.

[143] Mathiesen BV, Lund H, Hansen K, Ridjan I, Djørup S, Nielsen S, et al. IDA's Energy Vision 2050. Copenhagen: Aalborg University; 2015.

[144] 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.

[145] Hansen K, Mathiesen BV, Skov IR. Full energy system transition towards 100% renewable energy in Germany in 2050. Renew Sustain Energy Rev 2019;102: 1–13. https://doi.org/10.1016/J.RSER.2018.11.038.

[146] 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 decarbonisation. J Clean Prod 2020;272.

[147] 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. https://doi.org/10.1016/j.apenergy.2016.03.046.

[148] Dominković DF, Dobravec V, Jiang Y, Nielsen PS, Krajačić G. Modelling smart energy systems in tropical regions. Energy 2018;155:592–609. https://doi.org/10.1016/j.energy.2018.05.007.

[149] Connolly D, Lund H, Mathiesen BV. 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.

[150] Robinson JB. Energy backcasting A proposed method of policy analysis. Energy Policy 1982;10:337–44. https://doi.org/10.1016/0301-4215(82)90048-9.

[151] Dreborg KH. Essence of backcasting. Futures 1996;28:813–28. https://doi.org/10.1016/S0016-3287(96)00044-4.

[152] Höjer M, Mattsson L-G. Determinism and backcasting in future studies. Futures 2000;32:613–34. https://doi.org/10.1016/S0016-3287(00)00012-4.

[153] Paehlke R. Backcasting as a policy tool: The role of values. Crit Policy Stud 2012; 6:337–48. https://doi.org/10.1080/19460171.2012.704975.

[154] 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. In: 5th Int. Conf. Smart Energy Syst. 4th Gener. Dist. Heating, Electrif. Electrofuels Energy Effic. - Langelin. Pavillonen, Copenhagen, Denmark, Copenhagen, Denmark; 2019. p. 244.

[155] 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.

[156] Østergaard PA, Andersen AN. Booster heat pumps and central heat pumps in district heating. Appl Energy 2016;184:1374–88. https://doi.org/10.1016/j.apenergy.2016.02.144.

[157] Ben Amer-Allam S, Münster M, Petrović S. Scenarios for sustainable heat supply and heat savings in municipalities - The case of HelsingØr, Denmark. Energy 2017;137:1252–63. https://doi.org/10.1016/j.energy.2017.06.091.

[158] Østergaard PA, Jantzen J, Marczinkowski HM, Kristensen M. Business and socioeconomic assessment of introducing heat pumps with heat storage in small-scale district heating systems. Renew Energy 2019;139:904–14. https://doi.org/10.1016/j.renene.2019.02.140.

[159] Pavičević M, Mangipinto A, Nijs W, Lombardi F, Kavvadias K, Jiménez Navarro JP, et al. The potential of sector coupling in future European energy systems: Soft linking between the Dispa-SET and JRC-EU-TIMES models. Appl Energy 2020;267:115100. https://doi.org/10.1016/j.apenergy.2020.115100.

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

[161] Mathiesen BV, 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. https://doi.org/10.1016/j.apenergy.2015.01.075.

[162] 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. https://doi.org/10.1016/j.energy.2018.06.222.

[163] Hansen K, Breyer C, Lund H. Status and perspectives on 100% renewable energy systems. Energy 2019;175:471–80. https://doi.org/10.1016/j.energy.2019.03.092.

[164] Darby SJ. Demand response and smart technology in theory and practice: Customer experiences and system actors. Energy Policy 2020;143:111573. https://doi.org/10.1016/j.enpol.2020.111573.

[165] 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. https://doi.org/10.1016/j.energy.2018.09.091.

[166] 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. https://doi.org/10.1016/j.rser.2016.07.001.

[167] Schröder M, Abdin Z, Mérida W. Optimization of distributed energy resources for electric vehicle charging and fuel cell vehicle refueling. Appl Energy 2020;277: 115562. https://doi.org/10.1016/j.apenergy.2020.115562.

[168] Neves D, Pina A, Silva CA. Demand response modeling: A comparison between tools. Appl Energy 2015;146:288–97. https://doi.org/10.1016/j.apenergy.2015.02.057.

[169] O'Connell N, Pinson P, Madsen H, O'Malley M. Benefits and challenges of electrical demand response: A critical review. Renew Sustain Energy Rev 2014; 39:686–99. https://doi.org/10.1016/j.rser.2014.07.098.

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

[171] Brown T, Schlachtberger D, Kies A, Schramm S, Greiner M. Synergies of sector coupling and transmission extension in a cost-optimised, highly renewable European energy system 2018.

[172] 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. https://doi.org/10.1016/j.apenergy.2018.09.084.

[173] 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. https://doi.org/10.1016/j.apenergy.2018.08.109.

[174] Lombardi F, Pickering B, Colombo E, Pfenninger S. Policy Decision Support for Renewables Deployment through Spatially Explicit Practically Optimal Alternatives. Joule 2020;4:2185–207. https://doi.org/10.1016/j.joule.2020.08.002.

[175] 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. https://doi.org/10.1016/j.egypro.2015.07.843.

