TEMOA-Europe: an open-source and open-data energy system optimization model for the analysis of the European energy mix

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Highlights

- TEMOA-Europe is an open-source and open-database energy system optimization model.
- The first work presenting net-zero trajectory for Europe excluding Russian imports.
- The model matches historical data and considers industrial price-elastic demands.
- Future projections are in line with the announced pledges of European countries.
- Renewables cover most of the demand by 2050 but fossil fuels are not phased out.

Keywords
Open energy system modeling; European Green Deal; Net-zero emissions by 2050; TEMOA-Europe.

List of abbreviations

CCS	Carbon capture and storage
CHP	Combined heat and power
CSP	Concentrated solar power
EIA	Energy Information Administration
ENSPRESO	ENergy Systems Potential Renewable Energy SOurces
EPR	European pressurized reactor
ESOM	Energy system optimization modeling/model
ETM	EUROfusion TIMES
EU	European Union
GDP	Gross domestic product
GEC	Global Energy and Climate
GHG	Greenhouse gas
GWP	Global warming potential
IEA	International Energy Agency
JRC	Joint Research Center
LNG	Liquified natural gas
NZE	Net-zero emissions
OECD	Organization for Economic Cooperation and Development
OEO	Open Energy Outlook
OSeMOSYS	Open-Source Energy Modelling System
PV	Photovoltaic
RES	Reference Energy System
TEMOA	Tools for Energy Model Optimization and Analysis
TPES	Total primary energy supply
UNFCC	United Nations Framework Convention on Climate Change
WEO	World Energy Outlook

Abstract

Energy system modeling tools allow to perform comprehensive analyses for the optimal integration of supply and demand technologies in different scenarios. Open tools, in particular, increase the reliability of such tools and their policy relevance. This work aims to present TEMOA-Europe, an open-data and open-software model instance for OECD Europe. Such model is developed on a time scale up to 2050 and calibrated against acknowledged energy statistics up to 2020. This work is the first to present a net-zero emissions by 2050 trajectory envisaging the absence of Russian energy imports starting from 2030. Despite the stringent constraints, TEMOA-Europe is able to provide results for a decarbonization scenario with growing end-use demands – among which some are reduced for the effect of the elasticity to gas price – considering a larger use of renewable source already starting from the near future and

reduced energy intensity. Renewable energy represents more than 60% of total energy supply by 2050 in the computed pathway. The results are also compared to the projections of the International Energy Agency for the Announced Pledges Scenario (since results for the Net-Zero Emissions Scenario are not publicly available), showing large agreement except for the outcomes concerning wind electricity generation.

1. Introduction

Europe represents one-sixth of the global economy, with a nominal gross domestic product (GDP) of 16.6 trillion dollars in 2022 [1], concurring with one-tenth of the global energy consumption and CO_2 emissions [2]. Considering the pressing need for climate change mitigation and greenhouse gas (GHG) emission abatement [3], starting in 2019, the European Commission has been laying the foundations for the realization of the European Green Deal [4] to transform Europe into the first carbon-neutral continent by 2050 through a socially fair transition. The first milestone for achieving the climate-neutrality target is established in the framework of the Fit for 55 [5] policy package to reduce GHG emissions by at least 55% against 1990 levels.

More recently, [6]the exacerbation of the Russia-Ukraine conflict in the first months of 2022 has both been part and cause of the inflation issue [6] experienced almost globally, and the subsequent, unprecedented sanctions imposed against the Russian Federation have led to the ongoing crisis in the supply of primary energy and non-energy commodities (natural gas, above all). Such crisis is especially hitting the European continent, traditionally strongly dependent on Russian fossil fuels [7]. In response to the difficulties and the perturbations to the global energy market caused by such a situation, the European Commission has been adopting the REPowerEU Plan [8] with the triple target of saving energy, incentivizing the production of clean energy and diversifying the energy supply.

Since the Saudi-Israeli conflict [9] and the subsequent global energy crisis triggered by the embargo on Saudi Arabia's oil products in the 1970s, energy system optimization models (ESOMs) have been recognized as useful tools to identify the optimal resource allocation. From the mid-1980s, the focus of this class of models shifted to energy-environment interactions, producing models for long-term forecasts concerning not only energy but also emissions [10]. Indeed, ESOMs are characterized by a wide and detailed description of energy supply and demand technologies (the "technology-richness" peculiarity, deemed as necessary in, e.g., [1] and [2]) in terms of technical, economic and environmental features [11]. This comes at the price of accurately characterizing the various processes or parts of them composing the energy system under exam. Typically, ESOMs optimize the energy system under analysis targeting the minimum cost throughout the entire time horizon and adopting a perfect foresight approach.

As energy and climate issues are increasingly becoming crucial issues at the European level, this work aims to present the potentialities of the open-software and open-database ESOM TEMOA-Europe. The model is used to produce unbiased energy analyses for Europe, providing full accessibility to all the embedded technical and economic data on the Github platform [12]. This work shows how it is able to reproduce historical statistics about several energy indicators and compares its results with acknowledged analyses, such as those by the International Energy Agency (IEA). The model provides a representation of the European energy supply and energy-intensive demand sectors (industry, transport, buildings and agriculture) with a high degree of disaggregation, i.e., relying on a techno-economic characterization for many technologies in all demand and supply sectors. Starting from the energy balances for the year 2005, the model performs projections up to 2050. A set of educated constraints is adopted to guarantee a realistic energy system's development and represent specific energy policies. The model determines the optimal energy mix in terms of technologies to be adopted according to the cost-effectiveness of their installation and use, the associated GHG emission trajectory and the total cost of the depicted energy system.

TEMOA-Europe can serve as a tool to assess the effects of announced policies and expected targets on the entire energy system. In this context, this is the first analysis to provide an overview of the evolution of the energy system on a long-term time scale considering two important aspects that will shape the future of the European continent. Namely, they regard the intention to transform Europe into the first carbon-neutral continent by 2050 [4] and the interruption of energy imports from Russia from the end of this decade [8]. Several energy system analyses have tried so far to depict plausible pathways for the transition towards a carbon-neutral European energy system. The European Union (EU) submitted its long-term carbon-neutrality strategy [13] to the United Nations Framework Convention on Climate Change (UNFCC) in March 2020 in the framework of the Paris Agreement [14], providing a pathway for technology deployment in the different energy-intensive sectors and GHG emissions reductions. In response to the commitments of the European Green Deal, the multinational oil and gas company Shell provided a timeline for carbon-neutrality by 2050 fostering the acceleration of clean technologies, the adoption of targeted behavioral incentives (in the form of economic subsidies and carbon taxes) and the development of technologies for emissions removal [15]. The Joint Research Center (JRC) reported a comparison of 16 scenarios, studied with the JRC-EU-TIMES model, aiming at carbon-neutrality by 2050 in [16], assessing the possible role of different low-carbon technologies. The analysis in [17] examines through EU cost-optimal timelines to net-zero emissions (NZE) by 2050 using 7 models, among which one ESOM, the EU-TIMES. Nonetheless, none of the mentioned analyses envisages the sudden interruption of energy trades with Russia. The only recent work to consider this aspect is the World Energy Outlook (WEO) published in 2023 by the IEA [18]. The WEO 2023 adopts a global-scale, bottom-up partial-optimization modeling framework allowing for a set of analytical capabilities in energy markets, technology trends, policy strategies and investments across the energy sector, the Global Energy and Climate (GEC) model [19]. The GEC and Tools for Energy Model Optimization and Analysis (TEMOA) modeling frameworks are very similar in terms of data inputs and outputs, and despite the larger spatial scale analyzed in the former, a comparison between the outcomes from the two of them is possible, as the GEC results also envisage regional insights. However, results for the NZE by 2050 scenario are not provided in [18] at the regional level, making this work the first ever to provide quantitative results for a European carbon-neutral pathway. Moreover, the model is fully calibrated to also match IEA statistics [20] from 2010 to 2020 as far as energy supply by source and type (where available, i.e., for oil and coal) are accounted for, as much as energy consumption by fuel and sector, imports/exports, electricity generation by source and CO_2 emissions by sector.

The choice of TEMOA as modeling framework to develop TEMOA-Europe is due to the growing awareness towards open science, i.e., the possibility to freely disseminate data and results from scientific research, increasing responsiveness and spreading knowledge regardless of the economic status of the recipients [21]. The importance of that issue is so relevant that it also falls within the priorities of the European Commission [22]. In particular, the open science purpose can be realized in the field of energy modeling by providing open access to both models and data, leading not only to higher quality, reliability, and recognition of the results of energy projection tools [23], but also to attempts for expanding the capabilities of traditional models. Nonetheless, energy scenarios have been criticized mostly for their lack of realism, as they cannot fully reproduce the actual behavior of the energy market and can be strongly biased by external assumptions about its developments [24]. Among the wide range of existing ESOMs [25], the most relevant example of bottom-up, technology-rich energy modeling framework [26] is represented by the TIMES model generator [27] (and its ancestor MARKAL [28]). TIMES combines a technical engineering approach with macroeconomic parameters, using a linear programming formulation to produce the least-cost optimized composition of the energy system. The time horizon used in the optimization covers a medium-to-long term scale and the model assumes that the underlying market works in partial equilibrium considering competitive markets with a perfect foresight approach, as is typical for models of the TIMES family [29]. Out of the different applications of TIMES, the JRC-EU TIMES Model is an example of policy-relevant modeling tool used by the European Commission for the anticipation and evaluation of technology policy at the European level [30]. Although the database of the JRC-EU TIMES Model, available at [31], is one for the few open and publicly available, the TIMES generator relies on proprietary software to read the input data, solve the optimization problem, and postprocess the results [32]. TIMES cannot be then currently defined part of an open modeling environment, as being part of a complex environment based on commercial and proprietary software, i.e., VEDA [32]. Note that the TIMES source code can be downloaded for free only after having signed a Letter of Agreement and requested credentials. However, the optimization problem (maximization of the consumer and producer surplus or equivalently the minimization of the cost of the energy system) is formulated in a way that cannot be modified without the ETSAP approval (that obtains the intellectual property of any approved changes) [33]. To increase model transparency and accessibility, several open-source tools or frameworks have been developed in the recent years for ESOM analyses, with some focusing on the entire energy system, such as the Open-Source Energy Modelling System (OSeMOSYS [34]) and TEMOA [35], both aimed at replicating the TIMES optimization algorithm [36]. Today, a remarkable body of works has adopted OSeMOSYS for deterministic scenario analyses to assess optimal energy transition pathways at different national and international scales (e.g., for South American countries [37]). Concerning TEMOA, the set of publications involving its applications is more limited thus far, including the presentation of the modeling framework [35] and its uncertainty analysis tool for multi-stage stochastic optimization [38]. An example of the application of TEMOA for the analysis of the United States energy system is presented in [39], to assess the impact of the absence of federal climate policies up to 2040. Another important TEMOA-based project is the Open Energy Outlook (OEO), a non-policy biased analysis for informed energy and climate policy in the USA [40]. Other TEMOA-based applications adopt its stochastic optimization feature, as in [41] and [42] to assess the role of uncertainties on the total cost of the energy system in different decarbonization pathways for Sudan and the US, respectively. The modeling framework has also been compared against other open ESOM tools: indeed, the work in [43] presents the only published comparison between a TEMOA-based model instance (TEMOA-Italy) with the equivalent TIMES model (TIMES-Italy), demonstrating that the two tools provide comparable results in a business-as-usual scenario. This comes with the advantage of a largely reduced complexity in building the model instances with simple relational databases using SQL files with a fixed and straightforward structure in TEMOA (allowing easy database management and consultation). On the other hand, TIMES requires to work with several Microsoft Excel files [32], to be filled in according to specific requirements for working properly, thus strongly expanding the learning curve and preventing an easy management and verification of the inputs for the models. Nonetheless, TIMES can rely on a wider community of users, on a larger set of already implemented parameters and equations to capture very specific details concerning the behavior of the energy system (even though it has to be said that the use of TIMES at the maximum of its capabilities is scarcely exploited) and on the powerful, newly developed graphic user interface VEDA 2.0, to perform model runs in a quick and organized way. In any case, while more details concerning the comparison of the features of the three modeling frameworks are provided in [43], it is sufficient to say here that OSeMOSYS and TEMOA have already proved themselves to be mature enough to be comparable to TIMES [23].

All in all, the choice of TEMOA for the development of this case-study, i.e., an open-source model for the European energy system, is mainly due to three reasons, and namely the possibility to use freely powerful open-source solvers as CPLEX [44] and Gurobi [45]; the use of Python, allowing to rely on numerous software packages (among which Pyomo [46] for the development of linear programming problems) and libraries; the possibility to easily build large-scale energy systems in SQL relational databases.

The paper is structured as follows: in Section 2, TEMOA-Europe is described in detail and the underlying technical, economic and social features are illustrated; Section 3 shows the results of the model in a representative energy scenario providing a comparison against IEA outcomes, while Section 4 presents the conclusions and future perspectives of this work.

