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EMPIRE: An open-source model based on multi-horizon programming for energy transition analyses

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ABSTRACT

Energy and power system models represent important insights on the technical operations of energy technologies that supply the energy consumption in time steps with hourly resolution. This paper presents the European Model for Power system Investments with Renewable Energy (EMPIRE) that combines short-term operations with the representation of long-term planning decisions including infrastructure expansion. The EMPIRE model has an unique mathematical modelling structure based on multi-horizon stochastic programming, which means investment decisions are subject to short-term uncertainty represented by different realizations of operational scenarios. The model is open source and ready to use to analyse energy transition scenarios towards 2050 and beyond. This paper outlines the building blocks of the model and its software structure. We also present an illustrative example of results from using the software.

Code metadata

Current code version	0.1.2
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX_2020_62
Code Ocean compute capsule	N/A
Legal Code License	MIT License (MIT)
Code versioning system used	git
Software code languages, tools, and services used	python, pyomo
Compilation requirements, operating environments & dependencies	python, pyomo, pandas, cloudpickle, openpyxl and pyyaml (see the projects's environment.yml file for supported versions)
If available Link to developer documentation/manual	https://www.ntnu.edu/web/iot/energy/energy-models-hub/empire
Support email for questions	Stian Backe stian.backe@ntnu.no

Software metadata

Current software version	0.1.2
Permanent link to executables of this version	https://github.com/ntnuiotenergy/OpenEMPIRE/releases/tag/v0.1.2
Legal Software License	MIT License (MIT)
Computing platforms/Operating Systems	BSD, Linux, OS X, macOS, Microsoft Windows, Unix-like
Installation requirements & dependencies	python, pyomo, pandas, cloudpickle, openpyxl and pyyaml (see the projects's environment.yml file for supported versions)
If available, link to user manual - if formally published include a reference to the publication in the reference list	https://github.com/ntnuiotenergy/OpenEMPIRE/blob/v0.1.2/EMPIRE_software_documentation.pdf
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1. Motivation and significance

Analysing strategies to achieve decarbonization of the energy system requires the representation of the techno-economic

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characteristics in the long-term (e.g., decades) along with the short-term (e.g., hours) operational aspects of the energy system. Some existing models consider myopic investment period(s) and short-term operations, e.g. [1,2]. In the long-term, strategic decisions regarding timing of asset investments and their lifetime are important to represent, and such decisions depend on short-term operations [3]. More recent models consider multiple investment periods and short-term operations, e.g [4]. With high shares of variable renewable energy sources (VRES), it is not only important to represent the short-term *variability* of VRES, but also the *uncertainty* of the VRES variability [5], i.e., considering different VRES profiles rather than a single deterministic VRES profile. The E2M2 model [6] considers uncertain VRES variability, but lack the simultaneous consideration of multiple investment periods.

In the **E**uropean **M**odel for **P**ower system **I**nvestments with **R**enewable **E**nergy (EMPIRE),[1] there is a unique optimization modelling approach with strong interrelations between three key characteristics: multiple long-term investment horizons, short-term representative operational periods, and operational uncertainty. Our main contribution is a model that flexibly consolidates these three key characteristics to allow insights on the link between long-term horizons, short-term operations, and operational uncertainty in a large-scale power system (see Fig. 1).

The distinctive modelling framework in EMPIRE is based on multi-horizon stochastic programming [8], i.e. long-term decisions are affected by short term scenarios varying by VRES availability and load profile realizations. The benefit of the multi-horizon structure is reduced computational challenge while still providing robust strategic planning decisions through the assumption of independence among short-term scenarios. EMPIRE offers a particular focus on preserving statistical correlations and properties for stochastic input data, and the tool offers flexible tuning of representative short term scenarios across the spatial scope within each investment period.

