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Research Paper

Enhancing energy transition with open-source regional energy system optimization models: TEMOA-Piedmont

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A R T I C L E I N F O

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A B S T R A C T

This paper describes TEMOA-Piedmont, a model to perform long-term energy planning at regional level for Piedmont (Italy). The model has been developed from scratch within the fully open access TEMOA framework, involving a single spatial region and a time horizon extending from 2011 to 2050. The model introduces the novelty of focusing on a sub-national case study. Despite their potential, regional models are not yet diffuse in the energy programming and policy definition of the countries but are gaining their role and attention in recent years. A regional model enables consideration of local characteristics in production and consumption of energy carriers and helps to spot the barriers and opportunities for energy transition, thereby supporting both national and local policy makers. The methodology adopted for TEMOA-Piedmont in developing each sector of the model varies following the structure of the available data. The benchmark of the model was done comparing the outcomes of the model with the data of the Regional Energy and Environmental Plan and Italian transmission system operator, showing an excellent alignment, with differences limited to a few percent both for the power and demand sectors. At the same time, TEMOA-Piedmont is tested on future scenarios relevant to the peculiarities of the local energy system (local pollution issues and a relevant share of the hydroelectric resource), providing an example of the model policy relevance. Finally, the robustness of the model is tested through illustrative scenarios, and the associated results are presented.

1. Introduction

The energy transition aims to remedy the past impacts and plan a less compromising and more reliable future. Such targets, strongly emphasized also by the United Nations' Sustainable Development Goals (SDG), in particular the seventh, i.e., affordable and clean energy [1], can be addressed through the Energy System Optimization Models (ESOMs). These tools are widely used by academics, decision-makers, and energy planners [2] to examine the long-term implications of decarbonization and neutrality policies and assess the technological and economic requirements [3] of such plans in a cost-optimal configuration.

Open science has advanced energy system modeling by improving access to data and frameworks [4]. Transparency in model assumptions, input data, and output verification is another crucial feature enabled by open models [5]. Another task enhanced thanks to the open-source energy models is the development of the reduced-spatial-scale models. While within The Open-Source Energy Modelling System (OSeMOSYS), models with reduced space scales have been developed, for instance for Pantelleria Island [6] or Turin airport [7], at the moment of writing this paper, the only sub-country models developed within the Tools for Energy Modeling Optimization and Analysis (TEMOA) framework study North Carolina [8] and Pantelleria Island [9] as their case. Given the multi-dimensional nature of the energy transition, which requires collaboration among local, national, and international stakeholders [10], local energy system models offer numerous benefits for its successful implementation.

Intrinsically, the country-level energy models adopt a wholistic approach representing an average of the techno-economic state of the sectors nation-wide. Considering that normally, industries are distributed unevenly on a territory, and that their characteristics vary substantially from region to region, relying only on national models typically leads to overlooking some activities, or final demands. An example could be water-related energy consumption. In fact, missing the electricity needs of these technologies may lead to 40 % underestimation of the electricity demands, as shown in [11]. Another challenge associated with the large-scale models concerns emission sources, sinks and

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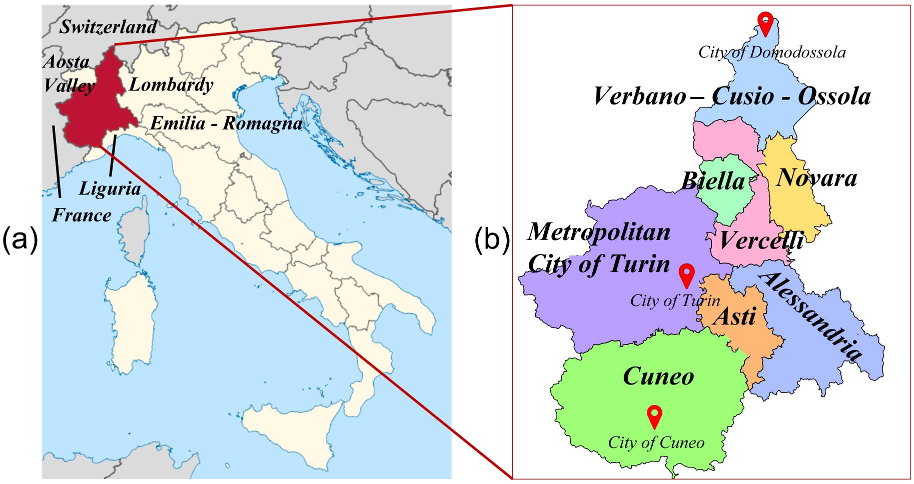