2. TEMOA-Europe

TEMOA-Europe is a model of all the European energy sectors to produce long-term (currently up to mid-century) energy system optimization analyses in an open-database and open-software environment. ESOMs like TIMES and TEMOA work in partial equilibrium, i.e., they simultaneously configure commodity production and consumption and their price according to the maximization of producers' and consumers' surplus, which is the main indicator of economic welfare. Energy-intensive end-use demands must be satisfied at each time step at the minimum cost for the model to obtain a solution, subject to several constraints to represent policy targets or existing limits for system performances and technology adoption. In case demands are not affected by commodity prices (i.e., specified by the user for the entire time horizon of the model), the minimization of the total cost of the system is equivalent to the maximization of the total surplus [29]. Moreover, models based on TIMES and TEMOA work in the assumption of perfectly competitive markets, meaning that a single consumer/producer cannot decide the quantity and price at which each commodity can be bought/sold. Nonetheless, the presence of constraints influencing the availability of specific commodities inevitably introduces imperfections in the market computed by the model [29]. Eventually, competitive markets are characterized by perfect information, extended in ESOMs to the entire planning horizon, so that each agent has perfect foresight, i.e., complete knowledge of present and future market parameters [29].

In this section, the TEMOA-Europe dataset is presented in detail concerning its spatial and time scales, the structure of its reference energy system (RES) and the end-use demands to be satisfied. Since this work has the aim to present the model and its capabilities, the underlying assumptions for the development of a future energy scenario and other user-defined constraints are explicited in detail, including constraints for the availability of resources with limits for both extraction and import. The scenario described here forces the achievement of the main targets of the European Green Deal [4] and of the REPowerEU Plan [8]. More in detail, the achievement of NZE by 2050 – with the intermediate step of -55% with respect to 1990 levels by 2030 [5] – and the suspension of energy trade with Russia by 2030 are taken into account.

The TEMOA-Europe database, as for all TEMOA-based model instances, is built according to the guidelines in [47] and to the extensions presented in [43], and is available at [12]

2.1. Spatial scale, time scale and treatment of time

All the sectors of the energy system of those European countries adhering to the Organization for Economic Co-operation and Development (OECD) are represented in TEMOA-Europe, as reported in **Figure 1**. Note that OECD Europe involves all the EU-27 countries with the exception of Croatia, Romania and Bulgaria, while involving the United Kingdom, Iceland, Norway and Switzerland which are not EU members[1].

OECD Europe is treated as a single region and is built starting from energy statistics provided by the IEA for the year 2005 (the "base year" of the time horizon for the analyses) [48]. Since TEMOA is conceived as a capacity expansion model, such statistics are properly rearranged in terms of available technology capacity following the EUROfusion TIMES Model [49] and used as a starting point for future projections. Having all OECD-Europe represented as a single region means that all the countries share a single set of socio-economic drivers and the same features for all the technologies in the database. Therefore, results cannot be analyzed for individual countries, as in the JRC-EU-TIMES [30], which includes a different characterization for all the EU countries. Import and export processes represent the link to other regions of the world that are not explicitly modeled. Having a single region implies a reduced

[1] Note that the EU does not have jurisdiction over all the countries included in the TEMOA-Europe spatial scale.

complexity in constructing, populating and managing the model. Moreover, the targets set by the European Green Deal require all the countries to act as a whole with common targets and a coordinated set of actions, so the analysis of Europe as a single entity leads to interesting policy prescriptions anyway.

The database on which the model currently relies on allows the exploration of future energy scenarios up to the year 2050. The TEMOA-Europe time scale (from 2005 to 2050) is articulated over several time steps of 5 years each. In such a way, inputs should be specified for every time step and results are computed for the whole time series concurrently.

Figure 1. *Map of the OECD Europe countries included in TEMOA-Europe.*

The subdivision of each milestone year into more refined time slices is performed in TEMOA-Europe considering three seasons (intermediate, summer, winter) and three "times of day" (day, night and peak), leading to 9 time slices per year, as performed in the JRC-EU-TIMES Model [31] and reported in **Table 1**. Most of the year is allocated to the *Intermediate* season (42%), while day and night almost share the same duration in all the seasons. The subdivision in seasons and times of the day is useful to identify the different behavior of intermittent energy technologies (specified according to different capacity factors) and the distribution of service demands with a specific time pattern (e.g., space heating/cooling, lighting).

Table 1. *Subdivision of the time scale of each milestone year among seasonal and daily time slices in TEMOA-Europe, elaborated by the authors based on* [31].

Time of day \ Season	Summer	Intermediate	Winter
Day	11.4%	19.3%	15.1%
Night	12.5%	21.1%	16.4%

Peak	1.0%	1.8%	1.4%

2.2. Reference energy system and parameters for the techno-economic characterization

Figure 2 represents the structure of the TEMOA-Europe RES. As a common approach in ESOMs, technological substitution throughout the considered time horizon is taken into account, distinguishing among 3 kinds of technologies in TEMOA-Europe [32]:

- **Base year technologies**, used to model the demand and the energy use at the beginning of the time horizon. The base year demand is calculated by combining energy statistics concerning total energy consumption with dummy efficiency values and coefficients associated to the generic technologies for which an existing capacity is there. In this way, base year energy consumption is allocated to the existing capacity (see **Table 2**) of a specific technology. In the TEMOA-Europe database, base year technologies can be identified by the *_EXS* at the end of their code name (e.g., *TRA_ROA_CAR_GSL_EXS* is the base year technology that identifies gasoline cars).
- **Fuel technologies**, exclusively used to track fuel consumption (and consequently CO_2 emissions) in the different sectors, thus not corresponding to actual technologies. In the TEMOA-Europe database, fuel technologies are identified by the *_FT* in between the name of the sector and the fuel they produce (e.g., *IND_FT_COA* is the fuel technology producing industrial coal).
- **New technologies**, used to model the energy use throughout the model time horizon, are added to the existing fleet of base year technologies from the second time step on and may include both currently available and innovative technologies still not present of the market, requiring hypotheses for the first year of availability. New technologies require a characterization in terms of the parameters reported in **Table 2**, among which efficiency alone is mandatory to at least define a technology. In the TEMOA-Europe database, new technologies are identified by the ending *_NEW* in their code name (e.g., *RES_CK_ELC_NEW* is the new technology representing electric stoves for residential cooking).

Apart from the few parameters reported in **Table 2**, all the technologies constituting the RES may be described according to a broader set of technical and economic features, described in detail in [47].

Figure 2 reports the structure of the RES built in TEMOA-Europe. The power sector is its core part, as it connects the upstream sector to end-uses. In the power sector, fossil fuels, uranium and renewable energy sources can be provided as inputs for several technologies to produce electricity (centralized or decentralized) and heat, either generated in dedicated heat production plants or in combined heat and power (CHP) generation plants. Among traditional alternatives, the ETM electricity generation module includes coal, oil, gas, biomass, nuclear fission, wind onshore/offshore, solar photovoltaic (PV), concentrated solar power (CSP) and marine energy technologies. Besides well-established technologies, the TEMOA-Europe electricity generation module includes fossil and biomass plants equipped with carbon capture and storage (CCS) and Generation IV fission reactors, all made available after 2030. Dedicated heat generation plants include coal, oil, gas, biomass, geothermal and solar thermal technologies.

Table 2. *Main parameters for the characterization of energy technologies in ESOMs.*

Type of parameter	Definition	Description
Technical	Efficiency	Input-to-output transformation parameter
	Capacity factor	Utilization factor to define the available capacity fraction during a specific time slice
	Technical lifetime	Operational lifetime
	Capacity to activity	Conversion factor to be used in case capacity units differ from activity units
	Existing capacity	Capacity installed prior to the beginning of the time periods set for the optimization
Economic	Investment cost	Total cost of investment in new capacity
	Annual fixed operation and maintenance cost	-
	Variable operation and maintenance cost	-
	Technology-specific discount rate (optional)	Interest rate on investment for a specific technology
Environmental	Emission activity	Emission rate for the specific technology

On the left-hand side of the RES in **Figure 2**, supply modules generate the commodities required to feed the end-use demand modules on the right-hand side. Those technological modules belonging to the upstream sector first provide for the inland extraction of primary fossil resources, such as hard and brown coal, heavy oil and oil sands (then processed to obtain either heavy fuel oil or crude oil) and natural gas. Apart from primary fossil resources, the TEMOA-Europe upstream sector also accounts for the nuclear fuel cycle. While the representation in **Figure 2** simplistically reports uranium in output from extraction processes as directly provided as input for the power sector, TEMOA-Europe includes several steps, such as uranium mining, enrichment of natural uranium and processes for the production of uranium oxide-, mixed oxide-, trans-uranium-, natural uranium- and minor actinide-based fuels as from [50]. Reprocessing of spent nuclear fuel, deposit of both spent fuel and high-level waste and reprocessed fuel are also considered. On the other hand, renewable energy potentials include geothermal, hydroelectric, solar, wind, biomass and marine energy. In particular, the biofuels production chain is taken from the JRC-EU TIMES Model [31] and starts from biomass potentials including starch crops, sugar crops, grass crops, rapeseed, industrial waste/sludge, wood products, municipal waste, biogas and liquid biofuels. Biomass potentials can be then further processed in biorefineries (for bioethanol, methyl ester from vegetable oil, hydrotreated vegetable oil, ethyl tertiary-butyl ether, biodiesel and biokerosene synthesis) and eventually used as fuels in blending with fossil fuels or directly used as fuels (e.g., wood pellets stoves for residential space heating). Indeed, primary resources (mainly fossil resources) are either transformed or refined ("Transformation" block) into those secondary commodities to be used as fuels in end-use sectors. Some secondary transformation processes may require electricity and steam (generated in the power sector), apart from primary fossil commodities. Secondary transformation processes produce coke and coke oven gas, town gas, blast furnace gas, refinery feedstock, synthetic oil and fuel additives, e.g., methyl tertiary-butyl ether. Heat produced in refineries may be then recovered to get steam to be employed again in transformation processes. Refined fossil fuels may be blended with biofuels (gasoline, gas oil and natural gas), synthetic fuels (gasoline, gas oil, jet kerosene and natural gas) and hydrogen (natural gas). Note that this last step is generally not mandatory as the optimization algorithm chooses whether to produce low-carbon fuel blends (apart from legal requirements currently in charge for gasoline and gas oil, as from [31]). Besides inland extraction, primary fossil fuels and uranium can also be imported or exported. In particular, the different importers/destinations of exported commodities can be distinguished in such a way that different trade costs or constraints can be applied.

The supply side of the TEMOA-Europe RES includes a hydrogen module accounting for its production (through fossil fuels, biomass and electricity via electrolyzers), storage and delivery to the natural gas network and end-uses. Eventually, the sequestration module in TEMOA-Europe accounts for the storage of CO_2 captured by CCS-equipped plants through enhanced oil and coalbed recovery techniques, injection in depleted oil and gas fields, deep saline aquifers, deep ocean, mineralization and afforestation processes. Otherwise, the captured CO_2 can even be used to produce synthetic fuels using hydrogen (for syngas, synthetic gas oil and synthetic kerosene production) or electricity to generate synthetic gas oil, kerosene and methanol through co-electrolysis processes.

Commodities generated in the supply side represent the inputs for the demand side. Residential and commercial buildings, industry, transport and agriculture represent the TEMOA-Europe demand modules. As mentioned before, pre-assigned end-use demands must be satisfied at each time step and the optimized structure of the demand-side is built starting from the available set of end-use technologies. The details for the construction of the industrial and the transport sector are reported in [11] and [51], respectively, even though some minor updates have been carried out in recent times concerning the addition of new technologies and/or the values of some techno-economic parameters.

All the parameters for the characterization of the several technologies included in TEMOA-Europe can be found in the provided database [12], while details concerning the adopted values for the techno-economic parameters are mostly based on public literature or already existing energy system models. In particular, the upstream sector is built on the basis of the EUROfusion TIMES Model (ETM) [49] (excluding the full review of resource availability data, performed in preparation of this work and presented in **Section 2.4.2**, and the biofuels production chain), as well as the portion of the sequestration module concerning CO_2 storage in physical sinks and removal through afforestation (which in turn adopts data from the TIAM-WORLD [52]). Even the technologies in the power sector are based on ETM, albeit costs and discount rates for electricity generation technologies have been updated for this work relying on data from the latest World Energy Outlook by IEA [53]. The hydrogen sector is based on [54] and the synfuels production module is built based on [55]. Regarding end-use sectors, details about the road transport sector can be found in [51], while [11] presents the rationale for the construction of the techno-economic database for those industrial energy-intensive subsectors modeled in full detail in terms of available technologies (iron and steel, non-ferrous metals, non-metallic minerals, chemicals, pulp and paper); the buildings and agriculture sectors are based on ETM [56].

All in all, more than 1000 technologies (including almost 100 fuel technologies, which do not properly represent actual energy production/consumption devices, and 65 import/export processes for coal, oil, biofuels, uranium and hydrogen) and more than 400 commodities (almost 350 physical commodities representing energy carriers, energy services, materials and 44 demand commodities – out of which *OUT_DMY* and *SNK_DMY* are just used to take dummy outputs into account – besides emission commodities used to represent GHG outputs in the different sectors of the RES, including CO_2, CH_4 and N_2O) are included in TEMOA-Europe.

