



# TIMES-Europe: An Integrated Energy System Model for Analyzing Europe's Energy and Climate Challenges

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## Abstract

This paper introduces TIMES-Europe, a novel integrated multi-sectoral energy system optimization model for Europe based on the TIMES generator. We describe its main specifications and assumptions as well as its underlying methodology, and summarize the type of policy questions that it can help answering. TIMES-Europe can be used to analyze policy instruments designed for implementing the EU Green Deal and Fit-for-55 program, and to create strategic energy decarbonization and climate change mitigation insights for Europe against the backdrop of its interactions and relations with neighboring countries. Thanks to its technology richness across all main sectors—including power production, transport, industry and the commercial, agricultural and residential sectors—it allows for performing in-depth studies on the role of a large range of low-carbon options in the energy transition of all European countries, both jointly and individually. Three characteristics render TIMES-Europe particularly valuable: (1) it covers the entire European energy system and its main greenhouse gas emissions, (2) it includes all EU member states individually as well as a large set of countries in the EU's vicinity, and (3) it can be used to generate high-level strategic insights as well as detailed recommendations for both national and EU policies. TIMES-Europe is especially suitable for analyzing system integration, which makes it an ideal tool for assessing the implementation of the energy transition and the establishment of a low-carbon economy. We present several research and scenario examples, and characterize opportunities for future energy and climate policy analysis.

**Keywords** Energy transition · Europe · Energy security · Renewable energy · Sector integration

## Highlights

- We developed a new detailed technology-rich bottom-up energy system model for Europe.
- It allows for analyzing net-zero emission pathways across all sectors of the EU energy system.
- It includes all EU member states and a large set of countries in its vicinity.
- It allows for analyzing cross-sectoral interactions between national and EU policies.
- It can be used to study synergies and trade-offs between energy security and climate control.

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## 1 Introduction

With the Paris Agreement, countries around the world have pledged to take action to limit the global temperature increase to 2 °C, and preferably 1.5 °C [1]. In order to meet the Paris Agreement targets, emissions of greenhouse gases (GHGs) should be drastically reduced in the near future, which makes the transition to a decarbonized energy system a strategic priority for all nations in the world. Integrated energy-economy-environment (E3) models are widespread tools to quantitatively analyze the future development of energy systems under various climate policy scenarios. During the past decades, these models have been extensively used by, for example, the Intergovernmental Panel on Climate Change (IPCC) in its reports exploring possible GHG emission reduction pathways until the end of the century [2]. E3 models represent the energy system at a specific geographical scale, which can range from (sub)urban agglomerates, to countries and regions or continents, up to the entire world. They operate at varying levels of regional

disaggregation: having access to models that can be used at different geographical scales and at different levels of regional disaggregation provides the possibility to analyze a wide spectrum of energy and climate policy questions. In this paper we introduce a novel E3 model, TIMES-Europe, that has been developed in the Energy & Materials Transition research group of the Dutch Institute for Applied Scientific Research (TNO). TIMES-Europe covers all member states of the European Union (EU) as well as a large set of its neighboring countries.

At this very moment in time, critical steps are being taken in shaping the EU's long-term energy and climate policy. On June 24, 2021, the European Parliament adopted the EU Climate Law, which makes a 55% reduction in CO<sub>2</sub> emissions in 2030 compared to 1990 levels—and complete carbon neutrality in 2050—legally binding. To reach the 2030 target, the European Commission (EC) presented the Fit-for-55 package of legislative proposals in July, 2021 [3]. In the summer of 2022, the first concrete proposals emanating from the package were brought to the European Parliament. It is widely expected that a large part of the Fit-for-55 legislation will be enacted by January, 2023. Among others, these proposals involve a transformation of the current emission trading system (ETS) including a more stringent CO<sub>2</sub> emission reduction target for 2030 of 62% with respect to 2005. They also put in place more ambitious GHG emission reduction targets for sectors that are covered by the Effort Sharing Regulation (ESR), and establish a 40% renewable energy goal for 2030, replacing the one currently in place of 32%. Most recently, the EC published the REPowerEU plan [4], aimed at improving the EU's energy security by means of a reduction of its dependency on fossil fuels imported from Russia. In particular, the REPowerEU plan aims at reducing the EU's dependency on Russian natural gas imports by speeding-up the energy transition, which would increase the renewable energy target even further to 45%.

With the long-term energy and climate policy of the EU being shaped and under the current extraordinary geopolitical circumstances on the European continent, the development of TIMES-Europe—an integrated multi-sectoral technology-rich model built with the TIMES generator [5, 6] encompassing both the EU and a broad range of neighboring countries—is both timely and important. A number of TIMES models for Europe exist already [7, 8]. Nevertheless, we believe that the development of our present model is of added value. TIMES-Europe represents the various sectors of the energy system with sufficient level of detail to be able to make sensible policy recommendations to the EU Commission. Yet the model is lean enough to be able to adapt to rapidly changing policy and geographical developments. This paper introduces the base version of our model, which represents all sectors relevant to the

energy system for the EU27 + UK. We underline the great importance of including candidate EU member states and the regions bordering the EU to make reliable energy and climate policy recommendations and sensible future energy system projections. In the future we will extend the base version of TIMES-Europe to incorporate all European countries and important regions bordering it. At present none of the existing models encompasses all 47 regions that will be incorporated in TIMES-Europe. Using TIMES-Europe, we are well equipped to study energy transition projections in support of the EU's twin challenge of contributing to mitigate global climate change and securing future domestic energy supply. The detailed representation of individual EU member states in TIMES-Europe allows us to investigate how national and European energy and climate policies may interact. How can they reinforce each other, and when could they potentially be mutually counter-productive? These are the types of questions that we intend to answer with TIMES-Europe. In addition, with the ETS as main instrument to drive the decarbonization of industry and electricity generation, these two sectors can only be adequately studied using an integrated sector-coupled energy system model for Europe. The same holds for the role of hydrogen, synthetic fuels, and biofuels in the future energy system: useful projections require a full European geographical scope, including that of bordering regions, and a complete representation of sectoral coupling. TIMES-Europe includes an extensive database that describes the entire current European energy system, featuring the characteristics of installed supply technologies (expressed through stocks, efficiencies, capacity factors, emission factors, costs, and lifetimes) and of present energy service demands (e.g., residential heat and passenger transport). In addition, detailed descriptions of future supply and end-use technologies are included. TIMES-Europe complements the modeling suite at TNO EMT by providing the missing link between its well-established models OPERA [9] and TIAM-ECN [10, 11], which optimize the energy systems of, respectively, the Netherlands and the entire world. TIMES-Europe gives us the opportunity to study the interactions between a broad range of energy and climate policies at both the national and EU level. We intend to use this newly developed model also to provide a detailed European context to national energy transition scenario studies conducted for the Netherlands [12].

In this paper we provide a detailed description of the TIMES-Europe model. Section 2 gives a general overview, including an explanation of the TIMES generator employed to develop TIMES-Europe. In Section 3 we describe the various supply and demand sectors that are covered by the model, highlighting our design choices and the types of data that we used for its construction. In Section 4, stylistic

scenarios are defined to illustrate the possibilities of the model, followed by a discussion of the scenario results in Section 5. In Section 6 we conclude with a brief outlook, in which we discuss future research avenues as well as opportunities for further development of our new TIMES-Europe model.

## 2 Model Description

### 2.1 ETSAP-TIMES Generator

TIMES-Europe is a multisectoral technology-rich model built using the TIMES modeling environment [5, 6]. TIMES—The Integrated MARKAL-EFOM System—is a linear optimization partial equilibrium model generator with perfect foresight, developed and maintained by the Energy Technology System Analysis Program (ETSAP) of the International Energy Agency (IEA). The TIMES code is written in the GAMS modeling language and is available under an open-source license [13]. The objective function of a TIMES model consists of the discounted total energy system costs over the full time horizon. The model computes the energy system parameters, which minimize the objective function. In calculating the objective function, the net present value of the sum of annual costs is calculated for each region. Subsequently, these regional costs are accumulated into a single total cost. The annual costs include annualized investment costs in new technologies, fixed and variable operational and maintenance (O&M) costs, costs related to trade and import and export, and to the production of resources. Furthermore, they can comprise dismantling costs, delivery costs, and taxes and subsidies. The residual values of all investments still active at the end of the time horizon (EOH) are accounted for as negative costs, which are applied in the year after the EOH. For a more detailed description, the reader is referred to Smekens et al. [14]. The objective function is calculated with Eq. (1):

$$NPV = \sum_{r=1}^R \sum_{y \in Y} (1 + d_{r,y})^{RY-y} \cdot ANNCOST(r, y), \quad (1)$$

in which  $NPV$  is the net present value of the total system costs for all regions combined;  $ANNCOST(r, y)$  corresponds to the total annual costs calculated per region ( $r$ ) and year ( $y$ );  $R$  and  $Y$  represent, respectively, the sets of regions and years for which  $ANNCOST$  is calculated (the latter includes all years in the time horizon and the year following EOH);  $d_{r,y}$  is the general discount rate (which can be differentiated by region and year and can differ from process-specific discount rates that are used in the calculation of  $ANNCOST$ ); and  $RY$  corresponds to the reference year for discounting.