Fig. 1. Piedmont region within Italy (a) and the provincial subdivisions (b) (Note that in this work, the term 'Region' is used to denote two different concepts: one refers to the administrative divisions of Italy (Piedmont Region), and the other refers to the coverage area of a model (region)).

decarbonizing opportunities. Regional emission sources which determine the emission types can vary significantly between zones and may differ substantially from those observed at broader scales. Consequently, providing effective solutions and appropriate action plans even on a national scale requires accurate identification and precise quantification of these region-specific characteristics. Consequently, providing effective solutions and appropriate action plans even on a national scale requires accurate identification and precise quantification of these region-specific characteristics [12].

Of even greater importance are the spatial distribution and productivity of renewable resources, which cannot be effectively captured through national models. This aspect requires particular attention when formulating the energy roadmap. For instance, wind energy potential in Italy varies significantly from south to north. Southern regions possess high wind energy potential, while northern regions are far less productive. Similarly, geothermal resources are exploitable in central regions but are absent in other parts of the country. Therefore, while a resource can contribute substantial shares in a region's energy transition plan, it may remain insignificant at national level or in other regions. This aspect in conjunction with the evolution of the energy systems must be taken into account. The traditional structure, once centralized and limited to conventional power plants, is now transitioning towards decentralization and diversification of the energy mix to better accommodate regional renewable potentials and ensure a more adaptable energy network. In addition to supporting energy policies, accurate recognition of regional needs and assessment of self-sufficiency, facilitates the alignment of the transition with the local conditions and needs [13], thereby enhancing the resilience of the system and overall transition. Addressing these challenges requires more than merely splitting or rescaling national models to sub-national levels because some critical questions regarding the most suitable splitting criteria and rescaling factors may arise. Furthermore, it is necessary to evaluate whether such criteria or factors are uniformly applicable across all sectors and extensible to all regions of a country.

In light of the preceding arguments and the fact that regional energy models are far more accurate than national models in terms of policy planning [12], region-tailored models can facilitate the achievement of national targets by providing supplementary monitoring and solutions. Materializing energy transition requires also transition in the energy system modeling approaches.

In recent years, open science has evolved many scientific disciplines including energy system modeling by increasing access to data and frameworks [4]. Transparency in model assumptions, input data, and output verification is another crucial feature enabled by open models [5]. The development of the reduced-spatial-scale models is enhanced thanks to open-source energy models. However, while within The Open-Source Energy Modelling System (OSeMOSYS), models with reduced space scales have been developed, for instance for Pantelleria Island [6] or Turin airport [7], at the moment of writing this paper, the only sub-country models developed within the Tools for Energy Modeling Optimization and Analysis (TEMOA) framework study North Carolina [14] and Pantelleria Island [9] as their case.

The objective of this work is to show the potential of open-source models, specifically TEMOA, in bridging the gap between national and regional energy and environmental policies by providing TEMOA-Piedmont model, the first Italian regional ESOM developed in the open-source TEMOA framework [15]. Given its relevance in the Italian context, Piedmont was selected as the case study for the development of the regional model [14]. The choice of TEMOA is due to the successful benchmarking performed through the complex Italian model case study with respect to The Integrated MARKAL-EFOM System (TIMES) Model Generator [16]. In addition, TEMOA implements advanced methodologies such as Monte Carlo analysis, Modeling to Generate Alternatives (MGA), robust optimization [17], and stochastic optimization [18].