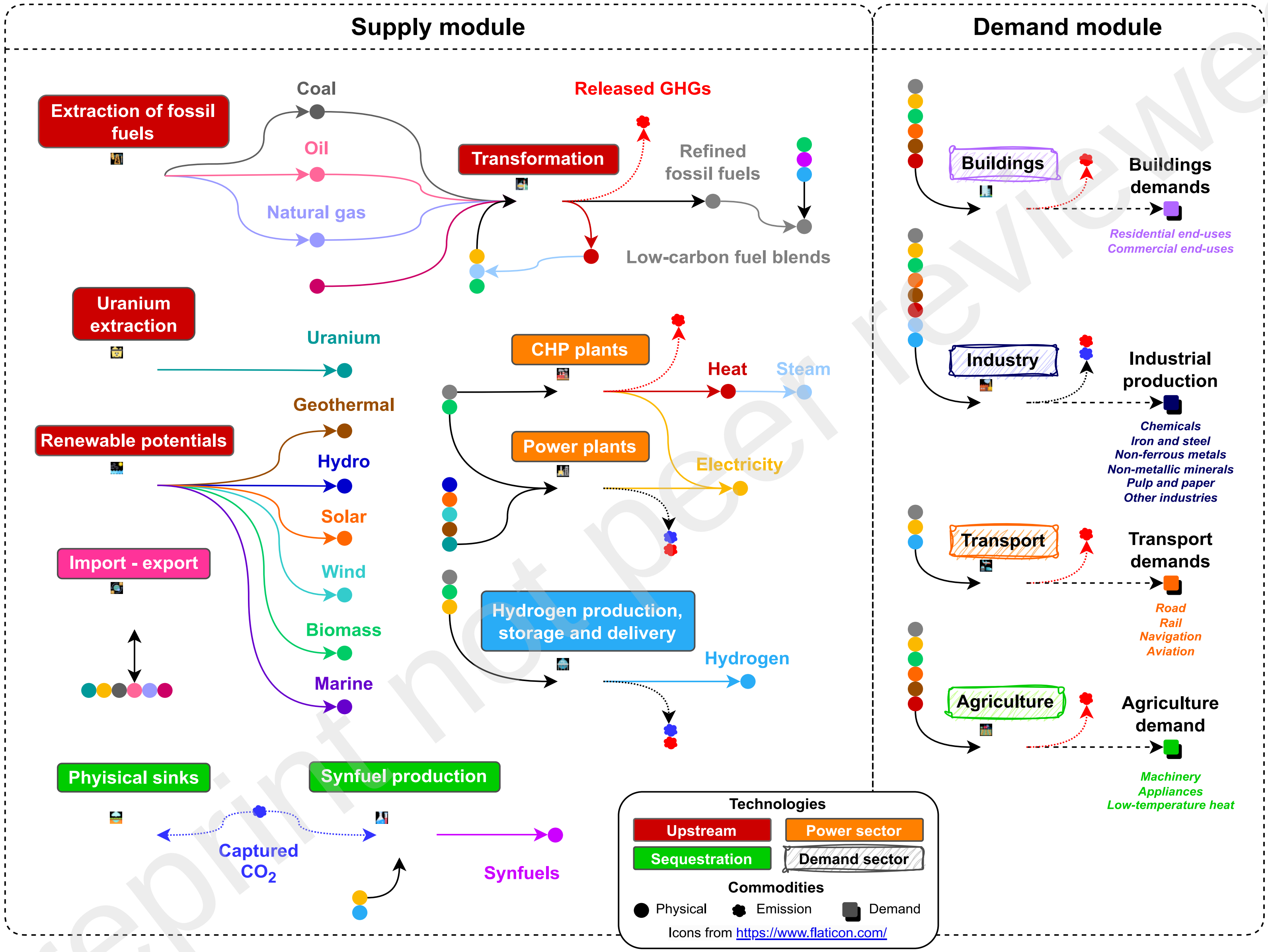

Figure 2. *Reference energy system of the TEMOA-Europe model.*

2.3. Demand projection

In TEMOA-Europe, demand levels are established a priori according to a set of socio-economic drivers. Their trends are assigned on the basis of the Energy Information Administration's (EIA) projections for GDP and population as from [57]. The future projection of energy service demands is performed according to **Equation 1**, where $\mathrm{Demand_t}$ and $\mathrm{Demand_{t-1}}$ and the service demand levels at time step t and $\mathrm{t-1}$, respectively, δ_t and $\delta_{\mathrm{t-1}}$ are the driver values at time step t and $\mathrm{t-1}$, respectively, while $\mathrm{e_{d,t}}$ is the elasticity of the driver to the demand, associated to the time step.

$$\mathrm{Demand_t} = \mathrm{Demand_{t-1}} \cdot \left[1 + \left(\frac{\delta_\mathrm{t}}{\delta_{\mathrm{t-1}}} - 1\right) \cdot \mathrm{e_{d,\,t}}\right] \qquad 1$$

Elasticities of such kind are usually adopted to correct demand projections to capture changing patterns in energy service demands in relation to socio-economic growth, such as a saturation in some energy end-use demands, increased urbanization, or changes in consumption patterns once the basic needs are satisfied [29]. Moreover, their value can be varied to depict alternative scenarios with different demand levels. Driver projections until 2050 are taken from the International Energy Outlook 2021 [57].

Figure 3 reports the results of the projections performed through **Equation Error! Reference source not found.** for most of the end-use demands envisaged in TEMOA-Europe highlighting, for example, the effects of the COVID pandemic for 2020 values. In particular, **Figure 3a** reports demands in the residential sector, **Figure 3b** for the commercial sector, **Figure 3c** and **Figure 3d** road transport demand and non-road transport demand, respectively, while **Figure 3e** reports demands in the industrial sector and **Figure 3f** agriculture demands. It goes without saying that, for each demand, at least one end-use technology must exist that can satisfy it. Major details concerning the units of measurement, the driver associated to each demand and where to find such information in the model database are reported in **Appendix A.1**.

Such "deterministic" end-use demands are generally used in ESOMs for scenario analyses. However, other elasticities may be used to adapt demand for energy services to the computed price of the commodities involved in the energy system under analysis. Such parameters, either called "price elasticities" or "elasticities of substitutions", can be implemented in TIMES [29] and have also been tested in TEMOA [58]. An attempt to implement price-elastic demands for three industrial subsectors to be reactive after possible increases in gas prices, following the analysis in [59], is also performed in this work on TEMOA-Europe. Short-term and long-term price elasticities are computed in [59] for the following subsectors: chemicals; non-metallic minerals; pulp, paper and printing; mining and quarrying; food and tobacco; textile and leather. The former three are explicitly represented in TEMOA-Europe, so the deterministic demand projections performed in **Equation Error! Reference source not found.** are somewhat corrected in response to the increase in natural gas price (expected due to the interruption of Russian supply). Therefore, after the results for the deterministic run are obtained, a second run is performed to compute a new value for the indicated demands. The projection of the price-elastic demands follows **Equation 2**, where $\mathrm{e_{p,t}}$ is the price elasticity. Short-run price elasticities indicated in [59] for the mentioned industrial subsectors are applied for periods between 2025 and 2035, while long-run elasticities are taken into account from 2040 on. The demand for the time step t is calculated according to **Equation 2** when **Equation Error! Reference source not found.** provides a higher value for the demand so that the effect of price is only taken into account when relevant.

$$\mathrm{Demand_t} = \mathrm{Demand_{t-1}} + \mathrm{e_{p,t}} \cdot \frac{\mathrm{Demand_{t-1}}}{\mathrm{Price_{t-1}}} \cdot (\mathrm{Price_t} - \mathrm{Price_{t-1}}) \qquad 2$$

Figure 4 shows the comparison between the demands for the chemical, non-metallic minerals and pulp and paper subsectors when price-elastic demands are taken into account. The impact of price elasticity is especially evident in 2025 and 2030 for the three demands, which are around 20% lower than in the deterministic case in the former time period, and around 12% lower in the latter. This result calls for a further investigation on the effects of price-elastic demands in other sectors other than industrial production to assess its impact on the overall energy system.

2.4. Constraints

Constraints for time periods prior to 2020 are used in TEMOA-Europe to ensure that the model is able to reproduce the historical trends of the European energy system.

On the other hand, some constraints are adopted for future technologies deserve further insights. They can be defined by the user to model:

- the real-life mechanisms of technological substitution. For instance, old capacity at the end of its operational lifetime should be substituted avoiding abrupt investment in new capacity [29] through, e.g., minimum/maximum capacity constraints;
- physical and operational real-world phenomena through, e.g., minimum/maximum activity (production) constraints;
- trajectories to limit GHG emissions in future scenarios.

Although constraints are widely adopted for the definition of the different energy scenarios, it is commonly suggested not to adopt many restrictive constraints to avoid “railroading” the model, which should instead respond to its optimization paradigm [29]. Indeed, constraints should be used just to replicate either real life constraints on technological adoption and evolution, or the availability of resources, thus not to force model results to obtain the desired outcomes.

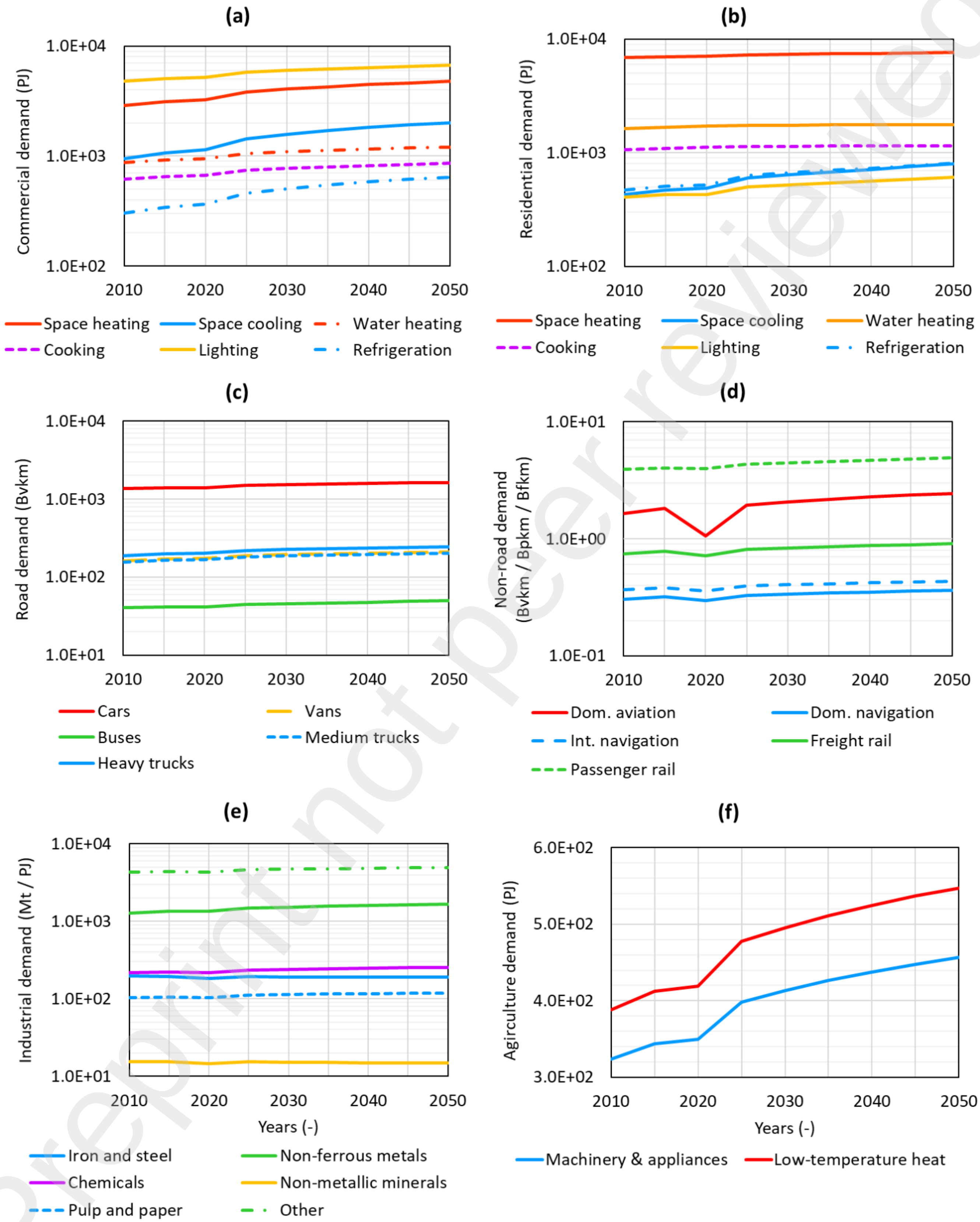

Figure 3. *Demand projections for the main end-use sectors in TEMOA-Europe.*

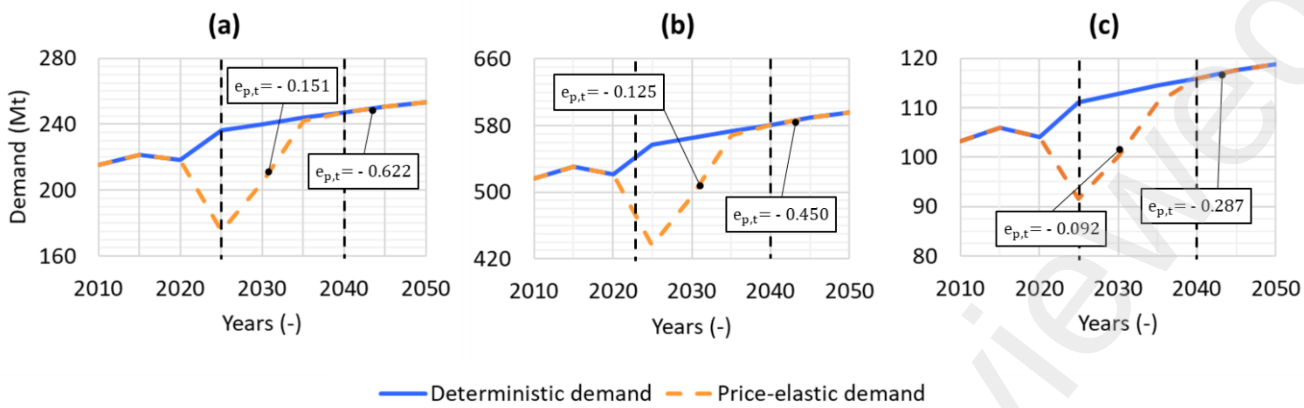

Figure 4. Demand projections in the case of price-elastic demand for a) chemicals; b) non-metallic minerals and c) pulp and paper.