When energy service demands are supplied exogenously, minimizing the total discounted energy system costs boils

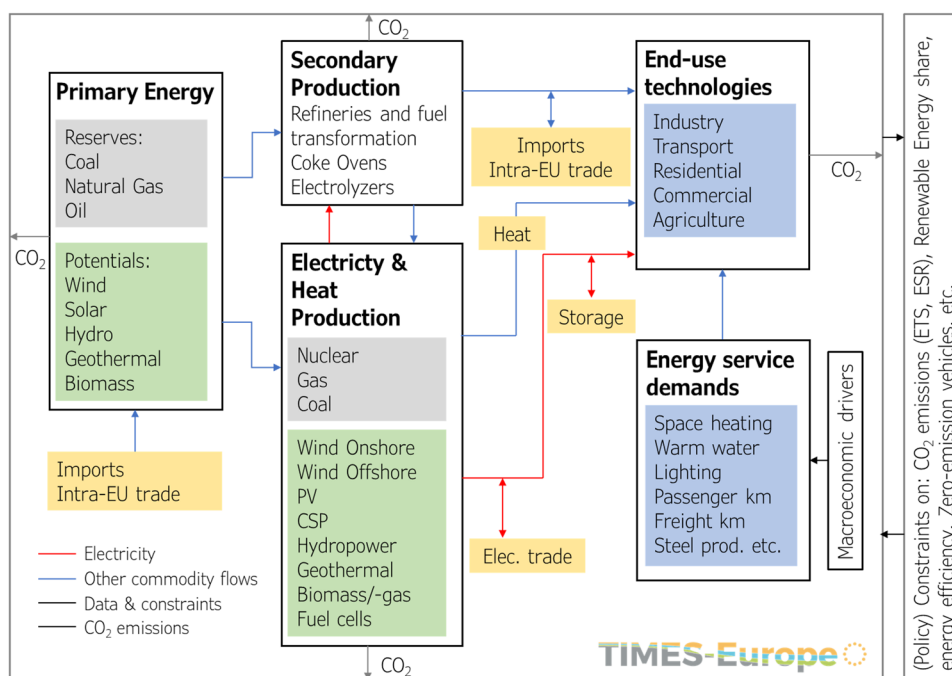
down to minimizing the total costs of meeting these demand levels. When price elasticities are introduced, however, the objective function becomes more complex and represents the total (consumer and producer) market surplus. Now, in the optimization process, TIMES must compute supply–demand equilibria, corresponding to the maximum total system surplus. This is equivalent to minimizing the objective function in Eq. (1) where now the loss of welfare resulting from reduced demands [5] is included in the annual costs. A more detailed description can be found in the TIMES model documentation [15]. Real-world boundaries to the optimization problem are captured with user-specified linear constraints, which constitute important components in scenario definition. Typically, these features limit the production or use of commodities, the deployment of technologies, and include assumptions on future development of demands and techno-economic parameters of technologies. They can also be applied to simulate policy measures, such as feed-in tariffs and subsidies.

The energy economy in TIMES is configured using a collection of processes (representing supply and demand technologies), commodities (including energy carriers, service demands, emissions, and materials), and commodity flows, which—all combined—form the so-called *reference energy system*. Large-scale TIMES models such as TIMES-Europe can create projections for the development of the energy system starting from an historical year, called the base year (BY), and spanning decades until the end of the century and beyond, based on scenario assumptions. For the BY, detailed characteristics of the reference energy system (including, e.g., technology stocks, efficiencies, capacity factors, and emission factors) are input to the model, while the commodity flows are typically calibrated using energy balances from Eurostat [16] or IEA [17]. For subsequent years, techno-economic input parameters describe the expected development of energy technologies into the future, compatible with the scenario under scrutiny. Such parameters include, among others, projections of technology costs and resource potentials. The projections of technology investment costs are made exogenously. Future demand projections are imported from other models and studies.

### 2.2 TIMES-Europe Overview

The structure of TIMES-Europe is schematically depicted in Fig. 1. The model contains a detailed representation of the upstream and power sectors as well as all main energy demand sectors, including end-use technologies and energy service demands, for each single country in the EU-27 plus the UK. TIMES-Europe includes both electric interconnections and gas pipeline infrastructure between these countries. Efforts are underway to expand its geographical scope to include all European countries as well as its neighboring

**Fig. 1** Schematic representation of the TIMES-Europe model

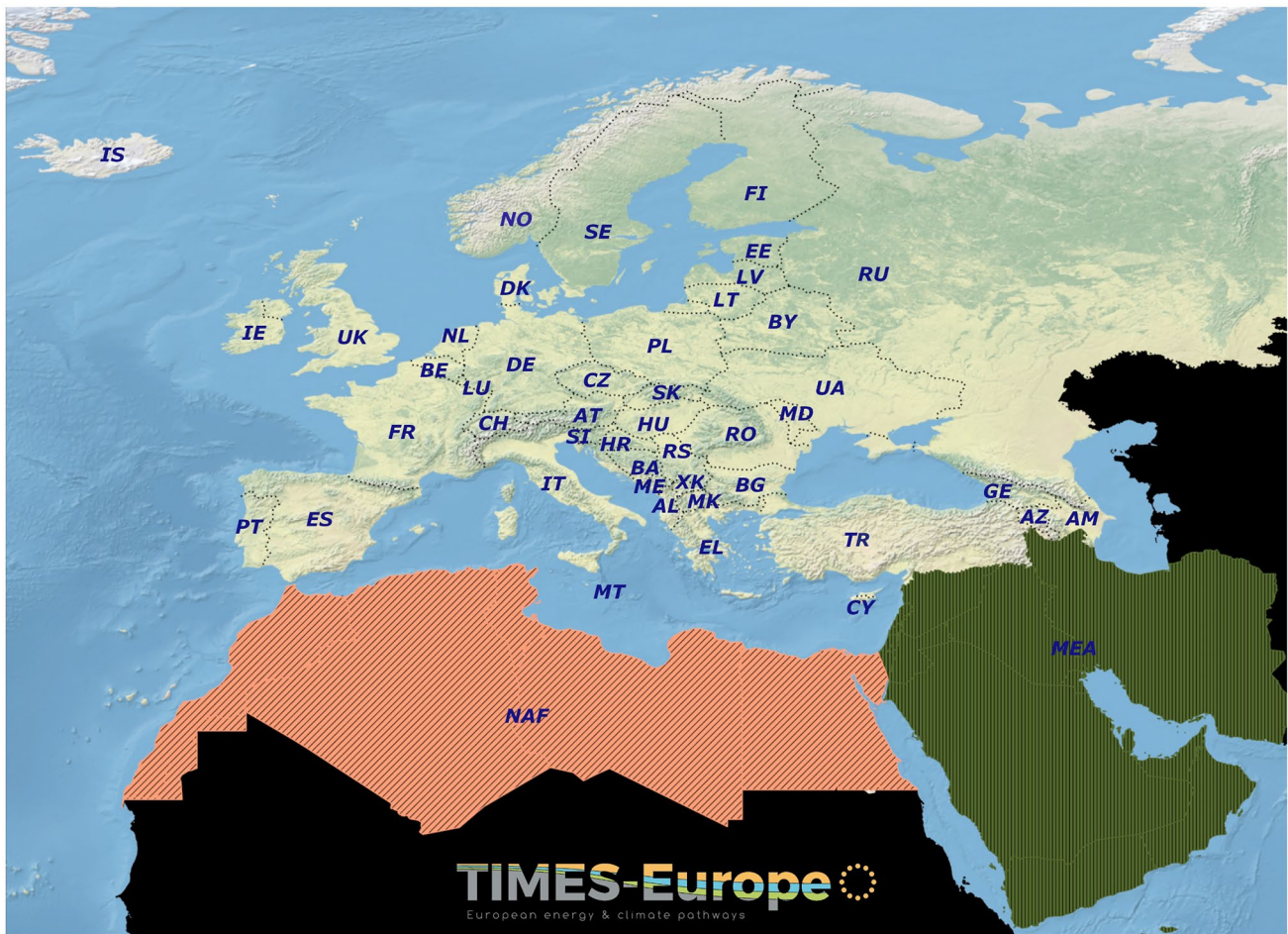


ones. Figure 2 highlights the regions which will be covered in TIMES-Europe. Energy commodity trade links will be implemented among all of the regions modeled. On the supply side, it includes both fossil energy resources and renewable potentials, fuel production, and transformation facilities and installations for conversion to electricity and heat. On the demand side, all main end-use sectors (e.g., residential, industry, and transport) are included; end-use technologies (e.g., heat pumps, buses, blast furnaces) produce to match the energy service demands (e.g., space heating, passenger transport, and demand for steel). TIMES-Europe contains a detailed representation of CO<sub>2</sub> emissions. These include emissions from fossil fuel combustion for energy generation in all sectors, as well as process emissions related to industrial processes (e.g., calcination in cement industry). Emissions from agriculture, forestry, and other land use (AFOLU) are currently not represented in the model, but we may stylistically simulate them and their changes in the future. Carbon dioxide capture and storage (CCS) options for fossil and bioenergy plants have been implemented. We intend to include additional CO<sub>2</sub> capture processes like direct air capture (DAC) in a future version of the model. Captured CO<sub>2</sub> is treated as a separate commodity flow for accounting purposes, which facilitates the implementation of carbon dioxide capture and utilization (CCU) pathways.