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

[177] 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. https://doi.org/10.1016/j.apenergy.2015.04.102.
[178] 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. https://doi.org/10.1016/j.energy.2019.01.004.
[179] Möller C, Kuhnke K, Reckzügel M, Pfisterer H-J, Rosenberger S. Energy storage potential in the Northern German region Osnabrück-Steinfurt. In: 2016 Int. Energy Sustain. Conf.; 2016. p. 1–7. https://doi.org/10.1109/IESC.2016.7569497.
[180] 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. https://doi.org/10.1016/j.esr.2018.08.012.
[181] 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. https://doi.org/10.1016/j.energy.2010.12.053.
[182] U.S. Energy Information Administration. International Energy Outlook 2016. Washington, DC; 2016.
[183] 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. https://doi.org/10.1016/j.enconman.2017.01.039.
[184] Østergaard PA, Andersen FM, Kwon PS. Energy systems scenario modelling and long term forecasting of hourly electricity Demand. Int J Sustain Energy Plan Manag 2015;7:99–116. https://doi.org/10.5278/ijsepm.2015.7.8.
[185] Kwon PS, Østergaard P. Assessment and evaluation of flexible demand in a Danish future energy scenario. Appl Energy 2014;134:309–20. https://doi.org/10.1016/j.apenergy.2014.08.044.
[186] Bossmann T, Staffell I. The shape of future electricity demand: Exploring load curves in 2050s Germany and Britain. Energy 2015;90:1317–33. https://doi.org/10.1016/j.energy.2015.06.082.
[187] Riva F, Gardumi F, Tognollo A, Colombo E. Soft-linking energy demand and optimisation models for local long-term electricity planning: An application to rural India. Energy 2019;166:32–46. https://doi.org/10.1016/j.energy.2018.10.067.
[188] Nijs W, Gonzalez H, Paardekooper S. JRC-EU-TIMES and EnergyPLAN comparison - Deliverable 6.3: Methodology report for comparing the scenarios between JRC-EUTIMES and EnergyPLAN; 2018.
[189] Krook-Riekkola A, Berg C, Ahlgren EO, Söderholm P. Challenges in top-down and bottom-up soft-linking: Lessons from linking a Swedish energy system model with a CGE model. Energy 2017;141:803–17. https://doi.org/10.1016/j.energy.2017.09.107.
[190] Andersen KS, Termansen LB, Gargiulo M, Gallachóirc ÓBP. Bridging the gap using energy services: Demonstrating a novel framework for soft linking top-down and bottom-up models. Energy 2019:277–93. https://doi.org/10.1016/j.energy.2018.11.153.
[191] Helgesen PI, Lind A, Ivanova O, Tomasgard A. Using a hybrid hard-linked model to analyze reduced climate gas emissions from transport. Energy 2018;156:196–212. https://doi.org/10.1016/j.energy.2018.05.005.
[192] Deane JP, Chiodi A, Gargiulo M, Gallachóir BPÓ. Soft-linking of a power systems model to an energy systems model. Energy 2012;42:303–12. https://doi.org/10.1016/j.energy.2012.03.052.
[193] Nijs W, González IH, Paardekooper S. JRC-EU-TIMES and EnergyPLAN comparison Deliverable 6.3: Methodology report for comparing the JRC-EU-TIMES and EnergyPLAN scenarios; 2018.
[194] Thellufsen JZ, Nielsen S, Lund H. Implementing cleaner heating solutions towards a future low-carbon scenario in Ireland. J Clean Prod 2019;214:377–88. https://doi.org/10.1016/j.jclepro.2018.12.303.
[195] Sadri A, Ardehali MM, Amirnekooei K. General procedure for long-term energy-environmental planning for transportation sector of developing countries with limited data based on LEAP (long-range energy alternative planning) and EnergyPLAN. Energy n.d. https://doi.org/https://doi.org/10.1016/j.energy.2014.09.067.
[196] Strachan N, Balta-Ozkan N, Joffe D, McGeevor K, Hughes N. Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system. Int J Hydrogen Energy 2009;34:642–57. https://doi.org/10.1016/j.ijhydene.2008.10.083.
[197] Blanco H, Nijs W, Ruf J, Faaij A. Potential of Power-to-Methane in the EU energy transition to a low carbon system using cost optimization. Appl Energy 2018;232:323–40. https://doi.org/10.1016/j.apenergy.2018.08.027.
[198] Novosel T, Perkovi L, Ban M, Keko H, Puk T, Kraja G. Agent based modelling and energy planning e Utilization of MATSim for transport energy demand modelling 2015;92:466–75. https://doi.org/10.1016/j.energy.2015.05.091.
[199] 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. https://doi.org/10.1016/j.enpol.2016.11.046.
[200] Cao KK, Cebulla F, Gómez Vilchez JJ, Mousavi B, Prehofer S. Raising awareness in model-based energy scenario studies—a transparency checklist. Energy Sustain Soc 2016;6. https://doi.org/10.1186/s13705-016-0090-z.
[201] Pianosi F, Sarrazin F, Wagener T. How successfully is open-source research software adopted? Results and implications of surveying the users of a sensitivity analysis toolbox. Environ Model Softw 2020;124:104579. https://doi.org/10.1016/j.envsoft.2019.104579.
[202] Carrillo AL, Martinez S, Falgueras J, Scott-Brown KC. A reflective characterisation of occasional user. Comput Human Behav 2017;70:74–89. https://doi.org/10.1016/j.chb.2016.12.027.
[203] Savidis A, Stephanidis C. Unified user interface design: Designing universally accessible interactions. Interact Comput 2004;16:243–70. https://doi.org/10.1016/j.intcom.2003.12.003.
[204] 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. https://doi.org/10.1016/j.rser.2016.01.090.
[205] European Commission. In-depth analysis in support of the Commission Communication COM(2018) 773 A Clean Planet for all. Brussels: 2018.
[206] 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. https://doi.org/ISBN: 978-87-91404-78-8.
[207] Lund H, Thellufsen JZ, Østergaard PA, Nielsen S, Sperling K, Djørup SR, et al. Smart Energy Aalborg; 2019.
[208] Chang M, Thellufsen J, Zakeri B, Lund H. Survey of energy system modelling tools - Results. Mendeley Data 2021;V1. https://doi.org/10.17632/6s59gbxh6p.1.