2.4.1. Greenhouse gases emissions

As TEMOA-Europe is developed as a model for insights concerning the development of the European energy system in the framework of the Green Deal, the underlying hypothesis for all the analyzed scenarios concerns a NZE by 2050 trajectory also compliant with the targets of the Fit for 55 and the absence of all Russian energy imports starting from (at most) 2030.

The model does not just account for CO_2 emissions, but also for CH_4 and N_2O, combined through their global warming potential (GWP) over 100 years [60] following the prescriptions in [61]. The majority of the technologies summarized in the RES in **Figure 2** are fueled by commodities contributing to different amounts of GHG emissions as from [62]: electricity and hydrogen are not envisaged among them, even though their production may generate emissions depending on the chosen fuel. The inventory in [62] also reports emission factors for different kinds of biofuels. However, burning biomass is considered as a zero-CO_2 process as the emitted CO_2 is fully compensated, as typically done in energy system models [31], even though CH_4 and N_2O are generated anyway. The CO_2 emission per unit of activity (output) of each technology is assigned through the parameter *EmissionActivity* in TEMOA.

To take into account a possible presence of biofuels or hydrogen in blending with fossil fuels, TEMOA-Europe is able to take that into account according to the dynamic methodology presented in [55]. Indeed, *EmissionActivity* is formulated to envisage the sum of:

- a component related to the direct emission per unit of emitting physical commodity consumed (the specific static emission factors for the different fuels assigned through *CommodityEmissionFactor* are related to the commodity-specific efficiency in the database preprocessing file mentioned above);
- a contribution from process-related emissions, when present (e.g., calcination in clinker production);
- a usually negative emission contribution at the fuel technology level in case the generation of low-carbon fuel blends is deemed as cost-effective (or necessary to satisfy constraints on GHG emissions) by the optimization algorithm (note that (this contribution can become positive in

some special cases, e.g., when considering blending of biogas in natural gas, since [62] reports a higher CH_4 emission factor for the former with respect to the latter)).

The imposed emission reduction CO_2 equivalent reported in **Table 3** sets a first constraint set in 2030 at a value that is 55% lower than the ~ 4.2 Gt estimated for 1990[2]. A progressive reduction towards 0 Gt by 2050 is prescribed, allowing the decarbonization of the energy system.

Table 3. *CO_2 equivalent reduction trajectory implemented in TEMOA-Europe.*

Period	**$CO_{2\,eq}$ limit (Gt)**	**Reduction with respect to 1990 (%)**
2030	2.52	55.0
2035	1.89	70.0
2040	1.26	85.0
2045	0.63	92.5
2050	0.00	100.0

As visible in the RES in **Figure 2**, TEMOA-Europe not only allows emission reduction through the adoption of low carbon fuel blends and low carbon technologies for both energy supply and consumption. Indeed, it also considers a sequestration module in which CO_2 can be either consumed (to produce synthetic fuels using captured CO_2 in CCS-equipped plants in the industrial and power sectors) or stored in physical sinks or directly captured from air. Unfortunately, the possibility to resort to such measures is not infinite (as it is in the real world) and is not given for free: synfuel production technologies incur in investment, fixed and variable operation and maintenance costs (as it also happens for most of the other technologies in the model), while carbon storage is priced in the order of some euros to some tens of euros per Mt of stored CO_2. Constraints for CO_2 storage are taken from the TIAM-World model [52], which sets cumulative bounds in the order of tens of Gt of stored CO_2 through enhanced oil recovery, depleted oil and gas fields, enhanced coalbed methane recovery, deep saline aquifers and storage in the deep ocean; afforestation is instead limited in every time period according to a growing trend up to 0.4 Gt by 2050.

Moreover, negative CO_2 emissions can be achieved through the adoption of biomass-based technologies equipped with CCS in the electricity generation sector. Note that CCS is only able to act on CO_2 emissions.

2.4.2. Availability of energy resources

Despite the decreasing trend in energy supply from fossil fuels, sharpened by the COVID-19 crisis in 2020 [63], Europe (OECD Europe in this specific case) is still strongly relying on them, as nuclear and renewables (biomass, above all) contributed to just the 30% of the energy mix in 2020 [20]. Moreover,

[2] The value provided in [85] (5.6 Gt) accounts for all $CO_{2\,eq}$ originated from human activities. Here, the focus is on the energy sector, which is estimated to contribute for the 75% to the mentioned value.

the EU has imported almost 50% of the resources necessary to satisfy its energy needs in the last two decades [20]. In this context, Russian imports represented up to 50% of the total primary energy supply (TPES) between 2010 and 2020 [64]. In 2010, Russian gas represented 62% of the total gas used in Europe, and 74% in 2020. Similarly, Russian oil represented 66% of the oil consumed in Europe in 2010 and 80% in 2020. On the other hand, coal imports from Russia represented just 13% of the coal consumed in Europe in 2010, and 29% in 2020.

Given this context, the limited available resources must be taken into account within the model for future projections, especially in light of the recent geopolitical issues.

Oil, coal and natural gas

In TEMOA-Europe, data concerning inland production, import and exports of crude oil, oil products, hard coal, brown coal and natural gas – including liquified natural gas (LNG) are representative of IEA statistics for OECD Europe [20].

Concerning assumptions for future development, a limit for the maximum available cumulative resources for inland production is imposed as from [52]. Moreover, maximum natural gas productivity declines by 15% per period (i.e., every 5 years as indicated in **Section 2.1**), against a historical trend observing -17% between 2010 and 2015 and between 2015 and 2020. Concerning coal, hard coal inland production declined by 23% between 2010 and 2015, experiencing a -40% decrease between 2015 and 2020; a different trend was observed for brown coal (-5% between 2010 and 2015, -29% between 2015 and 2020). Following these observations, hard coal productivity declines by 20% per period, and by 10% for brown coal in the model. Eventually, oil production decreased by 18% between 2010 and 2015, while increasing by 2% between 2015 and 2020. Given these values, its maximum productivity in TEMOA-Europe declines just by 5% per time period.

As mentioned in **Section 2.2**, imported products can be distinguished according to their region of origin, so that TEMOA-Europe is able to depict scenarios in which, e.g., imports from specific regions are reduced or avoided (as it is intended to do with Russia as from the targets of the REPowerEU Plan [8]). Imported products from other regions are differentiated according to their cost, listed in the table *CostVariable* and consisting of two components:

- The commodity price, retrieved from The World Bank's historical data and projections (actually performed up to 2024) [65]. The data points for 2025 are extracted linearly from the projections performed by The World Bank for 2023 and 2024. Then, the computed values are then left constant for the rest of the model time scale for this work as not to introduce strong hypotheses on the evolution of the commodity markets. The World Bank provides different cost trends even for the same commodity when traded on different markets. Therefore, the provided data are assigned when possible, while the average of those available is adopted for the other world regions with no particular corresponding market.

- The transportation cost, retrieved from the TIAM-World model [52] for each commodity and region and generally representing a small contribution (in a range below 10% of the total import cost).

Note that costs become a decisional parameter starting from the 2025 period, when the model is left free to choose between the different regions.

The availability of natural gas and LNG imports from each region can grow according to planned expansions of import capacity, regasification capacity and medium-to-long term agreements, as from [66]. In particular, gas imports are differentiated according to pipeline imports and LNG supply. Pipeline gas imports from Africa are allowed to be able to fully exploit the existing capacity in 2020 by 2030 in the absence of both expressed plans to expand it, to allow a maximum 2.8 EJ gas flow (no increase is forecast for LNG supply). The EU agreed for increased pipeline gas imports from Azerbaijan [67] to almost triple the current flow, while the realization of the EastMed-Poseidon project [66] to connect Italy and Greece with Israel for the supply of both natural gas and gaseous hydrogen should provide almost 400 PJ starting from 2027. Concerning LNG, three European energy companies (Eni, TotalEnergies and Shell) signed long-term agreements with Qatar [68], [69] for the yearly supply of almost 1.5 EJ of LNG, while the EU is considering an agreement with the USA for additional 50 bcm/year to get to a total 2.6 EJ per year [66]. The mentioned long-term agreements are considered as binding, so that TEMOA-Europe is forced to consider ~4 EJ of LNG to be supplied until 2050. On the other hand, regasification can be expanded up to ~12 EJ by 2030 [70] to consider planned projects for onshore (~9 EJ) and offshore (~3 EJ) regasification units. That would mean that the available LNG by 2030 could almost totally substitute Russian imports, which accounted for almost 14 EJ in 2020. Nonetheless, considering an average capacity factor for regasification units is well below 50% [20], [70], only 6 EJ are made available after regasification (note, however, that LNG can be also used directly as fuel for trucks and ships).

On the other hand, the assumptions adopted for oil and coal imports envisage the complete absence of Russian imports starting from 2025, as trade for these commodities is experiencing a remarkable decline [71]. However, oil imports demand can be substituted by other suppliers as is currently happening [72].

Concerning oil, gas and coal exports, they are forced to keep the same percentage over the sum of imports and exports as in the last decade (30% for oil and gas, 10% for coal). Such a constraint formulation is necessary as exports cannot be translated into monetary income in the current, single-region TEMOA-Europe formulation.

Uranium

The current large global uranium reserves falling in the cost category less than three times present spot prices, used in the conventional reactors, are supposed to last for about 90 years [73]. OECD Europe imports more than 99% of the required uranium, with just four countries (Kazakhstan, Niger, Canada and Russia) providing more than 90% of it in 2022 [74]. For this reason, uranium extraction and import are modeled as a single process in TEMOA-Europe. The associated cost is 80 €/kg of mined/imported uranium, increasing up to 160 €/kg in 2050 to reproduce the ongoing, steady price increase [74].

Renewable sources

Despite widely claimed as inexhaustible energy sources, renewable potential is limited by several factors. Indeed, the ENergy Systems Potential Renewable Energy SOurces (ENSPRESO)[1] [75] dataset considers setback distances as well as high resolution geo-spatial wind speed data for wind potentials and irradiation data and available area for solar applications. The maximum renewable potentials indicated in [75] for wind and solar power are indeed very high, albeit not infinite, with a solar PV potential per time period attested at 29000 EJ, at 1800 EJ for solar CSP, while wind onshore can guarantee up to 150 EJ and wind offshore up to 100 EJ. The solar thermal potential is not limited itself, but the development of solar thermal capacity for heat production is constrained according to the roadmap in [76] up to 340 GW_{th} by 2050.

Constraints for biomass development are based on the JRC-EU TIMES Model [31], which is also used as reference for building the biofuel production chain in TEMOA-Europe as mentioned in the comment to **Figure 2**. While the exploited biomass energy potential supplied 5.7 EJ in 2010 up to 7.1 EJ in 2020, the high development scenario elaborated in [75] and adopted in [31] leads to a maximum 9.1 EJ exploitable by 2050. The geothermal potential is limited according to [77] up to 4 EJ by 2050.

2.4.3. Constraints for capacity deployment

Concerning innovative technologies, maximum capacity deployment constraints are applied in TEMOA-Europe. Indeed, those technologies that present either low fuel consumption if compared to "conventional" alternatives or zero direct emissions may be selected from the model to cover the whole demand in their sector since their first year of availability, independently of their high cost. For this reason, some technologies are prevented from being able to experience an abrupt growth from one time step to another. The methodology adopted to compute such constraints is based on the well-established theory of S-curves for technology deployment [78] – envisaging a revolutionary (exponential development), an evolutionary (linear development) and a maturity (constant replacement of the existing technology base) phase – following two different approaches.

For electricity generation technologies presenting historical data series (coal, gas, oil, hydroelectric, biomass, nuclear, geothermal, solar PV, solar CSP, wind onshore, wind offshore and marine energy technologies), the projections are performed according to the methodology described in [79] relating historical development up to 2020 to plausible future deployment.

For those technologies presenting very poor or no historical data series, the maximum capacity constraint is retrieved through the method in [80], which is used to compute the fastest possible pathway towards a fixed target for the installation of a technology (the so-called "saturation capacity") starting from a technical parameter, i.e., its useful lifetime. The second kind of constraint is applied, in particular, to electricity generation technologies such as biomass plants and fossil fuel plants equipped with CCS and IV generation nuclear reactors targeting a saturation capacity of 500 GW_e: actually, the limited time frame considered for their availability in TEMOA-Europe leaves them well below 50 GW. In the electricity sector, a similar constraint is also applied to battery storage technologies for renewable electricity, which is expected to reach up to 600 GW by 2050. The same type of capacity limitation constraint is also applied in the hydrogen sector to reasonably limit the production of hydrogen to be used in fuel cell-based demand appliances: in particular, 3 groups are considered, limiting the adoption of hydrogen generation plants equipped with CCS, up to 270 GW by 2050, of water electrolysis-based hydrogen plants up to 680 GW by 2050 and of hydrogen plants in general to almost 1.4 TW by 2050. More details can be found in **Appendix A.1** and in the model database. In the transport sector, the constraint is applied to the deployment of hybrid, plug-in hybrid and full-electric road vehicles; to hydrogen-fueled trains; to LNG, dual fuel (heavy fuel oil and ammonia), ammonia fuel cell, and methanol ships. The saturation target is set to cover the whole transportation demand for each transport mode. Eventually, the mentioned constraint is applied to heat pumps in the building sector, again with a saturation capacity set to cover their whole water heating/space heating/space cooling demand.