At present, we have adopted 2015 as BY and 2060 as time horizon, with the possibility to extend the latter to 2100. The model's time horizon has a clear link with the European energy and climate policies, which aim at 2050

as target year for achieving carbon neutrality. Nevertheless, a model like TIMES-Europe is, with the proper input data, capable of making scenario projections for the second half of the century. However, we believe that to make insightful projections so far into the future, it would be sensible to combine this with multi-stage stochastics [18] in which uncertainties on the effect of current policies, the development of break-through technologies, and societal developments can be captured. Following the BY, the model's successive milestone years are 2016 and 2020, subsequently continuing with 5-year time steps throughout the entire time horizon. For each milestone year, decisions concerning investments, process activities, and commodity flows are taken by the model. In order to capture the main production and consumption patterns at seasonal and daily levels, each year is divided into 12 time slices that represent, respectively, day, night, and peak hours (3) for each of the seasons (4). The peak time slice corresponds to the peak demand hour for all seasons, with the exception of summer, for which it aligns with the hour of maximum photovoltaic (PV) electricity production. In TIMES-Europe, final energy service demands are projected exogenously, typically driven by population and gross domestic product (GDP). As data inputs for the TIMES-Europe energy-economy we primarily use the JRC-IDEES database [19], the ENSPRESO database [20], the EU Building Stock Observatory [21], the open-source JRC-EU-TIMES model with supporting publications [7], and the energy balances from Eurostat [16] and IEA [17].





**Fig. 2** The full geographical scope of TIMES-Europe, including the future extensions to encompass relevant neighboring regions

### 3 Detailed Model Description

#### 3.1 Power and Heat

For the power sector BY, we defined processes that cover all relevant electricity generation as well as combined heat and power (CHP) technologies (see Fig. 1). These include fossil-fuel based options using coal, natural gas, and oil, as well as low-carbon technologies using nuclear, biomass, wind, and solar energy—the latter through both photovoltaics (PV) and concentrated solar power (CSP)—or water (hydropower, tidal, and wave energy). For all technologies, except hydropower and nuclear energy, installed capacities for the BY were obtained from the JRC-IDEES database [19]. Installed capacities and decommissioning years for the period 2000–2015 were also retrieved from this database. These data were used to estimate the years in which particular capacities of electricity and CHP processes were put into service. Technology efficiencies and O&M costs were differentiated on the basis of the year of commissioning,

the data for which were obtained from the JRC-EU-TIMES model [7]. We used data from the ENSPRESO database [8] to specify the PV and wind energy availability factors at time-slice level. For the implementation of the current nuclear energy capacity in TIMES-Europe, we employed and simplified the extensive data on nuclear energy found in the input database of the JRC-EU-TIMES model [7]. We updated this information by checking the status of the plants that were expected to be shut down in the 2005–2020 period and by reviewing the reactors planned or under construction in the period until 2030. We accommodated all existing plants into three generic nuclear energy processes, equipped with country-specific capacity, efficiency, and availability factors. The variation of these parameters over time reflects whether installations are taken out of operation due to political decisions or end of their lifetime, which we assume to be 50 years. For hydropower, we undertook an analysis based on available Eurostat data [22]. From this analysis, we derived country-specific capacities for impoundment, run-of-river (RoR), and pumped-storage facilities, as well as

average annual capacity factors over the period 2005–2018. In the future we plan to use available monthly net electricity generation data [23], in order to further refine capacity factors to time-slice level. Techno-economic parameters of future electricity generation technologies were obtained from the JRC-EU-TIMES [7] and TIAM-ECN models [10, 11]. For renewable and CCS technologies, a learning curve approach was used to project future cost developments. The cost parameters correspond to the Baseline scenario from Tsiropoulos et al. [24].

## 3.2 Upstream Sector

Hard coal, lignite, crude oil, and natural gas are implemented as primary fossil resources in TIMES-Europe. These can be extracted and processed within the modeled regions, as well as traded across regions or imported from the rest of the world. Country-level estimates of European reserves for primary fossil fuels were obtained from the JRC-EU-TIMES model [21]. The reserves were updated to represent the 2015 reserves by accounting for primary energy production over the period 2005–2015 from Eurostat [16]. Secondary fuel production from refineries, liquefaction plants, and coke ovens is modeled using the Eurostat energy balances [16]. Projections of fossil fuel global market prices were adopted from the EU Reference scenario 2020 [25].

Annual country-specific biomass potentials are based on the ENSPRESO Biomass database [20]. The BY biomass production is obtained from the Eurostat energy balances [16]. In TIMES-Europe, bioenergy is available in several varieties. Next to woody biomass, biogas, and the biodegradable fraction of municipal waste, biofuels are available for blending with (or substitution of) conventional fossil fuels.

In the future energy system, hydrogen is produced through steam-methane reforming w/o CCS and several electrolyzer technology options (alkaline, solid oxide, and PEM).

## 3.3 Demand Sectors

The demand for energy carriers, such as electricity and natural gas among others, follows endogenously from the energy service demands and the technology choices that are made in the optimization process. For the BY, the energy service demands follow from statistics, while for future years, exogenous projections are made on the basis of three economic drivers: population, GDP, and GDP per capita (GDPC). Projections for future years are made using Eq. (2):

$$D_x(t) = D_x(t-1) \cdot \left( \frac{Dr_t}{Dr_{t-1}} \right)^{dc}, \quad (2)$$

in which  $D_x$  denotes the demand for service demand  $x$ ,  $Dr_y$  represents the value of the relevant demand driver in period  $y$ , and  $dc$  is a decoupling factor, used to tune the sensitivity of demand to its drivers. Appropriate drivers were selected for the different service demands. Population and GDP projections were obtained from Eurostat (EUROPOP2019, see [26]) and the European Commission [27], respectively. An overview of the energy service demands defined in TIMES-Europe, including the applied drivers for future demand, is included in Table 1.

### 3.3.1 Residential Sector

In TIMES-Europe, the residential building stock is differentiated with respect to building archetype and construction period. For each country, the total BY housing stock and its distribution over the seven construction periods considered in TIMES-Europe—pre-1945, 1945–1969, 1970–1979, 1980–1989, 1990–1999, 2000–2009, and 2010–2015—were obtained from the corresponding EU buildings factsheets made available by the EU Building Stock Observatory [28]. For the building stock, we only implemented permanently occupied dwellings, thus excluding dwellings like holiday homes and second houses. We introduced a subdivision of the total stock into three archetypes: 1) detached houses (DH), 2) semi-detached houses (SD), and 3) flats (FL), using data from the EU Building Stock Observatory [21] and Eurostat [29]. From these data the country-specific average floor space for each of the building archetypes was determined as well. We assume this subdivision to be valid for the stock of all individual construction periods. Population is the driver for future housing demand. In relation to the building stock, we define several categories of residential energy service demands: space heating (SH), domestic hot water (DHW), space cooling (SC), cooking (CK), lighting, and several categories of electrical appliances, which include refrigerators, dishwashers, washing machines, clothing dryers, television sets, and consumer electronics. This is achieved by defining “specific demands” for the different services per 1000 dwellings. For this purpose, we use the country-specific service demands from JRC-IDEES [19] and the dwelling stock data. The total demand for each of the residential energy services results from multiplying the specific demands by the number of dwellings. The specific demands for SH, DHW, and SC are differentiated with respect to building archetype. For DHW and SC, we assume a 25% lower specific energy demand for flats than for single-family houses. We disaggregated the country-specific SH demands from JRC-IDEES [19] into more detail, for which we introduced both building archetype and construction period as discriminators. This differentiation is realized through a stylistic bottom-up thermal housing model, which was used to derive relative SH

**Table 1** Energy service demands in TIMES-Europe including the drivers used for their projection into the future

| Sector      | Energy service demand                             | Unit                                     | Demand driver |
|-------------|---------------------------------------------------|------------------------------------------|---------------|
| Residential | Housing: detached/semi-detached/flat <sup>a</sup> | 1000 houses                              | POP           |
| Commercial  | Floor space <sup>b</sup>                          | m <sup>2</sup>                           | GDP           |
| Commercial  | Electrical appliances                             | 1000 units / mln serviced m <sup>2</sup> | POP           |
| Commercial  | Street lighting                                   | 1000 units                               | POP           |
| Agriculture | Total energy demand <sup>c</sup>                  | PJ                                       | POP           |
| Transport   | Passenger transport—car                           | Bpkm <sup>d</sup>                        | GDPC          |
| Transport   | Passenger transport—motorized two-wheeler         | Bpkm                                     | POP           |
| Transport   | Passenger transport—bus                           | Bpkm                                     | POP           |
| Transport   | Freight transport—LCV                             | Btkm <sup>e</sup>                        | GDP           |
| Transport   | Freight transport—HDV                             | Btkm                                     | GDP           |
| Transport   | Passenger train                                   | Bpkm                                     | POP           |
| Transport   | Passenger train—high speed                        | Bpkm                                     | GDP           |
| Transport   | Passenger train—metro/tram                        | Bpkm                                     | POP           |
| Transport   | Freight train                                     | Btkm                                     | GDP           |
| Transport   | Passenger aviation—domestic                       | Bpkm                                     | GDP           |
| Transport   | Passenger aviation—IntraEU/ExtraEU                | Bpkm                                     | GDP           |
| Transport   | Freight aviation—IntraEU/ExtraEU                  | Btkm                                     | GDP           |
| Transport   | Navigation                                        | Btkm                                     | GDP           |
| Transport   | International marine bunkers                      | Btkm                                     | GDP           |
| Industry    | Iron and steel                                    | Mt                                       | GDP           |
| Industry    | Alumina                                           | Mt                                       | GDP           |
| Industry    | Aluminum                                          | Mt                                       | GDP           |
| Industry    | Other non-ferrous metals                          | Mt <sup>f</sup>                          | GDP           |
| Industry    | Cement                                            | Mt                                       | GDP           |
| Industry    | Glass                                             | Mt                                       | GDP           |
| Industry    | Ceramics and other non-metallic minerals          | Mt <sup>g</sup>                          | GDP           |
| Industry    | Paper                                             | Mt                                       | GDP           |
| Industry    | Pulp                                              | Mt                                       | GDP           |
| Industry    | Ammonia                                           | Mt                                       | GDP           |
| Industry    | Chlorine                                          | Mt                                       | GDP           |
| Industry    | Ethylene                                          | Mt                                       | GDP           |
| Industry    | Other chemicals                                   | PJ                                       | GDP           |
| Industry    | Other industry products                           | PJ                                       | GDP           |