Piedmont (see Fig. 1a) lies in the northwest of Italy. It is bordered by Aosta Valley (another Italian region) and Switzerland from the north and shares the western border with France. Other southern and eastern neighbors of the region are the Italian regions of Liguria, Lombardy, and Emilia-Romagna. As evidenced in Fig. 1b, Piedmont is divided into seven provinces plus the Metropolitan City of Turin, which includes also the region's capital. With around 25000 km^2 of surface [19], Piedmont is the second largest region of Italy, giving home to 4.26 million inhabitants [20] in 2021. Almost 70 % of the region's surface is covered by mountains and hills [21], making it the third hydroelectric producer of the country [22]. Piedmont is the historical site of FIAT® automotive company (now Stellantis®). Other major economic sectors of the region are manufacturing, food and agriculture, textile, and electronics. The 136.8B€ GDP of the region in 2021, almost 8 % of the country's, took the fifth place among the Italian regions [23]. After the COVID crisis, the regional GDP, in line with the national trend is increasing [24].

TEMOA-Piedmont is the first open-source open-data energy optimization model of the Piedmont Region, as mentioned, a highly industrialized and densely populated area of Italy. The technological and economic details used for the development of the reference energy system of the model is based on online and fully accessible data. Besides validation, in order to check and challenge the model, two scenarios are developed and studied. The chosen scenarios, taken from the Regional plans, focus on the decarbonization of the transport sector and the

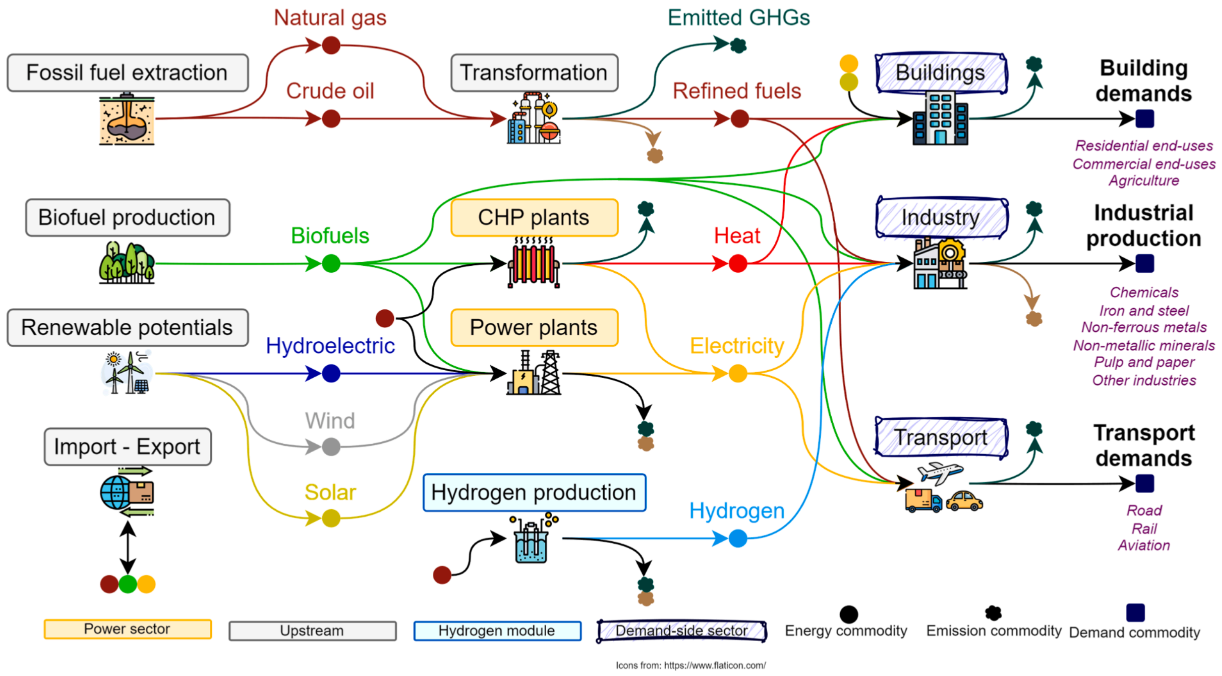

Fig. 2. Scheme of the TEMOA-Piedmont energy system. Energy carriers, represented with ballets flow across different sectors (the arrows) until reaching the final point of the transformation chain meeting a final demand showed in squares. The transformations have their specific emission factors showed with the small clouds.

evolution of the hydroelectric resources.