Given this modelling framework, EMPIRE minimizes a total annualized and discounted energy system costs for all investment horizons in one single optimization subject to energy asset lifetime constraints, load dispatch, generator ramping, uncertain availability of VRES, storage energy balance, operational losses, asset capacity constraints, and policy constraints (e.g. carbon emission limits). The output includes investment- and operational decisions in energy system assets, i.e. generation, storage, and transmission.

So far, the EMPIRE framework has been used in multiple European projects, industry studies, national projects and others [9–18]. In this paper, we make the EMPIRE framework openly available. Section 2 presents the software structure of the EMPIRE framework, before an illustrative example is presented in Section 3. Finally, Section 4 lists previous use of EMPIRE, as well as ongoing extensions of the model as presented in this paper.

2. Software description

2.1. Materials and methods

EMPIRE is based on a multi-horizon stochastic linear program, and it has been designed to support capacity expansion of the power system. The model represents a network of nodes and arcs where decisions are made in two temporal scales: investment time steps and operational time steps. Operational decisions are subject to uncertainty that is discretized in several stochastic scenarios. The network capacities and power flow is represented as linear net capacity transfer between nodes.

Fig. 2 lists the main benefits and limitations of the EMPIRE model as presented in this paper. The main benefits are related to the modelling framework, whereas the main limitations are related to user friendliness and software performance. The benefit of consolidating long-term, short-term, and stochastic power system aspects come at the cost of long solution time, however, this could be improved with decomposition techniques [19]. Another limitation is the lacking representation of long-term seasonal storage as EMPIRE considers operational periods shorter than a full year, which could be improved following Kotzur et al. [20].

The temporal resolution of EMPIRE is flexible in terms of number of investment periods, duration of representative time periods, and number of stochastic scenarios. For operations, hourly resolution is usually considered. The standard approach is to use four independent weeks representing seasons, as well as two additional peak days, within each stochastic scenario. Typically, three to ten different stochastic scenarios are considered for each investment period within one problem instance.

The EMPIRE formulation supports investment decisions in power generation, storage, and transmission with an objective of minimizing total system cost, which means it is simulating perfect competition. The strength of the model is that all investment decisions are linked together, and that investment decisions are linked with the short-term operation of the assets in several scenarios with different short-term profiles. The development of energy policy needs to address the impacts that power systems have on the environment. For EMPIRE, it is implemented as a carbon emission cap applied to the total CO2 generated in an investment period. For a more detailed mathematical formulation see [21].

The EMPIRE model is built and available in the Python-based, open-source optimization modelling language Pyomo [22]. To run the model, make sure Python, Pyomo and the third-party solvers are installed. EMPIRE is solved as a linear program. The software contains running options for the following three solvers: Gurobi [23], CPLEX [24] and Xpress [25]. For all three solver options, the solution method is set to be the interior point method [26] without crossover.

2.2. Software architecture

The EMPIRE model and all additional files in the repository [7] are licenced under the MIT licence meaning one can use and change the code by forking and tracking changes. Furthermore, you can change the licence in your redistribution but must mention the original author. The current configuration consists of seven input files and three monolithic python files. One of the python files is to run the whole system and called as 'run.py'. This file contains some of the singleton parameters and binary running options. The flow between the scripts are summarized in Fig. 3.

Sets define the temporal and spatial details of an instance, as well as available asset types. The temporal details include how many investment periods to consider, the duration of operational periods, and the number of independent seasons and scenarios within each investment period. Sets also allocate asset types to nodes and edges in a directed graph representing regions, e.g. countries, of the power system.

Parameters define technology costs and -characteristics, e.g. efficiency, availability, and ramping factor. Asset costs consist of investment costs based on capital and fixed O&M costs and operational costs based on fuel and variable O&M costs. All costs are constructed, annualized, and discounted automatically within the software.

There are six excel workbooks and six comma separated input files to provide actual data. The data excel files are sorted by the following themes: Sets, generation technologies, transmission

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[1] More Details and info on EMPIRE refer to: https://www.ntnu.edu/web/iot/energy/energy-models-hub/empire.