<sup>a</sup>In the residential sector, housing demand is the only service demand defined and exogenously projected, yet other energy demands (i.e., from space heating, cooling, warm water, cooking, and multiple categories of electrical appliances) are defined in relation to this demand

<sup>b</sup>Similar to the residential sector, several energy services are linked to the demand for m<sup>2</sup> of floor space. These include space heating, cooling, hot water and cooking. Building-related electrical appliances, including lighting, refrigeration, information and communication technology (ICT) and ventilation are defined as separate service demands independent of floor space (see next row)

<sup>c</sup>We assume fixed shares of sub-demands (based on 2015 data from JRC-IDEES). The applied sub-demands include lighting, ventilation, motor drives, heat, farming machines, pumping devices, and specific electricity uses

<sup>d, e</sup>Bpkm, billion passenger km; Btkm, billion ton km

<sup>f, g</sup>Heterogeneous outputs expressed in Mt lead eq and Mt bricks eq, respectively

requirements for the different building archetypes and construction periods for each country separately. This approach is inspired by the building stock module of the JRC-EU-TIMES model [30]. The thermal housing model represents the various archetypes as a collection of main building elements (i.e., wall, roof, floor, and window) and estimates the total annual transmission heat loss of the dwelling as

$$Q_{a,p}^h = 0.024 \cdot HDD \cdot \sum_i A_{i,a} \cdot U_{i,p}, \quad (3)$$

in which  $Q_{a,p}^h$  (in kWh) represents the annual transmission heat loss for building archetype  $a$  from construction period  $p$ .  $A_{i,a}$  (in m<sup>2</sup>) corresponds to the area of building element  $i$  belonging to building archetype  $a$  and  $U_{i,p}$  (in W/m<sup>2</sup>·K) to the thermal transmittance of building element  $i$  from



construction period  $p$ , which was obtained for each of the countries from the EU Building Stock Observatory [21]. HDD stands for heating degree day. HDDs are equivalent to the summation of the product of duration and temperature difference for periods when the outside temperature drops below a certain base temperature [31]. This threshold is defined as the lowest outside temperature which does not give rise to indoor heating. One HDD corresponds to outside temperature conditions of one degree below the base temperature for the duration of one day. HDD data was obtained from Eurostat [32]. This data originates from JRC, which uses a base temperature of 18 °C and the daily mean outside temperature for generating the HDD data. Only those days which have a daily mean temperature equal to or below 15 °C are included. The factor 0.024 is required to express  $Q_{a,p}^h$  in kWh instead of Watt-day.

The resulting  $Q_{a,p}^h$ , expressed in kWh/building and differentiated per country, building archetype, and construction period, can be interpreted as an estimate of the SH service demand, i.e., the heat loss is equal to the amount of heat needed to keep the house warm. One can thus disaggregate the total top-down SH that was obtained at country level from the JRC-IDEES database [19], through the following equation:

$$SH_{top-down} = c \cdot \sum_a N_a \cdot Q_{a,p}^h, \quad (4)$$

where  $SH_{top-down}$  is the total country-specific SH demand from JRC-IDEES [19],  $N_a$  is the number of dwellings of archetype  $a$ ,  $Q_{a,p}^h$  is the annual heat demand for building archetype  $a$  defined as a weighted average over the construction periods considered, and  $c$  is a correction factor. The latter accounts for the deviations (at country level) between the JRC-IDEES data and the bottom-up model results. These deviations are attributed to (i) the stylistic nature of the bottom-up thermal model, (ii) the amount of heated area being significantly lower than the total floor area for a number of countries, and (iii) dwellings already being renovated resulting in  $U$ -values that are better (i.e., lower) than those reported in the EU Building Stock Observatory database. With the (country-specific) correction factor  $c$  from Eq. (4), the SH service demand for building archetype  $a$  from construction period  $p$  was defined as

$$SH_{a,p} = c \cdot Q_{a,p}^h. \quad (5)$$

For SH, DHW, and CK, multiple processes are defined to produce the end-use demands in the BY. This is done on the basis of the JRC-IDEES database [19]; i.e., we use the differentiation of the end-use demands over the different fuel types from the database. For all other residential end-use demands, we define one electric end-use technology.

For future years the model is allowed to invest in new installations and appliances to meet the future residential service demand. New installations for SH and DHW include (combi-)boilers on different fuel types (i.e., electricity, natural gas, biogas, (bio)diesel and biomass, ground and air heat-pumps, solar thermal, and district heating). SC can be realized both with a reversible heat pump or with a dedicated air-conditioning system. Future appliances (e.g., for cooking, refrigeration, and dish-washing) have an improved efficiency over current ones. Techno-economic data was obtained from TNO factsheets [33] and JRC [34].

With respect to SH, alongside the new installations, also retrofitting processes are available, which the model can choose to deploy to reduce the residential SH demand, thereby simulating real-world renovation measures to improve building insulation. In the model this is realized through improved  $U$ -values for retrofitted building elements of existing dwellings. We obtained the relevant data from the ENTRANZE summary report [35]. The resulting SH demand after retrofitting is calculated as

$$SH_{a,p}^{retrofitted} = c \cdot 0.024 \cdot HDD \cdot \sum_i A_{i,a} \cdot U_{i,p}^{retrofitted}. \quad (6)$$

We defined three retrofitting variants, which provide shallow, medium, or deep retrofitting of the roof, wall, and window building elements. The improvements resulting from the renovation processes are summarized in Table A1 of Appendix A.

### 3.3.2 Commercial Sector

The overall energy consumption of the commercial sector is split into multiple energy services: space heating, space cooling, (commercial) hot water (CHW), cooking, building-related electric appliances (lighting, refrigeration, information and communication technology (ICT), ventilation, and others) and street lighting. These data and the associated energy commodity consumption (e.g., electricity, natural gas, and oil) are obtained from JRC-IDEES [19]. In combination with the useful commercial sector floor area from the same source, specific demands are derived for all but the building-related electrical appliances and street lighting (see also Table 1). These categories are defined independent of floor space. Consequently, the set-up of the commercial sector closely resembles that of the residential sector. In contrast to the residential sector, however, no differentiation with respect to building types (e.g., offices, hospitals, and education) is made. While this information is available from the EU Building Stock Observatory [28], it was not implemented, since reliable



information on the differentiation of energy demand with respect to building types is lacking.

BY and future technologies are defined in a similar way as for the residential sector. For the BY one (general) technology was defined per combination of end use and fuel type. For future years, SH, CHW, and SC technologies are differentiated in a way similar to the residential sector. Techno-economic data is obtained from TNO factsheets [33] and JRC [34].

### 3.3.3 Agricultural and Fishery Sector

For the agricultural and fishery sector, one energy service demand is defined, which is composed of several demand categories (see Table 1). These include demands for lighting, ventilation, motor drives, heating, farming machines, and pumping. For the BY this information is obtained from the JRC-IDEES database [19]. For future years, the ratios between the individual demands are kept constant. Multiple generic processes, which can have multiple fuel inputs, are set-up to meet the demands. The BY fuel consumption is calibrated using the JRC-IDEES data [19]. The processes are set up to allow for future fuel switching. Currently, no endogenous development of final energy demand in this sector is implemented. Projections for the development of energy demand in the agricultural sector are made as part of scenarios.

### 3.3.4 Industrial Sector

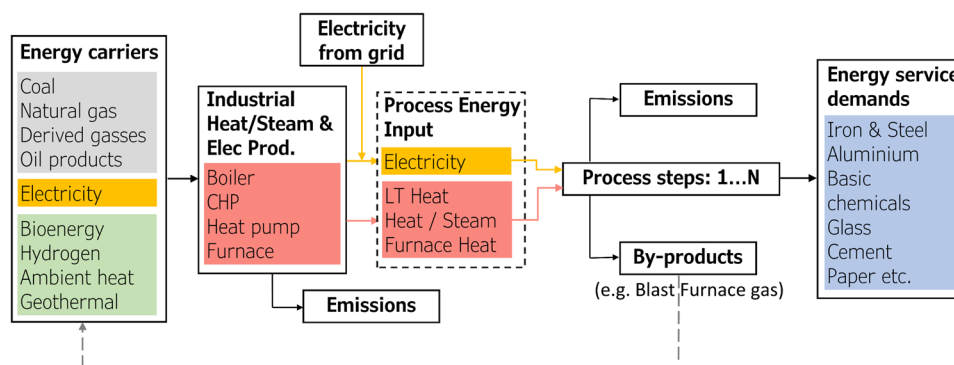
The industrial sector is divided into multiple subsectors: i) iron and steel (I&S), ii) non-ferrous metals (NFM), iii) non-metallic minerals (NMM), iv) paper and pulp (P&P), v) chemical industry (CHI), and vi) other industries (OIS). Sectors i–v cover about 85% of the scope 1 CO<sub>2</sub> emissions in industry. The OIS subsector encompasses a) food, beverages, and tobacco; b) transport equipment; c) machinery equipment; d) textile and leather; e) wood and wood products; and f) remaining other industrial sectors. The BY production and energy demand are derived from the Eurostat and IEA energy balances [16, 17] and the JRC-IDEES database [19]. The energy service demands of all industrial subsectors, except for OIS, are expressed as one or multiple commodities in Mt (see Table 1). For OIS the energy service demand is expressed in terms of useful energy demand, which corresponds to the process heat and cooling delivered, as well as the work performed, in all associated production processes. Projections for future energy demands are made on the basis of Eq. (2) using GDP as driver.