The paper is structured as follows: Section 2 delivers the presentation of the model, the methodology employed across various phases of sectoral development and the model parameters are outlined in the first eight subsections of Section 2.1. Section 3.2 includes the validation of the model against available data, while the latter part of Section 2 describes the implemented scenarios. Section 3 presents and discusses the outcomes of the analyzed scenarios. Finally, Section 4 concludes the paper by summarizing key lessons learned and suggestions for improving and extending the model.

2. Materials and methods

While a general introduction on the mathematical formulation of ESOMs, including the demand projection, and the detailed list of data sources for the TEMOA-Piedmont model are available in the supplementary material, the sub-sections of Section 2.1 is fully dedicated to the steps taken to develop the model and the studied story lines are outlined in Section 2.2.

2.1. *TEMOA-Piedmont model*

Since ESOMs are data-intensive [25], data collection remains a major challenge, especially for models without prototypes or at sub-national levels. Building a Reference Energy System (RES) requires detailed disaggregated data, often unavailable in the needed format. A simple scheme of the TEMOA-Piedmont energy system is shown in Fig. 2. The starting point for all energy carriers (commodities) in the model is the upstream sector (left part of Fig. 2) that encompasses the extraction, import and transformation of all primary energy vectors and the potentials of renewable energy resources. The commodities, after being 'created' in the upstream, are further consumed in the power sector or in the resting sectors (demand side), either directly or as secondary energy carriers. Consumption or transformation of energy carriers lead to different GHG emissions (CO_2, NO_2, CH_4 or SO_X) according to technology and fuel types. As visible in the Fig. 2, the demand side of the TEMOA-Piedmont includes transport, buildings (incorporating agriculture, commercial and residential sectors) and industry sectors. The transformation of energy carriers concludes with the desired final demand, which can be a service such as car transport or a product such as steel. Further details about the model's sectors will be given in the following. A detailed list of TEMOA-Piedmont sectors, sub-sectors, number of final demands, number of existing and new technologies, and applied drivers per sector is reported in Table 1.

To allocate the energy commodities to sectors and subsectors, where available, regional disaggregated data was used, while in their absence, some assumptions were made to allocate the non-disaggregated ones to the sectors and subsectors. A list of the referred resources for each sector is provided at the beginning of each section and a table containing all of them is provided also in the supplementary material. The TEMOA-Piedmont structure and its most important input parameters are described hereafter.

2.1.1. *The energy balance*

As far as the primary energy vectors are concerned, among the data collected from different resources, those relative to the electricity, taken from the Italian National Transmission Operator (Trasmissione Elettrica Rete Nazionale – TERNA – in Italian) [26] had the highest granularity or level of disaggregation. To allocate the rest of the commodities to sectors and sub-sectors, as mentioned before, additional assumptions were needed. Some of these assumptions were made based on subjective judgments considering the fuel type and the target sector. For example, gasoline was assumed to be consumed just in the transport sector and a similar hypothesis was done for jet kerosene, attributed just to the aviation sector. The share of natural gas in the transport sector was taken from a study done by the Piedmont Region [27]. Table 2 shows the noted values and assumptions made to disaggregate the main energy commodities among the sectors. In the table, the known values are reported without shares (i.e., without percentages inside the cells) while the cells containing percentages show both the final attributed value and the assumed percentage (in brackets) used to split the cumulative quantities. To calibrate the energy balance, a hybrid bottom-up, top-down verification was performed, while the validation of model outcomes is discussed in Section 3.2.