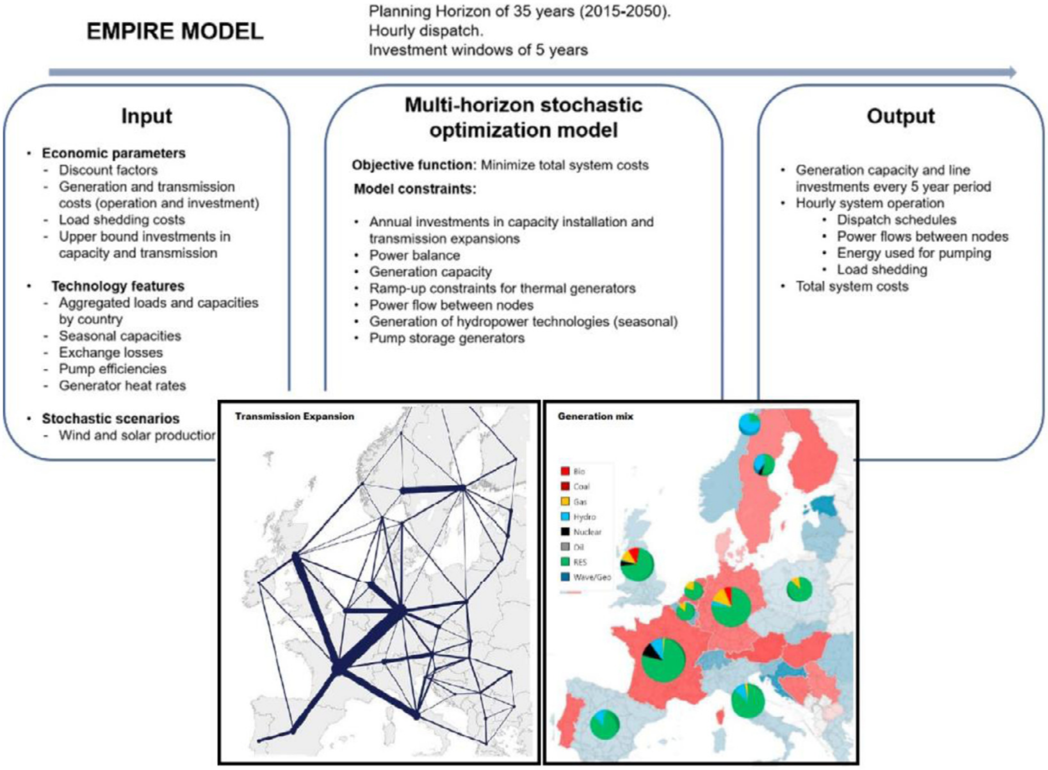

Fig. 1. Overview of the EMPIRE model. See software documentation [7] for a complete description.

Benefits

- Consolidates long-term, short-term, and stochastic power system aspects
- Preserves statistical correlations and characteristics of stochastic input
- Flexible parameter tuning
- Flexible solver options

Limitations

- High memory (RAM) requirement
- Long solution time
- Requires some Python coding skills
- Missing consideration of seasonal storage

Fig. 2. Overview of main benefits and limitations of this version of the EMPIRE model.

between countries, storage technologies, seasonal data, country (i.e. node) specific data and the general parameters. All of them have multiple sheets. The content of each input file is summarized in Fig. 4. Further details regarding data dimensions can also be found in the software documentation in the repository [7].

In addition to the excel input, stochastic data is generated through a random sampling return when running EMPIRE. The stochastic data include VRES availability and electricity load in different investment periods, seasons, and scenarios. Stochastic data is based on data from renewables.ninja[2] [27,28] and ENTSO-E [29]. More details on the scenario generation routine can be found in the software documentation in the repository [7].