The general modeling topology for the different industrial production processes is outlined in Fig. 3. Electricity, low-temperature (LT) heat, high-temperature (HT) heat, and

steam are obtained from multiple resources-technology combinations and form the inputs to one overall production process or a step-wise defined process chain depending on the level of modeling detail. For the BY, the final energy consumed in the production of the energy service commodities listed in Table 1 is obtained from the JRC-IDEES database [19] and normalized using the Eurostat energy balance [16]. For CHI the non-energy use—i.e., feedstock, like naphtha as raw material for the production of basic chemicals—is covered as well.

The I&S sector is of particular importance in the context of the energy transition, due to its high energy consumption and CO<sub>2</sub> emission level. Of all energy-intensive industries in the EU, the I&S sector is the largest CO<sub>2</sub> emitter. In the EU-27, it is responsible for approximately 190 Mt of CO<sub>2</sub> on an annual basis, which corresponds to roughly 5% of total CO<sub>2</sub> emissions [36]. In 2019, the EU I&S sector produced approximately 150 Mt of crude steel [37] with an associated energy consumption of 1738 PJ [16]. In order to be able to implement decarbonization pathways, I&S is represented in detail in TIMES-Europe. For the BY, both the electric arc furnace (EAF) and integrated steelworks production routes have been included. The EAF process is responsible for approximately 44% of the current total EU crude steel output [37]. It uses ferrous scrap, which is melted using electric arcs in an EAF to produce liquid steel. Impurities are removed in reaction with oxygen [38]. Essential elements of the integrated steelworks route include coke production in coke ovens and the aggregation of fine iron ore into sinter and pellets, all of which are fed into a blast furnace (BF), which is used to remove oxygen from the iron ore to produce hot liquid pig iron [38]. The carbon content of pig iron is lowered in a basic oxygen furnace (BOF), producing liquid steel for further downstream processing. Figure 4 illustrates the process steps (see also Fig. 3) included for I&S production in TIMES-Europe. The coke oven and BF processes have been modeled on the basis of Eurostat and IEA energy balances [16, 17]. Although coke ovens are part of the integrated steelworks route, they are covered in the upstream module. The reason is that coke constitutes a secondary fuel input to the BF. The detailed description of the BF and coke oven processes also enables us to model the use of blast furnace gas and coke oven gas for electricity and heat production as well as in downstream processes. We use energy statistics data from JRC-IDEES [19] and the Eurostat energy balance [17] to describe additional integrated steelworks as well as the EAF route process steps (see Fig. 4). These downstream processes represent the further processing of the liquid metal coming from the BOF or EAF to produce slabs and coils of steel with different finishes. These processes include casting and rolling to produce slabs and coils with different thicknesses, various surface treatments (e.g., galvanizing and electroplating), and the application of coatings.

**Fig. 3** Schematic representation of the industrial process topology in TIMES-Europe



In order to adequately project industrial decarbonization pathways, multiple substitute low-carbon process options are included in TIMES-Europe. The majority of industrial processes use heat as input. We have implemented a database with a broad range of future options to produce steam and heat for industrial processes (see Fig. 3 for a general process topology). In terms of process requirements, we distinguish between low-temperature heat (hot water, LT-heat), mostly used in the OIS, process heat / steam, and furnace heat. Low-temperature solutions include various heat pump options, while for process / steam technologies, boilers, CHP, and direct electric heating are available. Boiler and CHP technologies are fueled by coal, natural gas, biomass, or hydrogen and can run partly on electricity (hybrid boiler). Furnaces can be fueled by natural gas, hydrogen, biomass, and electricity. The heating technologies can be combined with CCS.

In addition to the low-carbon heating options, for the I&S subsector we have included more elaborate decarbonization options which modify or replace the integrated steelwork production route. These are derived primarily from the extensive data available from the Manufacturing Industry Decarbonization Data Exchange Network (MIDDEN) initiative [39]. MIDDEN was initiated by TNO and The Netherlands Environmental Assessment Agency (PBL) to provide a knowledge base for industrial decarbonization options aimed at Dutch industries. This has resulted in a rich portfolio of decarbonization options for the most important industrial subsectors, among which the I&S subsector [40]. Although geared toward The Netherlands, the resulting

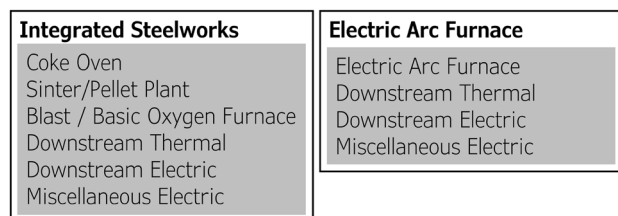
techno-economic data is fairly well representative of the whole European industrial sector. On the basis of this work, we have implemented multiple decarbonization options for the I&S sector:

- (i) *top gas recycling*: modification of an existing BF to facilitate recycling of the top gas, resulting in reduction of coke demand;
- (ii) *Hlsarna steel production*: elimination of pre-processing steps (coke, sinter and pellet production);
- (iii) *direct reduced iron (DRI) production* in a shaft furnace using natural gas or hydrogen;
- (iv) *electrolysis* of iron ore, either under low or high temperatures.

Options (iii) and (iv, low temperature) are combined with an EAF to provide the required carbon content for the production of liquid steel. In order to further reduce CO<sub>2</sub> emissions, options (i) to (iii) can be combined with CCS. For a more detailed description of these decarbonization options, see the MIDDEN Dutch steel industry publication [40]. In the future we intend to extend the rich description of possible future decarbonization routes to also include sectors outside I&S. For this purpose, we will use the broad set of available decarbonization options for different industrial subsectors available from MIDDEN [39].

### 3.3.5 Transport Sector

The transport sector includes road, rail, aviation, and marine subsectors. For the BY, the various transportation demands (see Table 1) are established using the JRC-IDEES database [19]. Technology processes are defined in alignment with these categories. For passenger and freight road transportation, we established one process per fuel type per vehicle service demand category (e.g., gasoline car and diesel bus). We differentiate between powered two wheelers, passenger cars, busses, light commercial vehicles (LCV), and heavy duty vehicles (HDV). For all road transport processes, we obtained the total stock, average efficiency, annual mileage,



**Fig. 4** Schematic representation of the model topology for the BY iron and steel sector

and average vehicle occupancy (for passengers or freight) at country level from the JRC-IDEES database [19]. The demands are expressed in billion passenger kilometers (Bpkm) or billion ton kilometers (Btkm) for passenger and freight transportation, respectively.

Rail, aviation, and marine transportation are modeled on the basis of demand and energy consumption statistics. Consequently, for each corresponding demand indicated in Table 1, one general process is defined, which can have different fuel inputs. Like for road transport, demand is expressed in either Bpkm or Btkm. For trains (passengers and freight; see Table 1) both diesel and electricity are available as fuel. Present-day aviation uses exclusively jet-fuel kerosene and is divided into intra-EU, extra-EU, and domestic transportation; the latter is solely reserved for passengers. This differentiation facilitates the modeling of aviation emissions that fall under the EU ETS, since it covers currently only intra-EU flights [41]. The marine categories are limited to freight transportation and consist of 1) navigation, which corresponds to intra-EU marine transport, and 2) international marine bunkers, corresponding to extra-EU transport. Present-day marine transportation primarily uses diesel and heavy fuel oil.

Demand projections for the different transport modes are made through Eq. (2) using population [26] and GDP [27] projections as drivers. The respective demand drivers are summarized in Table 1. Currently, all transport demand is considered to be annual, whereas in future versions of the model, we intend to implement time-slice fractions for a better representation of electricity use in road and rail transportation. In this way we may capture vehicle battery charging and discharging dynamics in the future energy system, including vehicle-to-grid interactions.