Table 1
Overview of the TEMOA-Piedmont main sectors, sub-sectors, demands, technologies numbers and the demand drivers.

Sectors	Sub-sectors	Commodities	Final demands (n.)	Technologies (n.)		Drivers
				Existing	New	
Upstream	**Extraction**	**Petroleum** **Natural gas**				
	Imports	**Petroleum**				
	Exports	**Natural gas** **Electricity**				
	Transformation (refinery)	**Oil Products**				
Electricity	**Solar, Wind, Natural gas power plants, Biofuel power plants**	**Renewables** **Natural gas**		15	15	
Transport	**Road (passengers and freight), Rail, Aviation, Two and three-wheelers**	**Diesel** **Biodiesel** **Gasoline** **Electricity** **Natural gas** **Jet Kerosene**	9	15	41	GDP
Industry	**Machine drive and steam, Chemicals, Iron and steel, Non-ferrous metals, Non-metallic minerals, Pulp and paper, Other industries, water and energy**	**Electricity** **Natural gas** **Diesel** **Heavy fuel oil** **Oven coke** **Coal** **Blast furnace gas** **Biofuels** **Ethane** **LPG** **Petroleum** **Naphtha** **Heat**	9	83	105	Industrial Sub-sectors Added Value, GDP
Agriculture		**Natural gas** **Electricity** **Diesel** **LPG**	1	1	1	Agriculture Added Value
Residential	**Space heating, Space cooling, Water heating, Refrigeration, Lightening, Dishwashing, Cloth washing, Cloth drying, Cooking, Other electric uses**	**Natural gas** **Electricity** **LPG** **Heavy fuel oil** **Biomass** **Heat** **Diesel** **Solar**	12	53	119	Population
Commercial	**Space heating, Space cooling, Water heating, Refrigeration, Lightening, Dishwashing, Cooking, Other electric uses**	**Natural gas** **Electricity** **LPG** **Heavy fuel oil** **Biomass** **Heat** **Diesel**	7	31	56	Commercial Added Value

Table 2
The main energy vectors (PJ) present in the sectors in the base year and the splitting shares (noted values are given without percentages and estimated ones have their shares inside brackets).

	Residential	Commercial	Agriculture	Industry	Power	Transport
Electricity	17.90	20.53	1.17	47.38		4.60
Natural Gas	*72.72* *(49 %)*	*43.63* *(29 %)*	*29.09* *(19 %)*	43.42	115.22	*0.92* *(3 %)*
Diesel	*2.06* *(50 %)*	*0.66* *(30 %)*	*6.02* *(20 %)*	1.79		81.86
LPG	*3.92* *(70 %)*	*0.56* *(10 %)*	*0.56* *(10 %)*	*0.56* *(10 %)*		3.96
Heavy Fuel Oil	*0.37* *(10 %)*	*0.37* *(10 %)*		*2.98* *(80 %)*		
Gasoline						*30.09* *(100 %)*
Jet Kerosene						*2.22* *(100 %)*

2.1.2. The time horizon

Figuratively the time scale of the ESOMs can be considered as having a horizontal and a vertical dimension: the horizontal dimension indicates the time horizon of the model while the vertical one points to the intra-annual time resolution of the model and could comprise seasonal, monthly, and daily dimensions.