As illustrated in Fig. 3, the EMPIRE model reads tab-separated values which are converted from user filled excel files of input data. Two python scripts act as an input conversion module, and convert the excel files into the text files with exact format that can be read by Pyomo. The first input conversion script is called ‘reader.py’, and it relies on standard Python packages such as ‘pandas’. The second input script is called ‘scenario_random.py’ relying on ‘pandas’ and ‘numpy’. If a new input file is to be added, or the name of an input is changed, the corresponding python file needs to be edited. For changes such as switching to a different type of input database, e.g. SQL, Access, etc., one needs to replace elements of this module in a way that will generate the tab-separated files in the same format as it is read by the parameter structure inside ‘Empire.py’.

The optimization code is built using the programming interface of Python which is called Pyomo [22]. It is currently compatible with the latest syntax as specified in ‘environment.yml’ (Pyomo 6.0.1). It uses the ‘abstract model’ structure of Pyomo which allows replacing inputs values externally from python. Modelling code contains set and parameter declarations, each being followed by the list of corresponding input files. Note that for every set and parameter, there is a separate text input file. After reading input sets and parameters, processing of some of the input is performed. Next, the variable declarations, expressions, objective and constraints follow in the given order, and thereafter the instance is created and solved using the specified solver option. After the instance is solved, the results are provided as comma-separated values, which can be opened as spreadsheets for graphical presentation or additional analysis in a number of applications.

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[2] https://www.renewables.ninja/.