At present, we limit future technology options to road transportation. Techno-economic parameters for passenger cars with an internal combustion engine (ICE) were obtained from König et al. [42]. We assumed an efficiency improvement of 0.5% per year, the other parameters are kept constant for future years. We estimate the cost development of battery electric vehicles (BEV) using a simple model, which uses the cost development of lithium-ion (Li-ion) batteries obtained from multiple recent studies [42–44]. Additional factors in this calculation are the cost, drive range, and battery size of BEV models, which are obtained from sales data

for the Netherlands in the period 2019–2020 [45]. A number of assumptions are made, which are detailed in section A.2 of Appendix A. Our BEV cost projections are summarized in Table 2. In order to make cost projections for the electrification of the other road transportation categories (busses, LCV, and HDV), we again used our battery cost projections. We established a vehicle base cost, defined as the vehicle investment cost excluding the battery pack. This we derived from the EU Reference Scenario 2020 investment cost data [46]. Subsequently, under the assumption of a drive range fitting the vehicle category, a cost projection of the total investment costs was made. The resulting cost projections are included in Table A.4. In addition to the electric options for the various vehicle categories, the model includes the following drivetrain options: improved efficiency gasoline and diesel, plug-in hybrid, LPG, CNG, and fuel cell options. Data for these options are all based on the technology assumptions available from the EU Reference Scenario 2020 [46].

For the other modes of transport, in order to fulfill future demand and meet emission reduction targets, fuel switching options have been implemented. These include for rail transport switching to electricity, for aviation switching to bio-kerosene, and in navigation to biodiesel. Additional future technology and fuel options for aviation and navigation will be implemented in future versions of the model.

### 3.4 Electricity Interconnections

Electricity trade between countries is modeled as pair-wise trade between nodes, in which each country is represented by a single node. In order to establish the present interconnection capacities and to provide the model with constraints on the future development of a pan-European grid, an analysis was made of historic cross-border physical flows available from the ENTSO-E Transparency Platform [47]. From the 2015 (BY) data series, the hour during which the maximum electricity flow occurred was identified for each pair of countries. Subsequently, this value was applied to define the net transfer capacity associated with this particular interconnection. Irrespective of the direction of the maximum flow, we assume the full capacity to be available for bi-directional flow. This procedure was repeated for 2020. For the BY, the resulting capacities are directly used to set the interconnection capacities, while for 2020 the maxima of the 2015 and 2020 values are taken. For future grid expansions, we differentiate between the near-term (2025) and the period beyond. For 2025, we adopted the starting grid as defined in the TYNDP2022 study by ENTSO-E and ENTSO-G [48]. This reference grid contains a best estimate of the planned interconnection upgrades and extensions until 2025 as foreseen by the transmission system operators (TSOs) of the

**Table 2** Cost development of multiple categories of BEVs implemented in TIMES-Europe

| BEV investment costs [k€ <sub>2015</sub> ] |      |      |      |      |
|--------------------------------------------|------|------|------|------|
| BEV category                               | 2020 | 2030 | 2040 | 2050 |
| Small (Cat A)                              | 23.2 | 21.2 | 20.4 | 19.9 |
| Medium (Cat C)                             | 39.9 | 37.6 | 36.5 | 35.8 |
| Large (Cat D)                              | 54.6 | 51.1 | 49.0 | 47.4 |

respective countries. Beyond 2025, we allow the model to optimize the pan-European grid. For this purpose, we define maximum bounds to future interconnection upgrades and expansions on the basis of the TYNDP2022 study [48]. In particular, we use the 2040 extended grid resulting from the “distributed energy” scenario for this. Bounds to the expansion of the pan-European grid will typically be adjusted as part of scenario building, keeping the maximum bounds as guideline for realistic grid expansions.

The investment costs for grid extensions were estimated from projects in different stages of realization (ranging from “under consideration” to “under construction”) from the TYNDP2020 Project Sheets [49]. Only cross-border projects were considered. From the project list a subdivision was made into four project categories: AC onshore, AC offshore, DC onshore, and DC offshore. We assume that future onshore and offshore interconnections are realized with, respectively, AC transmission lines and DC submarine cables. In order to determine their investment costs, we assumed fixed cable lengths of 100 km for over-land connections, while the shortest distance between the shores of the respective regions was applied for offshore cable lengths. The DC interconnections include two high-voltage substations. The resulting investment costs per interconnection are calculated with Eqs. (7a) and (7b):

$$Capex_{AC} = CAP \cdot Cable\ length \cdot I_{P,L}, \quad (7a)$$

$$Capex_{DC} = CAP \cdot Cable\ length \cdot I_{P,L} + 2 \cdot CAP \cdot I_S, \quad (7b)$$

in which CAP represents the interconnection capacity in GW,  $I_{P,L}$  resembles DC or AC cable investment costs per GW·km, and  $I_S$  refers to the substation costs. The unitary investment costs  $I_{P,L}$  are estimated from appropriate subsets of data from the TYNDP2020 Project Sheets [49] for AC onshore and DC offshore projects. The DC substation costs are in line with the range of converter costs given in Härtel et al. [50]. Table 3 summarizes the estimates of the cost factors. The same cost parameters apply to interconnections between all countries. The associated O&M costs are assumed to be equal to 1% of the CAPEX.

### 3.5 Storage and Conversion

Electricity storage and conversion options provide flexibility to the energy system. Currently, TIMES-Europe includes Li-ion network batteries, pumped hydro storage

(PHS), and compressed air energy storage (CAES). We implement their techno-economic parameters mainly according to Schmidt et al. [51] (see Tables A.4 and A.5 in the Appendix). For all storage options several energy-to-power (E2P) ratios are included. The range of E2P ratios for a given technology is based on an assessment of the most economic technologies as function of the discharge duration made in Schmidt et al. [51]. Consequently, for Li-ion batteries an E2P range of 2–8 h is used, for PHS of 8–32 h, and for CAES 16–128 h. CAES includes both diabatic (D-) and advanced adiabatic (AA-) CAES technologies [52]. At present, worldwide only two commercial CAES facilities exist which are both D-CAES. In D-CAES, the heat generated during the compression phase is lost. Consequently, it requires additional fuel to (re-) heat the compressed air expanding through the turbine. We model D-CAES in accordance with data on the McIntosh plant, AL, USA [53]. It uses natural gas as input fuel; the energy efficiency of the process, defined as the electrical energy output divided by the sum of the electrical energy input and the fuel consumption, amounts to 54%. In the concept of AA-CAES, thermal energy is extracted during compression and stored in thermally insulated structures using a suitable medium, such as molten salts or oil, which facilitates a higher overall system efficiency. We have adopted the techno-economic parameters for AA-CAES from Abdon et al. [54], which compares costs and efficiencies from several studies. We only use CAES in the form of energy storage in salt caverns, since this is considered to be the most economic option [55]. Therefore, CAES is only considered in countries with suitable salt structures in the underground. This information is obtained from the study by Caglayan et al. [56], which assesses the technical potential for hydrogen storage in salt caverns. Technology learning is only applied to Li-ion battery systems and is based on the analysis by Schmidt et al. [51]. The other technologies are either proven technologies or based on well-known processes and engineering, for which we expect limited cost reductions. We adopt the realizable PHS potential per country from Gimeno-Gutiérrez et al. [57]. This geographical information system (GIS)-based study includes existing reservoirs with sufficient head with a maximum distance of 20 km between them. The final realizable PHS potential takes into account constraints with respect to populated areas, transport infrastructure, distance to grid infrastructure, and natural areas.

Electricity storage balances the power system on different timescales and has electricity as input as well as output. Electricity conversion options, such as power-to-gas and power-to-liquid concepts, not only facilitate energy storage but also permit the transfer of energy from the electricity network to the gas network and other demand sectors. In this way, it enables not only the production of carbon-free or carbon-neutral

**Table 3** Estimates of the cost factors for AC onshore and DC offshore grid interconnections using Eqs. (7a) and (7b)

| Cost factor          | AC onshore | DC offshore |
|----------------------|------------|-------------|
| $I_{P,L}$ [M€/GW·km] | 1.4        | 2.5         |
| $I_S$ [M€/GW]        | -          | 100         |



synthetic fuels but in addition aids the flexibility of the energy system through inter-sectoral coupling. The available electricity conversion options have in common that they start with the production of hydrogen from electricity. Currently, power-to-hydrogen conversion is available in TIMES-Europe. We will continue to expand the set of power-to-X concepts, including the production of methane and synthetic fuels from electricity.

## 4 Scenario Definition

In order to illustrate the type of studies that can be conducted with TIMES-Europe, we defined several scenarios. Their main characteristics are summarized in Table 4. We defined a base scenario, for which we set only a limited number of general constraints, and three net zero (NZ) scenarios which differ with respect to the minimum share of renewable electricity required. The general constraints that are valid for all scenarios and apply to all individual countries are.

- *coal and oil fired plants*: no capacity growth allowed, phase-out in 2040;
- *nuclear energy capacity*: not allowed to grow beyond the level established by the 2015 capacity plus all installations planned or under construction until 2030;
- *PV and wind capacity*: sustained growth, year-on-year reduction of capacity for these technologies is forbidden;
- *passenger cars*: no growth in number of gasoline and diesel cars beyond 2020.

The use of biomass for electricity production was allowed to increase from the current level of 1.9 EJ [16] to 3 EJ, which was set as an overall (EU27 + UK) constraint for 2050.

For the present study, we choose to implement these scenarios on a reduced version of the model, comprising only the power and transport sectors. Electricity storage as well as its conversion to hydrogen and the trade of energy commodities and CO<sub>2</sub> are not enabled in the current runs. By employing a reduced version of the model, we aim at giving an example of the main capabilities of TIMES-Europe without having to go into the complexities of a full energy-system-level analysis, which we consider out of the scope of this article. Projections of future demand were made for the different transport sector energy service demands (see Table 1). For the total electricity demand of the individual EU27 countries, we adopted the “distributed energy” electricity demand scenario from the TYNDP 2022 study [48]. For the UK the overall electricity demand projection corresponding to the FES2020, “consumer transformation” scenario was used [58]. Time-slice fractions of the demand were based on historic hourly load data as obtained from ENTSO-E [47].