The methodology in [79] is applied at the global level. Still, the time scale is focused on Europe, thus **Figure 5** shows the prescribed maximum capacity development constraints for electricity generation technologies in TEMOA-Europe. It has to be remarked that they represent maximum constraints, therefore the evolution of the electricity sector after 2020 is not imposed, but each technology group has to stay below the prescribed threshold. Among the different trajectories shown in **Figure 5**, nuclear fission deserves special attention, with its capacity reaching a maximum of 80 GW_e by 2050, thus decreasing with respect to the current level of around 116 GW_e. Such result is indeed in line with the recent policies considering phase-out or limits to nuclear fission capacity installations, e.g., in Germany [81] and Spain [82].

Concerning electricity imports, the possible expansions to the interconnections between Europe and neighboring countries are limited considering 7 projects (either in permitting or planned or under consideration as from [84]) to expand electricity interconnections for a total of more than 7 GW_e.

In TEMOA-Europe, several technologies belong to every technology group, and details for their classification are provided in the *TechGroupWeight* table in the database [12]. The constraints are instead applied using the *MaxCapacityGroup* table, while *MaxActivityGroup* is used to replicate the actual electricity generation between 2010 and 2020.

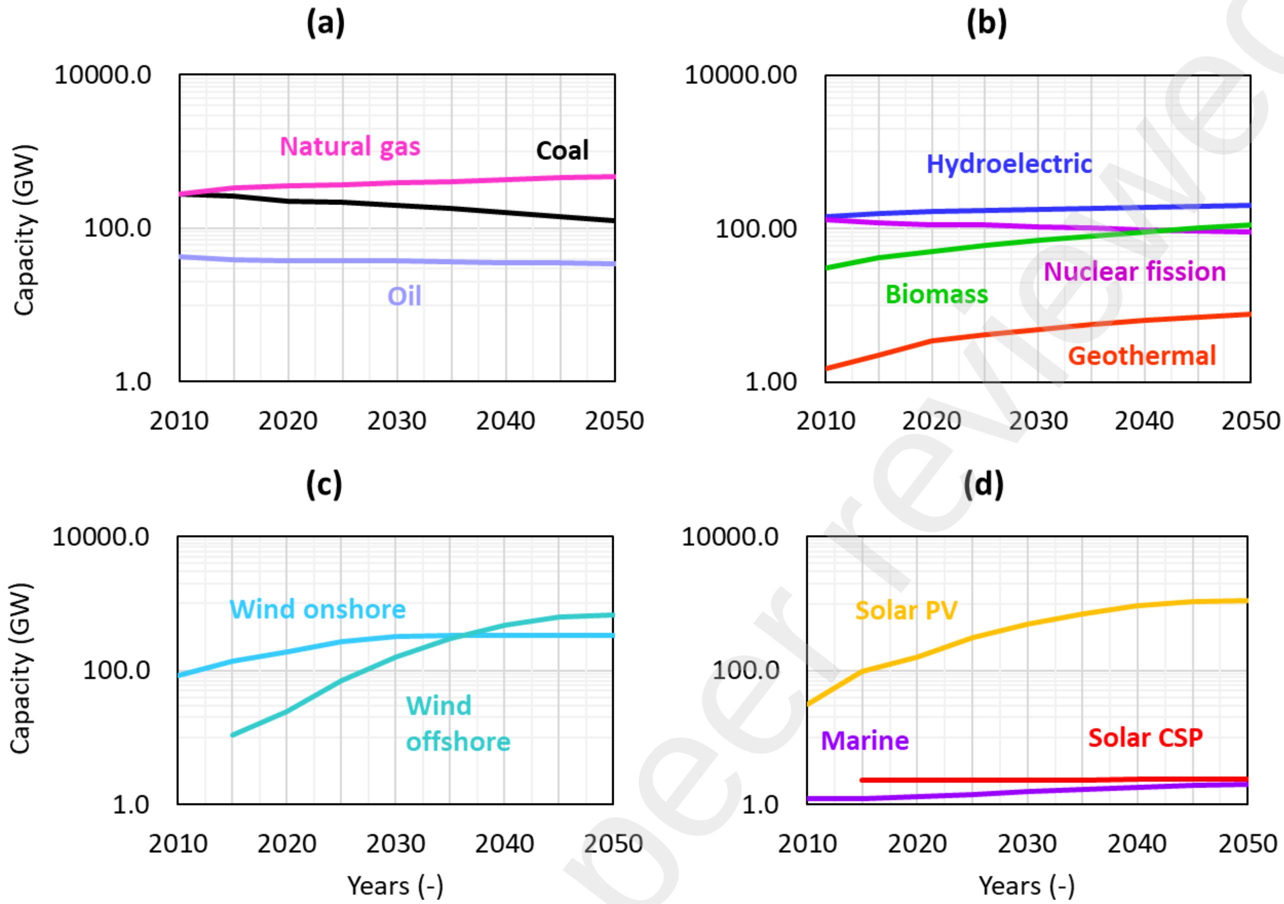

Figure 5. *Maximum installed capacity constraints for a) natural gas (ELC_FOSSIL_NGA_GRP in the TEMOA-Europe database), coal (ELC_FOSSIL_COA_GRP) and oil (ELC_FOSSIL_OIL_GRP) technologies; b) hydropower (ELC_HYD_GEN_GRP and ELC_HYD_PUM_GRP), biomass (ELC_BIO_GRP), nuclear fission (ELC_NUC_FIS_GRP) and geothermal (ELC_GEO_GRP) technologies; c) wind (ELC_WIN_ON_GRP and ELC_WIN_OFF_GRP) technologies; d) solar (ELC_SOL_PV_GRP and ELC_SOL_CSP_GRP) and marine (ELC_MAR_GRP) energy technologies.*

3. Results and discussion

The presented results will cover the GHG emissions trajectory to get to NZE by 2050, the primary energy supply mix and the composition of the electricity generation sector for the scenario considering all the features and founding hypotheses explained in **Section 2**[3]. Even though the impact of gas price on the evaluation of industrial demands for the pulp and paper, chemicals and non-metallic minerals subsectors in **Section 2.3** is non-negligible, a meaningful impact on the overall energy system is not obtained, thus the results are only shown for the "deterministic demands run" and further investigations will be performed to assess the impact of price-elasticity on the other sectors of the energy system.

[3] TEMOA-Europe is an integrated demand-supply model, so that the mentioned results also involve optimizing the energy consumption sectors in terms of technology and fuel mix. This will not be extensively addressed in the present work.

As mentioned in the **Introduction**, some results are also benchmarked against IEA statistics for historical periods and compared to IEA scenarios for future projections. Concerning the former, the adoption of equality constraints is necessary but not sufficient to guarantee matching past values. Indeed, the quality of data associated to the construction of the RES and demand projection has a large role, as the model works in perfect foresight even during historical periods (in this case, 2010, 2015 and 2020).

In particular, since the IEA does not provide regional insights for the NZE scenario, which would be directly comparable to the outcome of this work, the Announced Pledges Scenario (APS) is chosen here as a baseline for the comparison. Indeed, at least the EU already has plans for a full decarbonization of its energy system, making the APS quite close to a NZE scenario. Nonetheless, the regional focus of the IEA for Europe considers a different spatial scale than the OECD Europe examined here. Specifically, the results from TEMOA-Europe are compared against IEA scenario projections for "Europe" – which includes OECD Europe plus Albania, Andorra, Belarus, Bosnia and Herzegovina, Bulgaria, Cyprus Croatia, Kosovo, Moldova, Montenegro, North Macedonia, Romania, Serbia, Turkey and Ukraine – and the EU-27. For this reason, TEMOA-Europe results are expected to be in between those for OECD Europe and the EU-27 in most of the cases, while possibly more conservative in some others due to the imposed decarbonization constraint.

3.1. Greenhouse gases emissions

Figure 6 shows the trajectory for CO_2 emissions in the scenario considered in this work. Despite CO_2 has the lowest GWP-100 among the three GHGs (i.e., 1), it represents the largest contribution to CO_2 equivalent. Indeed, the CO_2 and $CO_{2\ eq}$ trajectories in **Figure 6** are basically indistinguishable. CO_2 emissions for the different sectors almost perfectly retrace IEA statistics [20] as shown in **Figure 6**. The slight differences in the residential and commercial sectors are due to the requirement of matching statistics about the energy consumption by fuel between 2010 and 2020. On the other hand, IEA statistics do not provide information concerning the upstream sector, which has an almost negligible contribution between 2010 and 2020 (< 4%). Concerning the industrial sector, IEA statistics only provide data for direct emissions, while process emissions are also taken into account in TEMOA-Europe and represent the reason for a difference around 5% with respect to the historical data points.

Concerning the general decrease after 2020, most of the demand sectors can be fully decarbonized by 2050 (see **Figure 6**, and mainly the focus on the 2040-2050 period). Industrial emissions decline by almost 60% in 2050 with respect to 2020 values, making industry the hardest-to-abate sector. As the power sector is the only one to allow negative emissions thanks to the presence of biomass-based plants equipped with CCS (which are necessary to guarantee the feasibility of the model to respect the imposed constraint on $CO_{2\ eq}$), CO_2 emissions from power generation decrease by more than 130% in 2050 with respect to 2020. All in all, the contribution of negative emissions in the electricity sector and removals due to afforestation measures allow to reach a net-zero CO_2 emissions balance by 2050.

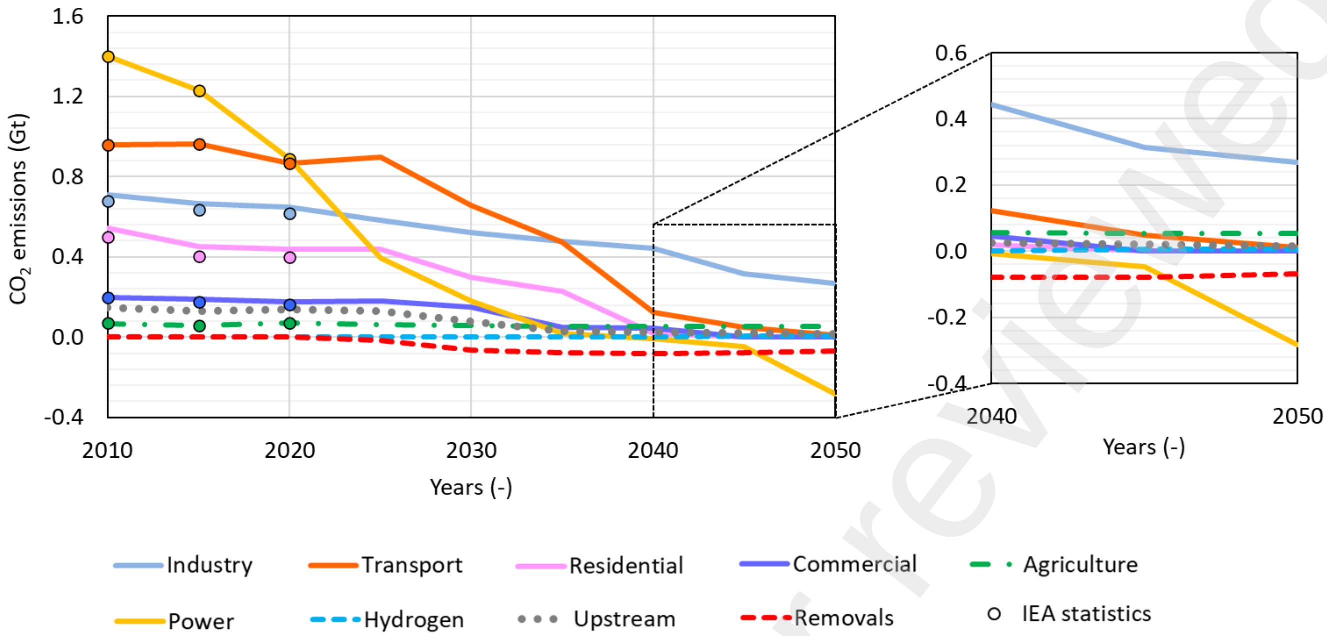

Figure 6. *CO_2 equivalent emissions trajectory by sector.*

Figure 7 highlights the negligible contribution of CH_4 and N_2O to the total amount of GHGs throughout the model time scale. The sum of the values in **Figure 7** and the contribution from CO_2 in **Figure 8a** for the examined scenario (considering, among others, limits for nuclear capacity and constraints for the development of CCS-equipped plants but also renewable capacity) show how net-zero emissions can be met by 2050, despite a negligible deviation from the imposed value. Nonetheless, a decarbonization scenario considering a focus on CO_2 alone would possibly depict a different evolution than the one presented here, as reducing CO_2 emissions may lead to an increase in CH_4 and/or N_2O due to the use of, e.g., biomass as fuel (as already mentioned in **Section 2.4.1**).