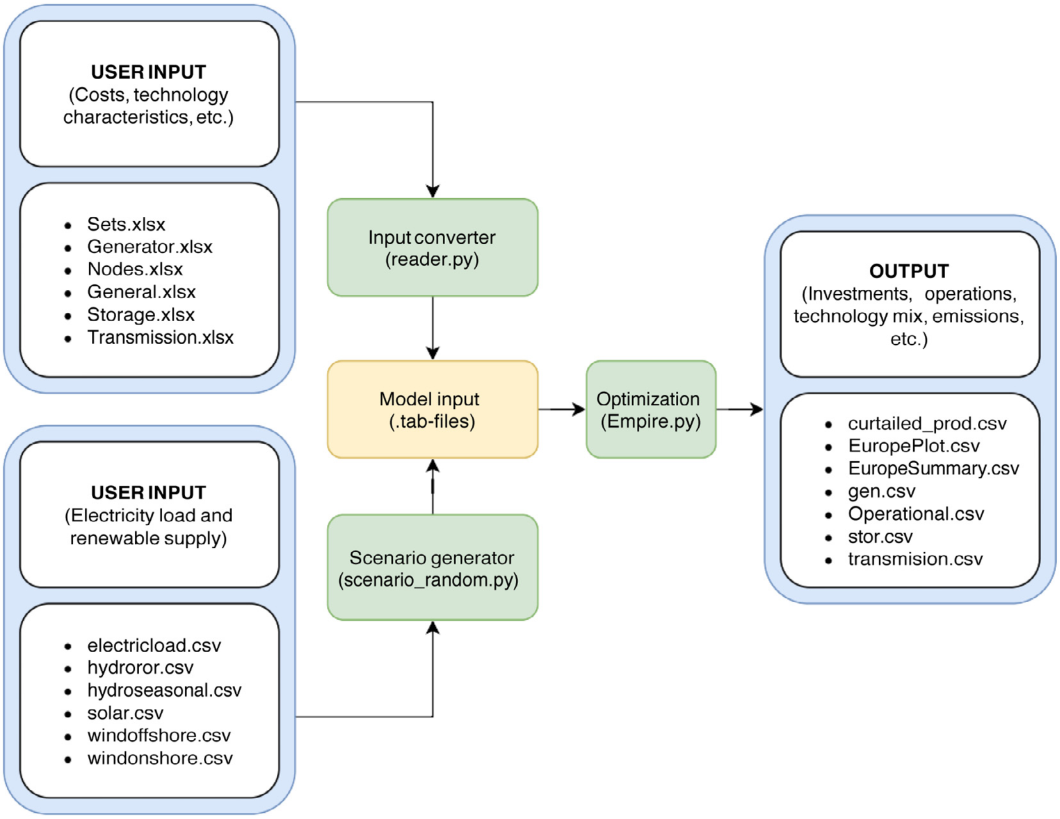

Fig. 3. Six excel and six comma separated files are used as input. Then the python files called 'scenario_random.py' and 'reader.py' converts those into plain text files. Python code of optimization model called 'Empire.py' reads these generates outputs as comma separated values.

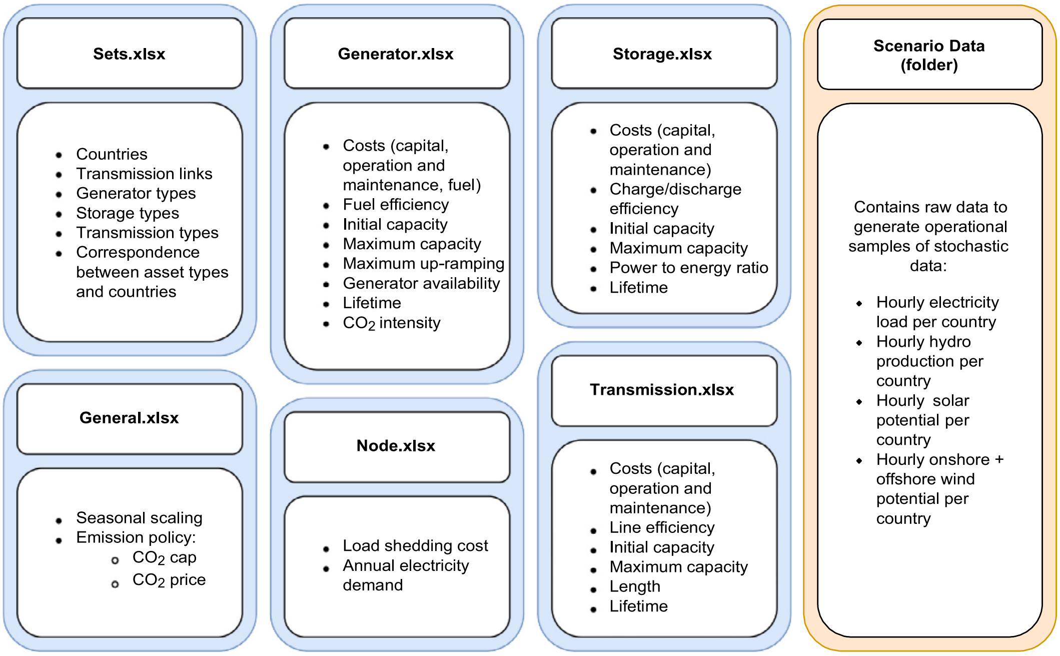

Fig. 4. Each input file in excel format contains multiple worksheets. Within every sheet there is exactly one data table and some additional data.

2.3. Software functionalities

EMPIRE allows researchers and policy makers to use their historical data that is collected from various parts of the world. With the inputs in the specified format, an overview of the power generation mix, investment projections, and details regarding storage technologies and transmission can be assessed per node and period. Note that a node refers to the smallest regional unit of the model. Thus, it does not have to be a 'country'. As long as one have available input parameters about load, supply, cost, and capacity, it is possible to change this unit while keeping the solving time and memory requirements at a reasonable size.

Similar fine tuning is viable for the time dimension. Current sample inputs have 5 years between each investment period, however, this can be modified.