We differentiate between a base scenario and three different NetZero (NZ) scenarios. While for the base scenario, no constraints were defined other than the ones mentioned above, for the NZ scenarios, targets were set on power sector CO<sub>2</sub> reduction, minimum renewable electricity share, and road transport emissions. For the NZ cases, the power sector's CO<sub>2</sub> reduction is set in line with the overall CO<sub>2</sub> emission reduction goals for the EU stated in the European Climate Law: carbon neutrality in 2050 and 55% CO<sub>2</sub> emission reduction (w.r.t. 1990) as intermediate goal in 2030. Given that the power sector falls under the ETS, and since electricity and CO<sub>2</sub> trade are not included in the model runs, this constraint is not an attempt to grasp the current or proposed policy in detail. Instead, we opted for a stylistic assessment of European emission reduction goals by imposing a CO<sub>2</sub> reduction target for each country, separately, rather than on EU level (see Table 4). The

**Table 4** Overview of the scenario definitions

| Scenario        | Power sector CO <sub>2</sub> <sup>a</sup> and RES <sup>b</sup> constraints | Road transport constraints                                                                                                                                                                                                                                                               |
|-----------------|----------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Base</b>     | -                                                                          | -                                                                                                                                                                                                                                                                                        |
| <b>NZ</b>       | 2030: – 55% CO <sub>2</sub><br>2050: Net zero                              | 2030: Country-specific ESR targets applied to road transport<br>2050: Net zero<br>Zero Emission New PC and LCV: <ul style="list-style-type: none"> <li>• from 2016: year-on-year growth of total fleet;</li> <li>• 2025: at least 15% of new vehicles;</li> </ul> 2035: all new vehicles |
| <b>NZ_RES40</b> | See NZ<br>2030 and beyond: RES ≥ 40%                                       | See NZ                                                                                                                                                                                                                                                                                   |
| <b>NZ_RES60</b> | See NZ<br>2030 and beyond: RES ≥ 60%                                       | See NZ                                                                                                                                                                                                                                                                                   |

<sup>a</sup>CO<sub>2</sub> reduction with respect to 1990 levels

<sup>b</sup>RES, renewable electricity share

**Fig. 5** Total electricity demand in the whole EU27 + UK region for the base year, 2030, and 2050 projected for the different scenarios



additional renewable electricity share (RES) constraint sets the requirement of a minimum share of renewable electricity generation on national level. Depending on the scenario, it is set to either 40% or 60% of total electricity generation.

Multiple policy measures are currently being proposed that will impact the trajectory for CO<sub>2</sub> emission reductions from road transport [59]. These include CO<sub>2</sub> reductions under the Effort Sharing Regulation (ESR), Renewable Energy Directive (RED), likely a new ETS system for road transport (and the built environment), and norms for fractions of zero emission vehicles in new passenger car and light commercial vehicle fleets. As outlined in Table 4, the road transportation constraints in our work partly reflect these foreseen measures, and will be updated in future studies.

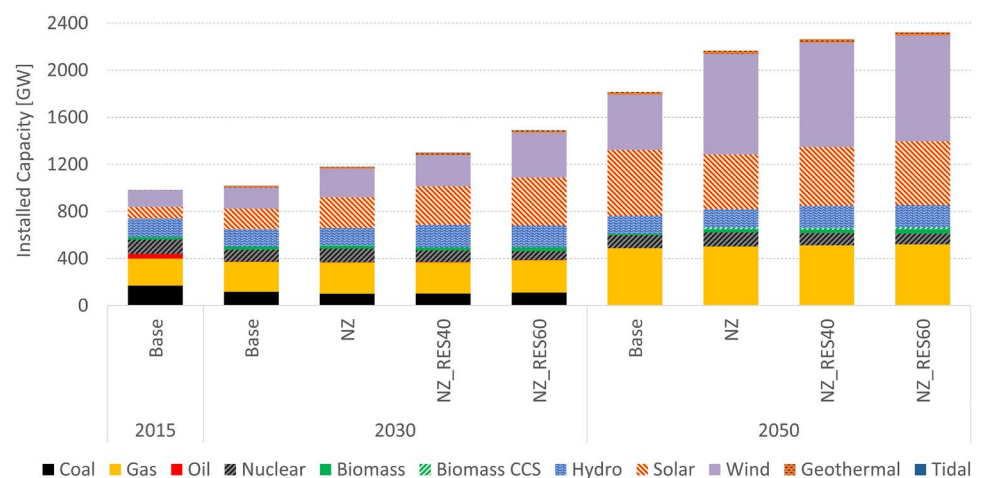
## 5 Results

For the various scenarios, the total electricity demand for the whole EU27 + UK region is shown in Fig. 5. The transport demand projections and future deployment of electric

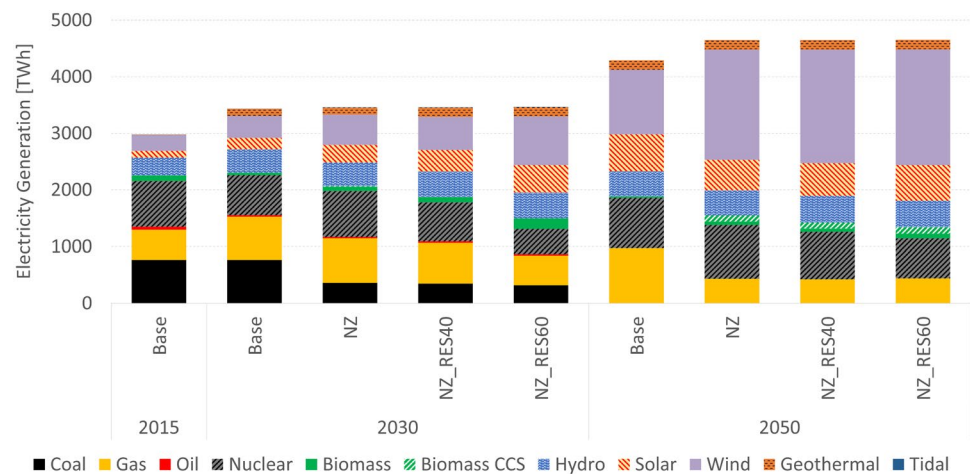
vehicles result in an endogenous increase in electricity demand for transportation (green portion of the bars in Fig. 5). The total exogenous electricity demand (i.e., from TYNDP 2022 [48]) is corrected for this additional demand. For this purpose, for all model years the endogenously calculated electricity demand resulting from BEV deployment in the base scenario projection is subtracted from the overall exogenous electricity demand. The orange portion of the bars in Fig. 5 represents the remaining exogenous electricity demand.

Figures 6 and 7 depict the evolution of the installed capacity and generation mix, respectively, projected under the different scenarios. Until 2030, the major developments include a significant reduction of the coal-fired capacity and an extension of PV and wind capacities. Natural gas capacity is projected to show a modest growth in all scenarios. In the base scenario, the PV capacity nearly doubles in 2030, while for NZ-RES60 it increases more than fourfold. Wind energy capacity almost triples in this 60% RES scenario. In 2050 PV shows the strongest growth in the base scenario, while in all other scenarios, the wind capacity expansion

**Fig. 6** Projected installed capacities for the base year, 2030, and 2050 under the different scenario assumptions detailed in Table 4



**Fig. 7** Projected electricity generation for the base year, 2030, and 2050 under the different scenario assumptions detailed in Table 4

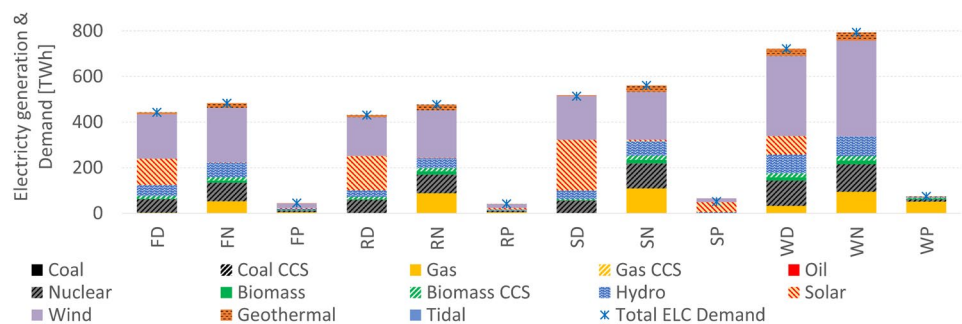


dominates, expanding up to 850–900 GW in 2050. Under the requirement of a carbon neutral electricity sector, the higher capacity factor of wind energy and, in particular, of offshore wind energy is driving this development. Strikingly, the natural gas capacity in 2050 is projected to nearly double with respect to 2030 levels in all scenarios. From Fig. 7 we observe that in 2050 wind energy is projected to become the major source of electricity in all scenarios. In the base scenario 1140 TWh of electricity from wind energy is projected, while the NZ projections range around 2000 TWh. Figure 6 shows a strong rise in natural gas capacity in 2050. Nevertheless, from Fig. 7 it is clear that the electricity generation from natural gas lags behind this capacity increase. It is found that across all scenarios, its utilization factor reduces significantly in 2050. This is most apparent from the NZ cases in which it is consistently reduced to below 10%. However, even in 2050 under the constraint of carbon neutrality, the model projects between 400 and 450 TWh of electricity production from natural gas-fired plants. Since the deployment of natural gas capacity is not restricted in the current scenarios (contrary to that of nuclear energy), it is used to provide flexibility to the energy system. The associated CO<sub>2</sub> emissions are compensated by the negative emissions associated with biomass CCS. The electricity generation from natural gas in these illustrative scenarios