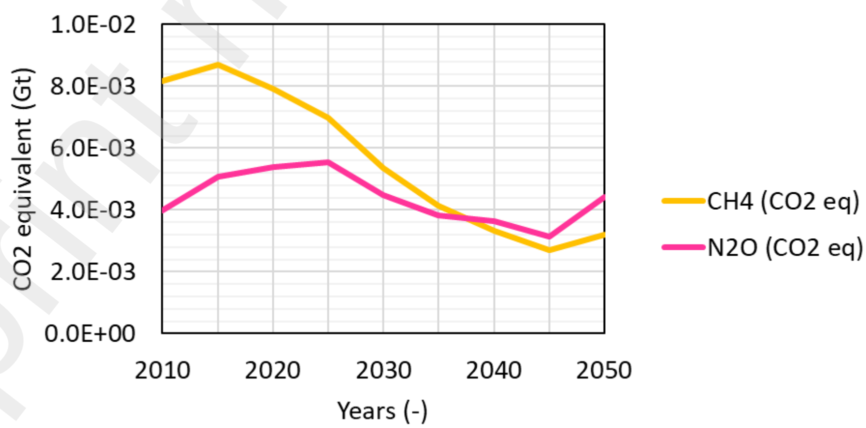

Figure 7. *Total emissions trajectory for CH_4 and N_2O.*

Figure 8 also reports the comparison of TEMOA-Europe results concerning the whole energy system (see **Figure 8a**), final consumption sectors (industry, transport, buildings and agriculture; see **Figure 8b**) and the power sector (see **Figure 8c)** against the IEA APS. In 2030, TEMOA-Europe results fall between the outcomes for Europe and the EU-27 provided in WEO 2023 for the whole energy system and final consumption sectors. On the other hand, the projections for the decarbonization of the power sector in TEMOA-Europe appear more ambitious in 2030 and 2050. In particular, while ~250 Mt can be captured thanks to biomass plants equipped with CCS in TEMOA-Europe, just 5 Mt are removed in the APS in EU-27. When considering Europe, the power sector emissions are still above 60 Mt in 2050. Such results indicate that TEMOA-Europe overestimates the potential contribution of biomass plants equipped with CCS with respect to IEA's expectations, while underestimating potential reductions in end-use sectors. All in all, the IEA APS results align with the TEMOA-Europe results concerning CO_2 emissions, indicating how announced pledges in Europe would be sufficient to get close to the NZE target if ultimately met.

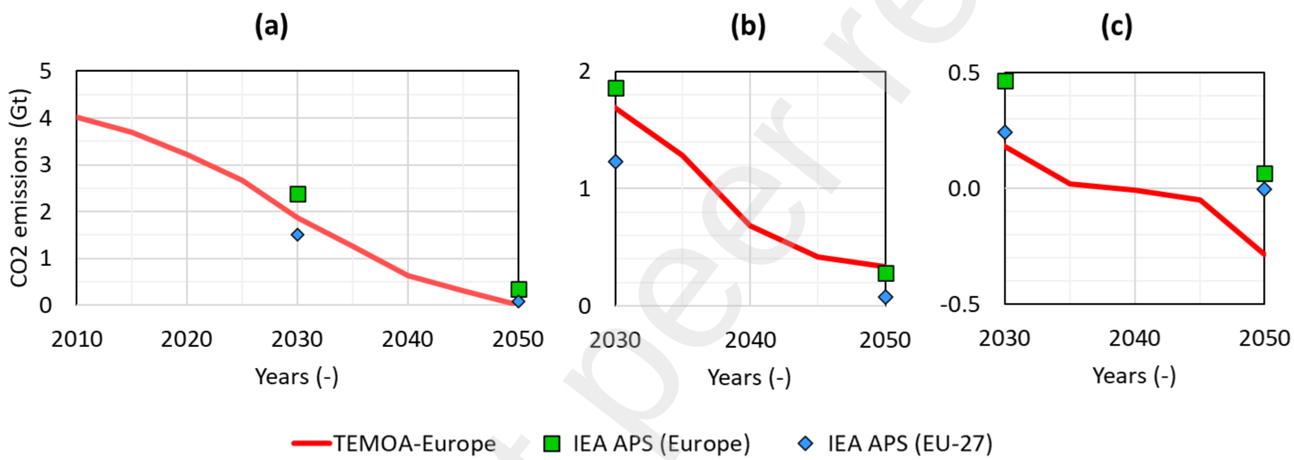

Figure 8. *CO2 emissions trajectory for a) the whole energy system, b) final consumption sectors and c) the power sector as computed by TEMOA-Europe and compared to the IEA APS scenario results for Europe and the EU-27.*

3.2. Total primary energy supply

Figure 9 highlights how a NZE by 2050-compliant scenario should envisage a progressive reduction of the reliance on fossil fuels already starting from 2025, with a decrease in TPES even with respect to 2020, when the implications of the COVID pandemic strongly hit energy consumption. Indeed, TPES is reduced from the 71 PJ computed in 2020 to 54 EJ in 2050. Renewable sources alone contribute to more than 60% of TPES by mid-century (against almost 19% in 2020) with 35 EJ, leading to a system dominated by clean sources (78% when also including nuclear energy). While oil and gas represent remarkable sources even in 2050 with slightly more than 5 EJ each, the increase in the adoption of solar-based technologies alone (especially in the electricity generation sector, but also in the buildings sector for space and water heating purposes) lead to more than 7 EJ in 2050 (5× with respect to 2020). On the other hand, the contribution of wind energy, mainly driven by the increase in offshore electricity capacity, reaches almost 16 EJ by 2050, becoming the dominant source and representing the 30% of total TPES.

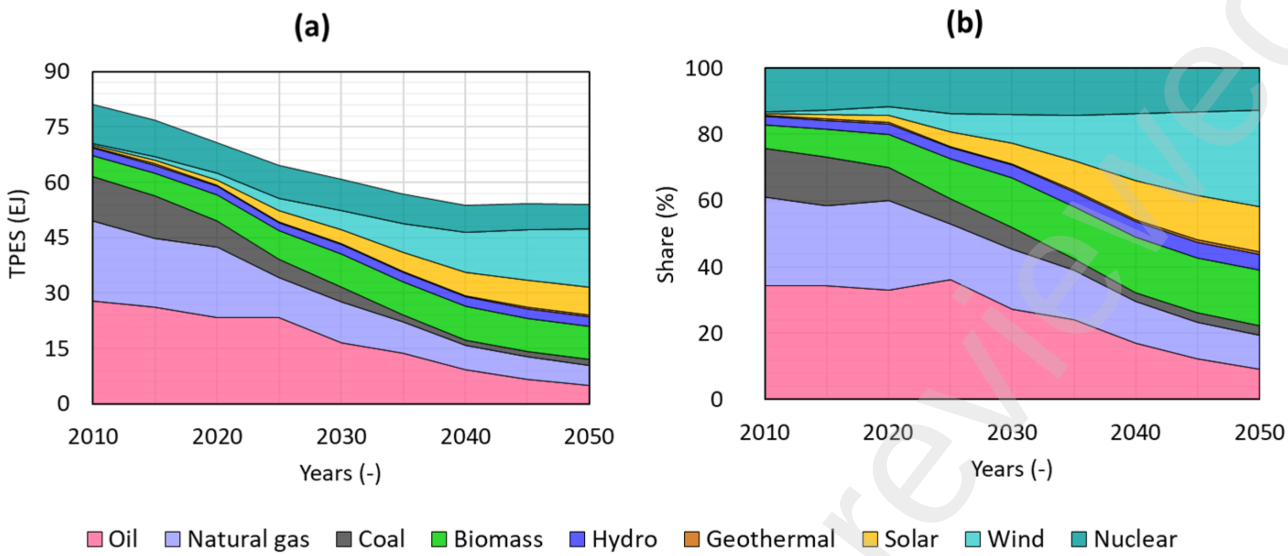

Figure 9. *Total primary energy supply in OECD Europe from 2010 to 2050.*

Figure 10 highlights how the RES built for TEMOA-Europe and its demand projection make it possible to match past trends. While it can perfectly retrace values for gas (see **Figure 10a**), coal (see **Figure 10b**) and oil (see **Figure 10c**), an almost negligible underestimation (~0.1%) is performed for the category "solar, wind and other" (see **Figure 10d**). On the other hand, nuclear energy contribution is overestimated by around 5% in 2010 and 2015 and 7.5% in 2020, though this allows for matching actual electricity production between 2010 and 2020.

Note also that the TEMOA-Europe scenario projections in **Figure 11** are in between IEA results for the APS. However, a reduction in TPES by around 20% between 2030 and 2050 is accounted for in the IEA scenarios, while TEMOA-Europe computes more pessimistic results (-11%). The outcomes for the penetration of renewable sources in the energy supply mix also observe a remarkably growing trend to get a minimum 65% share in TEMOA-Europe and IEA Europe, while IEA EU-27 accounts for a 70% renewable contribution.

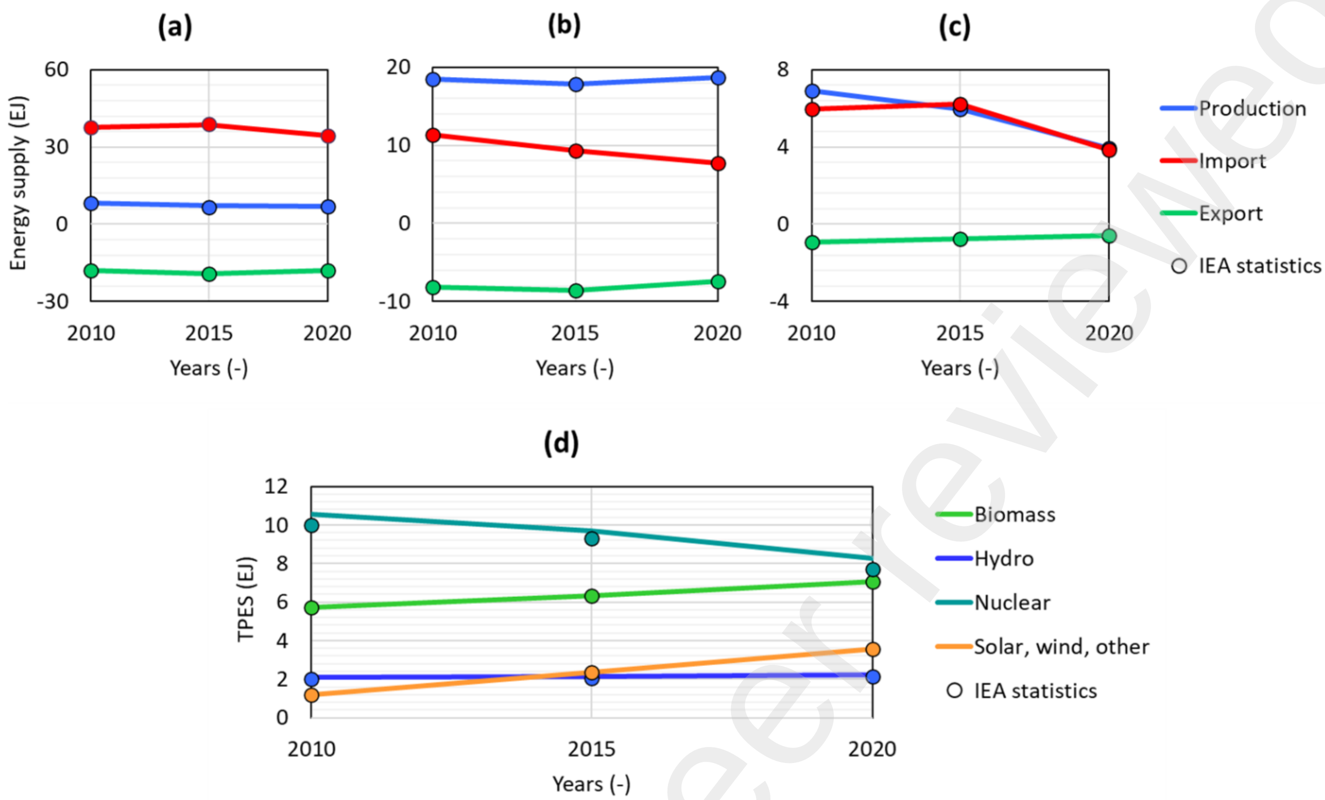

Figure 10. *Comparison between TEMOA-Europe results and IEA statistics for a) gas, b) coal and c) oil inland production, import and export; d) TPES for biomass, hydroelectric, nuclear, solar wind and other renewable sources.*

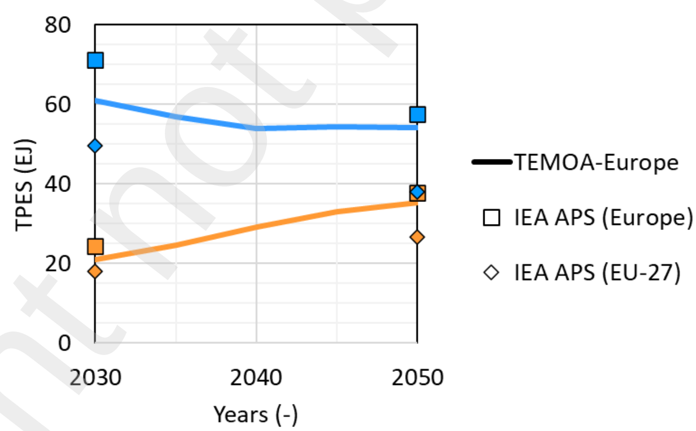

Figure 11. *Comparison between TEMOA-Europe results and the IEA APS scenario concerning TPES and TPES share obtained from renewable sources.*

3.3. Electricity generation

At a first glance, the evolution of the electricity generation sector reported in **Figure 12b** for the scenario considered in this work shows a 110% increase in electricity generation by 2050 with respect to 2020 levels (+4000 TWh). The historical data perfectly match IEA statistics [20] in terms of total generation and generation by source, as visible in **Figure 12a**. TEMOA-Europe depicts a smooth transition towards a cleaner electricity generation sector – anticipated by the CO_2 emission trajectory in **Figure 6** – allowing an almost complete phase out of unabated fossil plants by 2030. In that time period, unabated fossil generation accounts for just 190 TWh, corresponding to a 5% contribution compared to 34% in 2020. Traditional fossil plants are fully phased out only after 2040, while fossil-based CCS-equipped plants are not considered cost-effective and do not appear on the radar of electricity production. On the other hand, CCS-equipped biomass plants get a space starting from 2030 and contribute to slightly less than 4% of total generation by 2050. Renewable sources produce more than 6000 TWh by 2050 and represent nearly 80% of the total generation. To give some terms of comparison, such value is almost the double of the total electricity production reckoned in OECD-Europe in 2020. In particular, solar PV electricity increases by more than 9 times compared with 2020 levels, reaching more than 1400 TWh. Wind generation experiences the same increase, mainly driven by offshore wind (from 72 TWh in 2020 to 3400 TWh in 2050). The combined contribution of wind technologies reaches nearly 4400 TWh by 2050. Nuclear generation is strongly influenced by the progressive phase-out put in place, as shown in **Figure 5**, imposing a capacity reduction of at least 26% by 2050. However, nuclear generation is reduced by just 9% due to the adoption of more efficient fission plants falling in the European Pressurized Reactors (EPR) category and reaching an installed capacity of almost 70 GW_e.