A distinct advantage of using Pyomo is the freedom of switching between optimization solvers easily. If one wants to use different solvers than the three mentioned above, i.e., Gurobi, CPLEX, or Xpress, a complete list of compatible solvers can be reached through command line options after installing Pyomo. On the other hand, total duration of getting results, especially in terms of formulation time, is slightly sacrificed compared to using modelling syntax tailored for a specific solver. However, the difference is generally within bearable tolerances for strategic decision making. Other running options that can be tuned through binaries is turning on the ability to generate the formulation in the standard 'lp'-format.

In the current version, built in constraints cannot be modified in a way that will accept brand new constraints unless the model code is forked. However, many of the existing ones can be customized through modifying parameters purposefully, e.g., by changing set scales or modifying values of capacity parameters. Future developments include improving the model file by adding a callback piece which can accept new constraints as it is implemented in Switch 2.0 [4]. Further, existing modules can be combined in a main back-end code and mounted within a user friendly user interface (UI), which then can directly take input from the user and be connected to external databases for visualization.

Last but not least, being an open source code, EMPIRE supports replication of research findings, agreement among stakeholders, and better quality control through public review.

3. Illustrative example

In the following, we present an example study of a decarbonization scenario for the European power system in the period ranging from 2020 until 2060 in five-year investment steps. As EMPIRE is formulated as an optimization model, it is designing a least-cost development of the system with given emission reductions in line with a 1.5 degree scenario as quantified in [30]. The results include investments in generation, storage, and transmission capacities, as well as the utilization of such assets. The output can be used to shed light on questions such as: what is the optimal investment level and geographical distribution of VRES, and how should the transmission system and storage systems be developed and deployed to support this. These types of questions are of great importance, especially for policy makers and other energy sector stakeholders who wish to investigate our potential, challenges and opportunities for the decarbonization effort in Europe.

In this illustrative example, the geographical coverage of Europe includes the EU-27 (without Malta and Cyprus), and additionally Norway, Switzerland, the UK, Boznia Herzegovina, Serbia, and North Macedonia. All countries are modelled at a national level, except Norway which has been split into five regions. There are 27 individual generation technology types represented (four of which represent legacy installed thermal generation capacities), and two types of storage technologies (lithium-ion battery systems and pumped-hydro). We also assume a growth in electricity demand for each country towards 2060 based on a EU reference scenario [31]. We used the standard approach for representing operations, namely hourly resolution in four representative weeks and two peak days. Further, three stochastic scenarios were considered for each investment period. All input data used to set up this study is distributed alongside this paper in the OpenEMPIRE git repository [7]. This instance is built in Pyomo in 948 s containing 27 million constraints and 18 million variables, and it requires at most 108.2 Gb of RAM. The instance is solved with Xpress v8.8.3 in 8844 s on a server with a 2x 3.5 GHz Intel Xeon Gold 6144 CPU - 8 core, with 384 Gb of RAM. The solution time is comparable to similar instances of TIMES-Europe [32].

The aggregated European power sector results for generation capacity and energy mix from EMPIRE for the baseline scenario is shown in Fig. 5. It is clear from these results that the incumbent major technologies such as coal, natural gas and nuclear power will diminish in the European electricity mix over the next 15–20 years. This is caused by competition from onshore and offshore wind, and then later by significant deployment of solar PV. Some natural gas generation remains in the mix, most likely to provide added flexibility to the system and balance the VRES production. The most significant technology in Europe in the period after 2040 is onshore wind, with a total share of installed capacity between 35–45 % in the period 2040–2060. Given this massive deployment of onshore wind, it is important to question if the least-cost solution is in fact realizable in the sense that an eight fold increase of today's installed wind capacity may provoke fierce local public opposition [33]. Therefore, it would be relevant to also explore how the least-cost pathway to a decarbonized Europen power sector looks without this much wind. These, and related questions, can be further explored using the EMPIRE model.

Because EMPIRE represents stochastic input using probabilistic scenario generation, the solutions will vary between different EMPIRE runs with equally many stochastic scenarios. The stability of the solution will increase with more stochastic scenarios [34]. Three to ten stochastic scenarios are typically considered for each investment period. With five stochastic scenarios, ten different EMPIRE runs result in the mean objective function value of EUR 2.18 trillion with a standard deviation of EUR 0.02 trillion, i.e., a relative standard deviation of 0.91%.