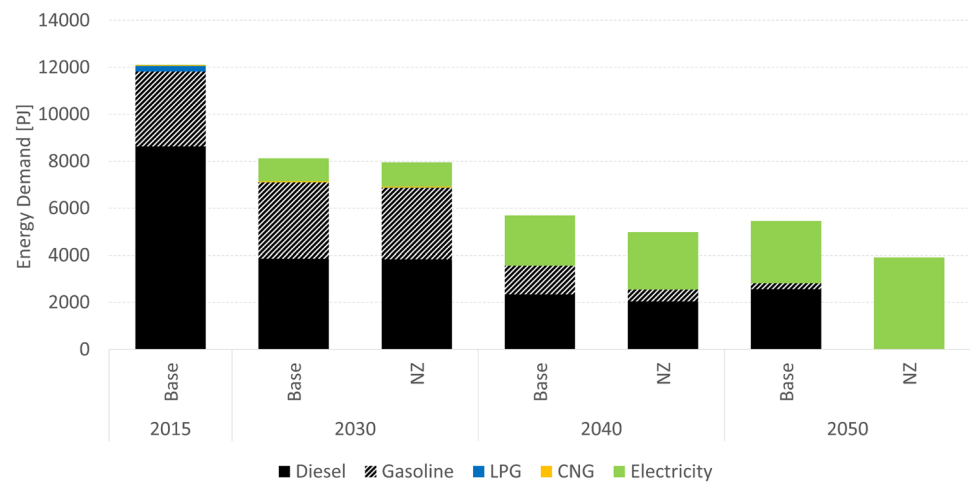
should therefore be interpreted as a need for CO<sub>2</sub>-free flexible capacity. Combined battery storage, seasonal storage, and demand side management are expected to play an important role in providing this flexibility, possibly substituting natural gas—a development which we plan to investigate in detail in future studies, using an upgraded version of TIMES-Europe. Including nuclear energy, around 35% of the generated electricity comes from dispatchable resources in the 2050 NZ projections.

Figure 8 depicts the variation of the generation mix over the different time slices for the whole EU27 + UK region for the NZ\_RES60 scenario for 2050. In the time-slice naming convention, the seasonal indicator (S, summer; F, fall; W, winter; R, spring) is followed by the day, night, peak indicator. From this result, a number of interesting observations can be made. First of all, it is apparent that in all time slices, electricity generation at least equals demand. Second, the electricity demand is higher during the night time slices; this may seem counterintuitive, but can be explained from the fact that the night time slices start at 8 p.m. and last 12 h, while the day time slices last only 11 h. Third, in the SP time slice and to lesser extent in the SD and RD time slices, an overproduction of electricity occurs. In the SP time slice, this can be mainly attributed to PV. As in these scenario runs, electricity storage was not included; this will

**Fig. 8** Timeslice analysis of the NZ\_RES60 scenario for 2050



**Fig. 9** This plot summarizes the evolution of the energy consumption in road transportation for the base and NZ scenarios



result in curtailment of the overproduction. With the option of electricity storage enabled, the surplus could be used to reduce the electricity generated from natural gas during the SN time slice. Fourth, while natural gas capacity is mainly deployed in night time slices, during the WP time slice, it is by far the most important technology. In fact, the WP time slice is to a very important extent responsible for the large natural gas capacity, which is installed. This becomes clear from an analysis of the average technology-specific capacity requirement per time slice for dispatchable resources, which is derived from the electricity generation per time slice, taking into account the time-slice year-fraction and the technology's availability factor (see Section A.4, Fig. A.2 of the Appendix). The outcome of this analysis illustrates that the WP time slice is indeed driving the large natural gas capacity requirement observed in Fig. 6. Electricity demand during WP requires approximately 500 GW of installed (flexible) natural gas capacity, while in the other time slices, it is limited to 110 GW. This analysis clearly indicates that seasonal storage and demand side management which can partly cover or mitigate the electricity demand in winter, especially during peak demand, are expected to limit the natural gas capacity requirements.

Figure 9 displays the evolution of the energy consumption in road transportation for the base scenario and one of the NZ scenarios. Since all NZ scenarios include the same CO<sub>2</sub> emission reduction measures (see Table 4), their associated transport sector optimization yields similar results. Clearly, the NZ scenarios, which are expected to have the largest extent of electrification of road transportation, show the strongest rise in electricity demand. The full electrification of road transport would result in an electricity demand of close to 4 EJ in 2050. Interestingly, already in the base scenario, there is a strong growth in the electricity demand from transportation. Consequently, the general constraint, which does not allow the GSL and DSL passenger car fleet to expand, in combination with the assumed BEV cost

reductions is already sufficient to replace a large share of the combustion engines. In the base scenario, a significant share of diesel fuel consumption remains from heavy-duty transportation (HDT) in 2050. In the NZ scenarios, full electrification of the road transport sector is enforced through a constraint for carbon neutrality (see Table 4). Certainly, one can debate whether it is realistic if HDT is fully covered by electric trucks and whether hydrogen fuel-cell technology could play a role here as well. Similarly, hydrogen fuel cells may be introduced in bus transportation and possible larger passenger cars. To study this we need to provide more detail to our representation of the transport sector. To this end, a differentiation between short-range and long-range HDT and an additional diversification of the passenger car portfolio—which at present is oriented toward small efficient vehicles—should be made. In the latter category BEV will completely dominate. In addition, we will need to represent the temporal charging profile of electric vehicles, whose electricity demand is currently defined on annual level. This will be the subject of future model enhancements.

## 6 Outlook

This paper gives an overview of the main characteristics of TIMES-Europe, a novel E3 optimization model for Europe. We describe in detail its structure and the underlying data resources, which enable an accurate representation of all supply and demand sectors of the European energy system. By way of example, we include and discuss a limited set of results from illustrative scenario runs with a focus on the power and transport sectors. In the near future we anticipate to extend the geographical scope of TIMES-Europe to include all European bordering regions, which allows to project future trade flows of energy commodities (e.g., electricity, natural gas, and hydrogen) relevant for the European energy system. We will thus be fully equipped to study



European energy transition and climate mitigation scenarios, taking into account arguments of energy security and availability of regional energy resources.

One of the strengths of TIMES-Europe lies in the fact that it covers all energy supply and demand sectors of individual European countries as well as the relevant interactions between them. In this way we are able to make projections for both the EU energy system (and its vicinity) and for its individual member states. It is thus ideally suited to study many near-term energy policy, energy security, and system-integration challenges from an energy system perspective. It also allows investigating the interaction between energy and climate policies of individual member states, as well as between these multiple national policies and those enacted by European policy instruments. We can thereby analyze under which circumstances they may be reinforcing each other, or in other cases actually be counter-productive. With the ETS being the main instrument driving the decarbonization of the industrial and power sectors, these sectors can only be adequately studied using an integrated sector-coupled model at a comprehensive European level. The same holds for the role of hydrogen, synthetic fuels, and biofuels in the future energy system: useful projections require complete sectoral coupling and a full European geographical scope that accounts for bordering regions.

To further advance TIMES-Europe as valuable tool for European energy system analyses, we intend to implement several improvements, some of which are already underway. First, we plan to integrate a detailed representation of tailor-made energy efficiency and CO<sub>2</sub> abatement options available to the individual industrial subsectors. For this purpose, we will take advantage of the extensive analyses of decarbonization options available in industry as published by MID-DEN [39]. Second, a detailed representation of hydrogen conversion and transportation infrastructure allows us to study the increasing cross-sector interactions between the power, industry, and transport sectors when large quantities of hydrogen are to be produced within Europe and/or its bordering regions. Third, we plan to extend the biofuel and synthetic fuel module of TIMES-Europe in order to further capture the sector-coupling benefits and trade-offs resulting from the likely growing use of these fuels. Alongside these developments, we will implement a detailed representation of the tools and legislation resulting from the Fit-for-55 [3] and REPowerEU [4] proposals, once they come into action. In the long run, we may also increase the number of time slices to capture energy demand and supply in different periods of the year, as well as the intermittency of renewable resources, even more accurately.

We strongly believe that with the development of TIMES-Europe, we can make a valuable contribution to analyzing the desirable and necessary shape of the future European energy system. With this model we are well equipped to

study and project European energy transition scenarios, while tackling research questions directly relevant for the formulation and design of EU climate policy and energy security strategy.

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**Author Contribution** S.L.L., S.S.S., K.S., and F.D.L. designed and developed the model. S.L.L. and B.v.d.Z. wrote the article and produced its final version.

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**Availability of Data and Materials** Questions with regard to further details on the model and the datasets used to generate it can be addressed to the first author.

## Declarations

**Ethical Approval** Not applicable.

**Competing Interests** B.v.d.Z. is on the editorial board of Environmental Modeling & Assessment and receives no compensation as member of the editorial board. He declares to have not been involved in the evaluation of this paper.

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