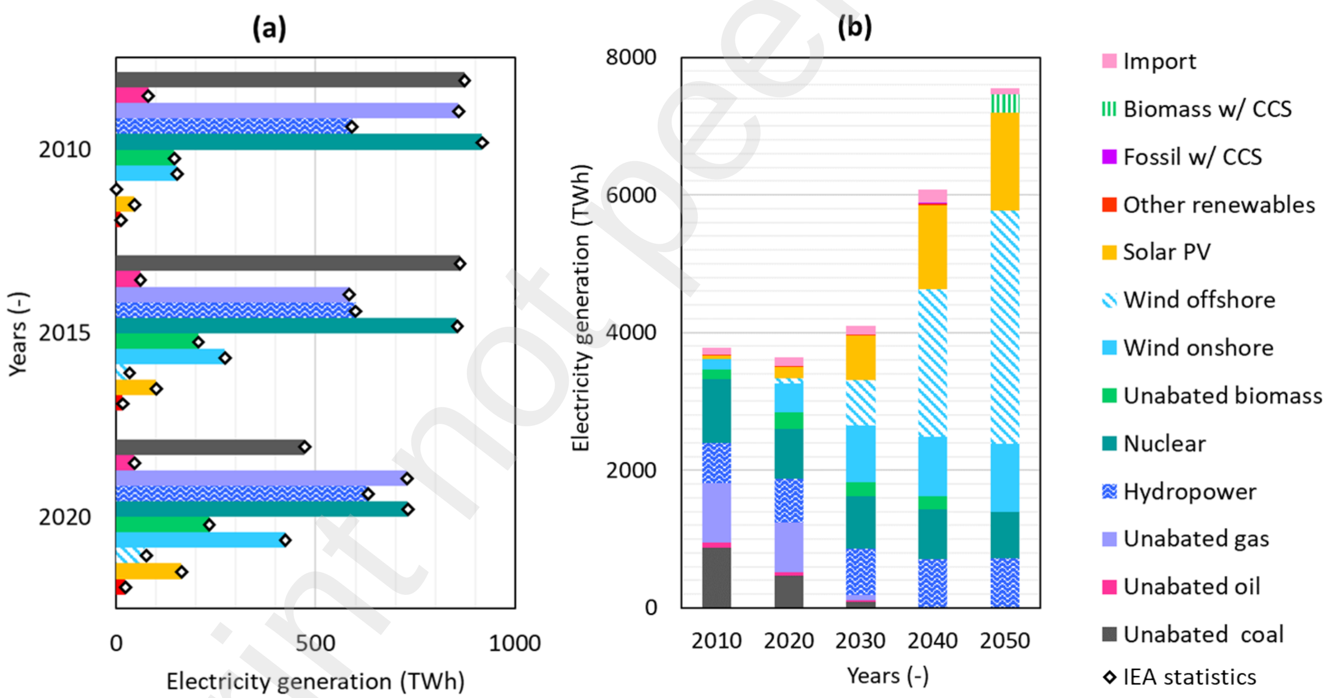

Figure 12. Computed electricity generation mix for OECD Europe from 2010 to 2050 ("other renewables" include geothermal, solar CSP and wave and tidal electricity generation).

Figure 13 compares TEMOA-Europe and the IEA APS results concerning the electricity generation sector. In this case, several differences can be noted. Starting from the total generation in **Figure 13a**, it is evident how TEMOA-Europe computes a similar value to the one estimated for the whole Europe.

The IEA envisages the almost complete phase-out of unabated coal and gas generation by 2050 (see **Figure 13b** and **Figure 13c**, respectively) in the EU-27 and Europe, and the same happens in TEMOA-

Europe, although it envisages a faster phase-out than the IEA, as visible from the figures computed for 2030.

The results from TEMOA-Europe regarding nuclear generation in **Figure 13d** are strongly influenced by the imposed constraint envisaging its progressive capacity reduction, which is not taken into account by the IEA. Indeed, the APS scenario shows an 8% increase between 2030 and 2050 in Europe, while an almost negligible decrease in the EU-27.

Concerning solar PV generation, TEMOA-Europe computes very close values to those estimated by the IEA APS for the EU-27, while PV generation for Europe is more than 20% higher. The point of major disagreement between the results of TEMOA-Europe and the IEA APS scenarios is about wind generation. In TEMOA-Europe, the contribution of wind to total electricity production in 2050 is the largest one, with an increase by almost 3 times between 2030 and 2050. On the other hand, the IEA expects wind generation to slightly more than double from 2030 to 2050 in Europe and the EU-27 scenarios, contributing to almost 50% of total electricity production by 2050 (against 60% in TEMOA-Europe).

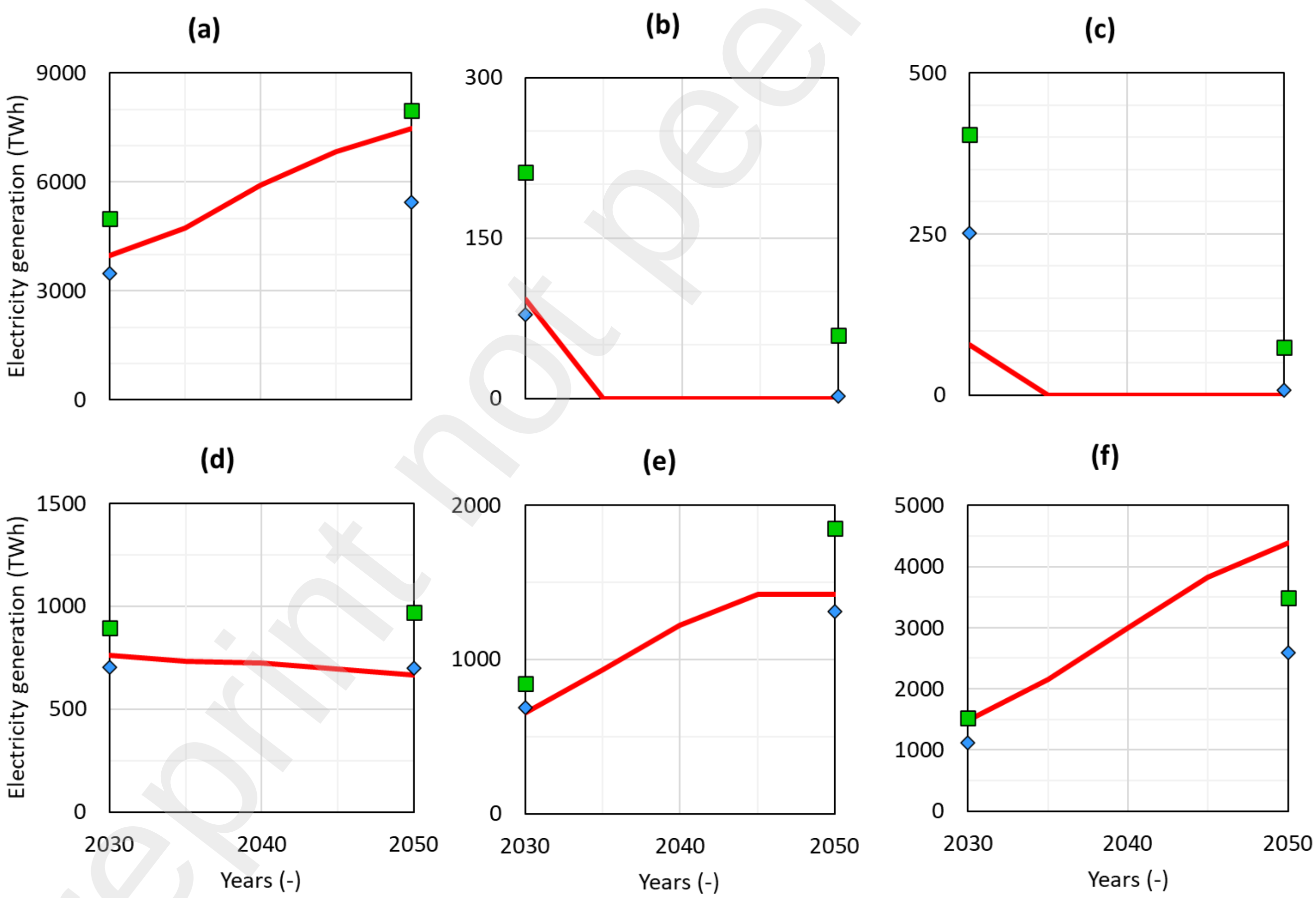

Figure 13. Comparison between TEMOA-Europe results and the IEA APS scenario concerning the electricity generation mix, and specifically a) total generation (excluding imports), b) unabated coal, c) unabated natural gas, d) nuclear, e) solar PV and f) wind.

4. Conclusions and future perspectives

The pressing issue of climate change and the fast-changing economic and geopolitical dynamics require decision-makers to anticipate and shape possible future outcomes under various scenarios considering resource availability and pricing, technology innovation, demand growth, and new energy and environmental strategies.

In the framework of the development of climate change mitigation and energy security issues to ease fast and effective decarbonization of the economy, energy system optimization models are key tools to drive investment choices and policy measures. Indeed, they include detailed, bottom-up technology specifications and adopt linear programming techniques to minimize the system-wide cost of energy provision and use by optimizing the installation of energy technology capacity and its utilization.

Nonetheless, the typical tendency of working with energy system models is to rely on proprietary frameworks based on hardly accessible databases that do not guarantee full transparency of the results. Open-database and open-code partial equilibrium ESOMs – like TEMOA – allow to improve the reliability and transparency of such tools and their results, increasing their policy relevance.

This work aims to present TEMOA-Europe, the first open-database and open-software model instance for energy system analysis concerning the European continent, and specifically OECD Europe. The examined time scale is compliant with the assessment of targets of the European Union to make Europe the first carbon-neutral continent by 2050.

TEMOA-Europe envisages a large portfolio of more than 1000 well-established and innovative supply and end-use technologies, providing a very high level of disaggregation and considering some technological options that are not included in any other energy system model instance [11]. This paper reviews all the constraints adopted in the model for the 1) definition of environmental targets, 2) future availability of energy resources, with particular reference to fossil fuels, and 3) trajectories for adopting crucial technologies.

TEMOA-Europe results are presented in this work for a representative scenario envisaging the progressive reduction of energy imports from Russia, which are completely banned starting from 2030, while net-zero emissions by 2050 are imposed as a mandatory objective. Moreover, an attempt to consider the elasticity of the demand to natural gas price in three industrial subsectors was carried out for this work, showing how considering the impact of increasing price gas has a non-negligible impact on the demand in the chemicals, non-metallic minerals and pulp and paper production sectors, though not impacting on the overall energy system.

First, all the results shown in this work concerning historical periods (i.e., 2010, 2015 and 2020) are compared against IEA statistics for OECD Europe (when available). In this sense, TEMOA-Europe is able to reproduce such a dataset with a very high accuracy. Moreover, the outcomes of the model for the representative scenario are compared to the available projections by the acknowledged WEO 2023 by the IEA [18], showing in general large accordance (except for the electricity generation sector, where TEMOA-Europe largely overestimates wind generation). However, the IEA does not provide specific results for a NZE trajectory for Europe, and the results are benchmarked against the so-called "Announced Pledges Scenario". This work, therefore, is the first to present projections for a European NZE trajectory, in addition to the fact that the TEMOA-Europe database is fully open and available online, allowing easy third-party verification.

TEMOA-Europe is able to compute GHG emissions (including CO_2, CH_4 and N_2O) originating from the energy sector and combined through their GWP over 100 years to return an emission reduction trajectory for the different sectors of the energy system (upstream, power generation, hydrogen generation, transport, industry, residential, commercial, agriculture). The other results shown here include trajectories for TPES until 2050, which gets to almost 50 EJ and is dominated by renewable sources, accounting for over 60% (against just 18% in 2020). A NZE by 2050-compliant pathway for the development of the electricity generation system is also presented here, highlighting the large role of renewable installations against the complete phase-out of unabated fossil fuels before 2040.

Nonetheless, the single scenario presented in this work primarily shows the high level of detail of long-term analyses that can be performed through TEMOA-Europe. In perspective, there is plenty of room for insights concerning improvements in the methodology and practical applications of the model.