4. Conclusions and extensions

4.1. Impact and use of EMPIRE in multiple projects

EMPIRE has been used in a variety of projects. It was first developed and used as part of the LinkS project [9]. In this context, the Global Change Assessment Model (GCAM) produced input to EMPIRE regarding annual European energy mix, while EMPIRE produced results regarding country-wise power system capacity expansion in Europe [10]. As part of the Centre for Sustainable Energy Studies (CenSES), EMPIRE was used to analyse Norway's role in a European context in [11,17]. Results show that expansion of Norwegian hydro and wind power is valuable for Europe as a whole. EMPIRE has also been used in the SET-Nav project [12,16,18] to stress-test capacity expansion results from EMPIRE in different scenarios. It is now being actively used in the H2020 European project openENTRANCE.[3] The project focuses on open-science in energy modelling and hence improving models interface, flexibility, and documentation, as well as opening data of all model analyses.

4.2. Extensions

In addition to the projects mentioned above, two tracks of development of EMPIRE extends its core version: Demand response (DR) and representative neighbourhoods.

Demand response was the first module extension of EMPIRE, and it is presented in [13]. The module considers both capacity expansion (reservation) and operation (activation) of DR, and

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[3] https://openentrance.eu/2021/02/22/empire-model/.

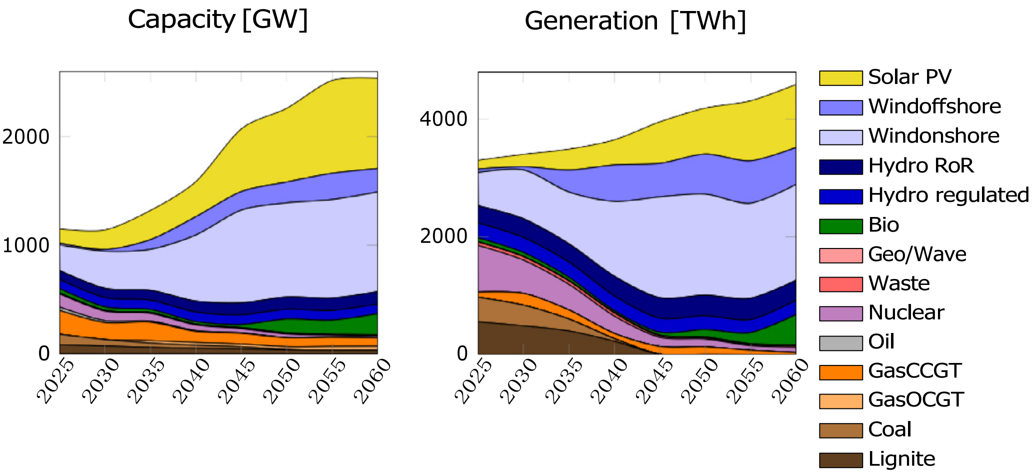

Fig. 5. Generation capacity and energy mix in Europe resulting from EMPIRE in the period 2020–2060.

it can represent different sectors. The DR can be a shiftable, curtailable, or interruptible load, and the implementation allows for a piece-wise linear cost function for activation costs.

As part of the Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN), another extension of EMPIRE represents energy assets in neighbourhoods presented in [15]. The idea was first presented in [14], and it involves analysing the coordinated development of the central power system and local energy systems by providing representative neighbourhoods as capacity expansion options. The representative neighbourhoods contain building energy systems, including local generation and storage, combined heat- and power (CHP) plants, and electricity-to-heat converters (e.g. heat pumps). In addition to building heat systems, the neighbourhood module focus on smart charging of electric vehicles which is represented as a shiftable volume load through the DR module.

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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