First, a detailed analysis of all the stated policies for realizing the European Green Deal and the climate-neutrality target will be implemented and tested in the model to assess their feasibility and effectiveness. In addition, the role of nuclear energy, which is strongly penalized in this work due to a forced phase-out (a consequence of the historical trend experienced in Europe so far), should be assessed. That could be important in the context of the economic analysis of the pathways for the development of the energy system in a decarbonization context, with particular regard to the cost of electricity and the profitability of new electricity generation projects.

On the other hand, the TEMOA formulation shall still benefit from a continuous update to improve the capabilities to represent the technical features of energy technologies, giving, for instance, the possibility to directly act on specific technology shares within groups instead of setting absolute values for maximum capacities/activities. Moreover, the dual formulation of its optimization problem will be exploited to endogenously assess the role of price-elastic demands and their effects on long-term energy system pathways. An extended TEMOA formulation for the endogenization of the capacity deployment constraints adopted in this paper to present realistic future scenarios and let costs decrease by the effect of growing reliance on the specific technology instead of just elapsed time is also in preparation.

CRediT author statement

Daniele Lerede: Conceptualization; Methodology; Software; Validation; Formal analysis; Investigation; Data Curation; Writing – Original Draft; Writing – Review & Editing; Visualization.

Valeria Di Cosmo: Conceptualization; Resources; Writing – Review & Editing; Supervision; Project administration; Funding acquisition.

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A.1. Appendix: Summary of assumptions and constraints

The categories of service demands that must be satisfied in TEMOA-Europe, along with their units of measurement and drivers to be used in **Equation Error! Reference source not found.** to project them throughout the model time scale (see **Figure 3**), are listed in **Table 4**. The specific driver and the related elasticity values for each time period and each demand commodity, as well as the base year demand levels, instead, are reported in the database of the model in the tables *Driver, Elasticity* and *Demand*, respectively; demand commodities are associated to the respective driver through the table *Allocation*. **Equation Error! Reference source not found.** is the adopted in the TEMOA-Europe preprocessing file, purposedly developed for the TEMOA models instances developed within the MAHTEP Group at Politecnico di Torino and used to automatically compute demands for the entire model time scale instead of specifying all the punctual values of the different service demands.

Table 4. *Categories of service demands and associated drivers in TEMOA-Europe.*

Sector	Service demand	Driver
Agriculture	Agriculture machinery and appliances (PJ)	Value added agricultural sector
	Low-temperature heat (PJ)	Value added agricultural sector
Commercial	Space heating (PJ)	Value added services
	Space cooling (PJ)	Value added services
	Water heating (PJ)	Value added services
	Refrigeration (PJ)	Value added services
	Cooking (PJ)	Value added services
	Lighting (PJ)	Value added services
	Other energy use (PJ)	Value added services
	Office equipment (PJ)	Value added services
Residential	Space heating (PJ)	N. of households
	Space cooling (PJ)	GDP per household
	Water heating (PJ)	Population
	Dish washing (PJ)	GDP per household
	Clothes washing (PJ)	GDP per household
	Clothes drying (PJ)	GDP per household
	Refrigeration (PJ)	GDP per household
	Cooking (PJ)	Population
	Lighting (PJ)	GDP per capita
	Other electric (PJ)	GDP per household
Transport	Cars (Bvkm)	GDP per capita
	Light commercial vehicles (Bvkm)	GDP
	Medium trucks (Bvkm)	GDP
	Heavy trucks (Bvkm)	GDP
	Buses (Bvkm)	GDP per capita
	Two-wheelers (Bvkm)	GDP per capita
	Three-wheelers (Bvkm)	GDP per capita
	Passenger trains (Bpkm)	GDP per capita
	Freight trains (Bfkm)	GDP

	Domestic aviation (Bvkm)	GDP
	Domestic navigation (Bvkm)	GDP
	International navigation (Bvkm)	GDP
	Non-energy use (PJ)	GDP
Industry	Iron and steel (Mt)	Value added iron & steel/non-ferrous metals
	Non-ferrous metals (Mt)	Value added iron & steel/non-ferrous metals
	Chemicals (Mt)	Value added chemicals
	Pulp and paper (Mt)	Value added other energy intensive industries
	Non-metallic minerals (Mt)	Value added other energy intensive industries
	Other industries (PJ)	Value added other industries

Table 5 lists the most innovative, low-carbon technologies included in TEMOA-Europe, along with the sector/subsector they belong to and the starting date for their availability.

***Table 5**. List of selected low-carbon technologies present in the TEMOA-Europe database.*

Sector	Technology	Start
Hydrogen production	Solid biomass steam reforming, centralized	2015
	Solid biomass gasification, decentralized, small	2015
	Solid biomass gasification, centralized, medium	2015
	Ethanol steam reforming, decentralized	2015
	Alkaline electrolyzer (Green WE), decentralized, small	2020
	Alkaline electrolyzer, centralized, large	2020
	Proton exchange membrane (PEM) electrolyzer, decentralized, small	2020
	PEM electrolyzer, centralized, large	2020
	Solid oxide electrolyzer cell (SOEC), decentralized, small	2020
	SOEC, centralized, large	2020
	Anion exchange membrane (AEM) electrolyzer, decentralized, small	2050
	Natural gas steam reforming w/ CCS, centralized, large	2030
	Natural gas steam reforming w/ CCS, centralized, small	2030
	Coal gasification w/ CCS, centralized, large	2030
	Coal gasification w/ CCS, centralized, medium	2030
	Biomass gasification w/ CCS, centralized, medium	2030
Synfuels production	Methane production from centralized underground storage hydrogen and CO_2	2030
	Methane production from centralized tank storage hydrogen and CO_2	2030
	Diesel production from centralized underground storage hydrogen and CO_2	2030
	Diesel production from centralized tank storage hydrogen and CO_2	2030
	Kerosene production from centralized underground storage hydrogen and CO_2	2030
	Kerosene production from centralized tank storage hydrogen and CO_2	2030

	Diesel production from co-electrolysis and CO_2 from emissions	2030
	Kerosene production from co-electrolysis and CO_2 from emissions	2030
	Methanol production from centralized underground storage hydrogen and CO_2	2030
	Methanol production from centralized tank storage hydrogen and CO_2	2030
	Methanol production from co-electrolysis using CO_2 from emissions	2030
Electricity generation (coal)	IGCC with CO_2 removal from input gas	2030
	IGCC with CO_2 removal from flue gas	2030
	Conventional pulverized coal with CO_2 removal from flue gas	2030
Electricity generation (natural gas)	Combined cycle with CO_2 removal from flue gas	2030
	Solid oxide fuel cell CO_2 removal	2030
Electricity generation (nuclear fission)	European pressurized reactor (EPR)	2020
	Fast reactor	2030
	Advanced breeder reactor	2040
	TRU-fueled accelerator-driven system reactor	2040
	MA-fueled accelerator-driven system reactor	2040
Electricity generation (biomass)	Crop gasification with CCS	2030
	Crop direct combustion with CCS	2030
	Solid biomass gasification with CCS	2030
	Solid biomass direct combustion with CCS	2030
Electricity generation (hydrogen)	PEM Fuel cell	2025
Road transport (cars)	Battery-electric	2010
	Plug-in hybrid	2010
	Fuel cell	2020
Road transport (light commercial vehicles)	Battery-electric	2015
	Plug-in hybrid bus	2020
	Fuel cell	2025
Road transport (bus)	Battery-electric	2015
	Plug-in hybrid	2015
	Fuel cell	2025
Road transport (medium trucks)	Battery-electric	2020
	Plug-in hybrid	2020
	Fuel cell	2025
Road transport (heavy trucks)	Battery-electric	2025
	Plug-in hybrid	2025
	Fuel cell	2025
Non-road transport (domestic aviation)	Liquid hydrogen	2040
Non-road transport (trains)	Gaseous hydrogen	2030
Non-road transport (domestic and international navigation)	Dual fuel	2020
	Methanol	2030
	Liquid hydrogen	2030
	Ammonia fuel cell	2030
Iron and steel industry (steel production)	HIsarna-BOF	2025
	Blast furnace-basic oxygen furnace (BF-BOF)	2030

	Direct reduced iron-electric arc furnace (DRI-EAF) with CCS	2030
	HIsarna-BOF with CCS	2030
	Hydrogen direct reduction-EAF	2030
	Ulcored with CCS	2030
	Ulcolysis	2030
	Ulcowin	2030
	Top-gas recycling BF-BOF with CCS	2040
Non-ferrous metals industry (aluminum production)	Hall-Héroult with inert anodes	2030
	Carbothermic reduction	2050
	Kaolinite reduction	2050
Non-metallic minerals industry (clinker production)	Dry process with post-combustion CCS	2030
	Dry process with oxy-fuel combustion CCS	2030
Non-metallic minerals industry (cement production)	Alkali-activated cement-based binders	2030
	Belite cement	2030
Chemical industry (High value chemicals production)	Naphtha catalytic cracking	2020
	Bioethanol dehydration	2020
Chemical industry (ammonia production)	Synthesis via electrolysis	2025
	Biomass gasification	2025
	Natural gas steam reforming (SR) with CCS	2025
CO_2 Sequestration	Afforestation	2010
	Enhanced oil Recovery (onshore)	2030
	Enhanced oil Recovery (offshore)	2030
	Depleted oil fields (onshore)	2030
	Depleted oil fields (offshore)	2030
	Depleted gas fields (offshore)	2030
	Enhanced Coalbed Methane recovery < 1000 m	2030
	Enhanced Coalbed Meth recovery > 1000 m	2030
	Deep saline aquifers (onshore)	2030
	Deep saline aquifers (offshore)	2030
	Deep ocean	2030
	Direct air capture with chemical absorption	2030

Table 6 reports a summary of the constraints implemented in TEMOA-Europe concerning the maximum inland production for fossil fuels, their maximum imported and exported quantities, in addition to the maximum exploitable renewable potential and the limits for capacity deployment in the electricity and hydrogen generation sectors for 2 milestone years of the model (i.e., 2025 and 2050). **Table 7** provides details concerning the assumptions for natural gas imports from different world regions to substitute Russian gas.

__Table 6.__ Summary of the constraints implemented in TEMOA-Europe.

Category	Subcategory	Additional information	Maximum constraint (2025)	Maximum constraint (2050)
Fossil fuels inland production	Oil (EJ)	Crude oil (-5% / 5 years)	5.9	4.6
		Oil products (-5% / 5 years)	6.5	5.0
	Coal (EJ)	Hard coal (-20% / 5 years)	1.2	0.4
		Brown coal (-10% / 5 years)	2.2	1.3
	Natural gas (EJ)	(-10% / 5 years)	6.9	4.1
Fossil fuel imports	Oil	From Russia	0 Mtoe starting from 2025	
		From other countries	+100% from 2025 wrt 2020	
	Coal	From Russia	0 Mt starting from 2025	
		From other countries	Maximum levels as in 2020	
	Natural gas		see **Table 7**.	
Fossil fuel exports	Oil		30% of imports + exports	
	Coal		10% of imports + exports	
	Natural gas		30% of imports + exports	
Renewable potentials	Solar	PV (EJ)	29000	
		CSP (EJ)	1800	
		Thermal (GW_{th})	340	
	Wind (EJ)	Onshore	150	
		Offshore	100	
	Biomass (PJ)	Starch crops	243	285
		Sugar crops	743	995
		Grass crops	1652	1668
		Rapeseed	810	1033
		Industrial waste/sludge	31	54
		Wood products	3047	2985
		Municipal waste	518	759
		Biogas	1234	1266
		Liquid biofuels	71	56
	Geothermal (EJ)		1.8	4
Capacity deployment	Electricity generation (GW_e)	Oil	38	35
		Coal	220	125
		Gas	370	475
		Hydroelectric	190	200
		Nuclear fission	111	90
		Biomass	60	110
		Geothermal	4.2	7.8

		Wind onshore	270	330
		Wind offshore	56	680
		Solar PV	310	1130
		Solar CSP	2.3	2.4
		Marine	1.4	2.0
		Battery storage	38	600
		Fossil w/ CCS	0	45
		Biomass w/ CCS	0	45
		Nuclear fission (IV generation)	0	45 (fast reactors) 1.2 (ADS TRU, ADS MA, ABWR)
	Hydrogen generation (GW)	Total	7.5	1400
		Electrolysis	3.7	680
		Fossil w/ CCS	0	270

Table 7. *Constraints on imports of natural gas via pipeline and LNG in TEMOA-Europe.*

Commodity	Import region	2020 import (EJ/year)	Maximum import (EJ/year)	Motivation
Pipeline gas	Africa	1.41 [83]	2.78 (starting 2030)	Maximum current pipeline capacity [83]
	Central Asia (Azerbaijan)	0.281 [83]	0.703 (starting 2030)	EU-Azerbaijan agreement [67]
	Middle East Asia (Israel)	0.00 [83]	0.387 (2030) → 0.703 (2050)	EastMed-Poseidon project [66]
	Russia	13.7 [83]	0 (2027)	REPowerEU [8]
LNG	Africa	1.010 [84]	2.000	Own assumption
	Latin America	0.182 [84]	0.182	-
	Middle East Asia	0.989 [84]	1.360 (starting 2030)	Long-term agreements with Qatar (Eni, TotalEnergies, Shell) [68], [69]
	Russia	0.568 [84]	0 (2025)	REPowerEU [8]
	USA	0.835 [84]	2.590 (starting 2030)	EU-USA agreement [66]