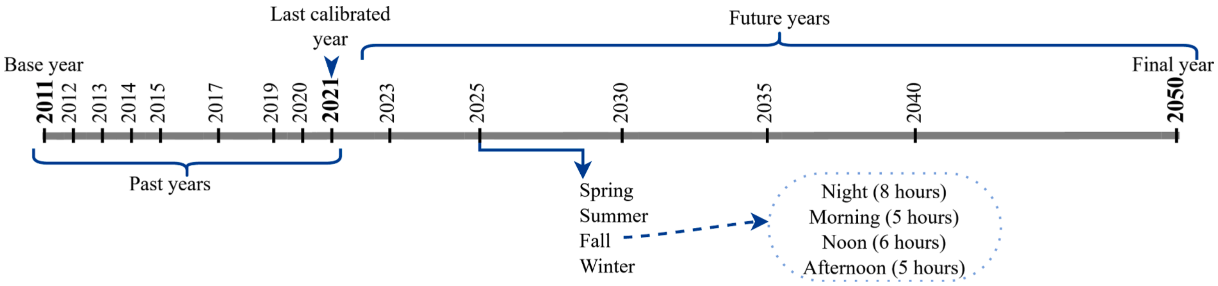

Fig. 3. TEMOA-Piedmont milestone years and typical time slices.

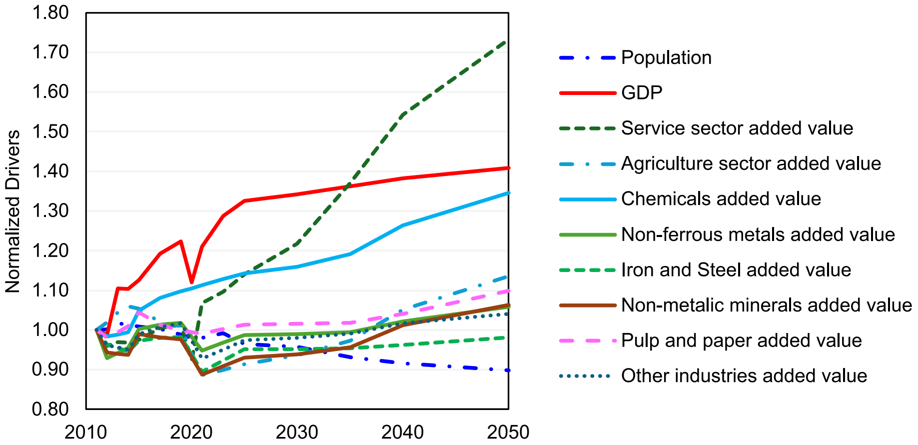

Fig. 4. Historic states and future projections of the drivers of the model, normalized with respect to the 2011 value.

The starting year, more commonly referred to as the "base year", of TEMOA-Piedmont is 2011. Besides data availability, the choice of the base year was also in a way to include some past years which are used to calibrate the model following the historical data (up to 2021). This helped us to check the behavior of the model whit respect to the known trends. The model extends until 2050 and is divided into 15 milestone years as shown in Fig. 3. The choice of the base year was driven by Italy's 15th census happening in 2011, an opportunity to access more data [28].

Because of the anomalies induced by COVID-19, the three most involved years in the pandemic (i.e., 2019, 2020, 2021) have been included separately in the model. To distribute the demand [7], the representative length of the day is divided into four sections (Fig. 3), obtained as their average length for the northern city of Domodossola and the southern city of Cuneo [29], highlighted both on Fig. 1b. As proposed in [30] the hours of the year (8760) have been distributed between four seasons (winter, spring, summer, and fall) visible in Fig. 3.

Note that TEMOA does not perform the optimization for the base year [31] while all other outcomes starting from the second year of the modelling are obtained by minimizing the total cost of production as the sum throughout all milestone years. The milestone years can be distinguished as "past" and "future", although irrelevant to the model. While past years have served to validate the capability of the model to replicate the historical configurations (shown in Section 3.2), future years are those involved in the implementation of different scenarios.

In an ESOM, the commodities flows terminate in a service demand which must be met in all milestone years. It is important to note that due to the range of services provided within each sector, they include more than one final service demand, with agriculture being the only exception. For instance, among the final service demands of the residential sector space heating, space cooling, lighting or cooking can be listed. Different service demands may have different drivers according to that specific service. For example, in the present model, all residential service demands have the regional population as driver while those of the commercial sector are chosen to be the regional added value of that sector. Drivers relative to past years are those already known and thus taken from the statistics [32]. Regarding the future predictions, for population, the demographic forecasts are taken from the studies conducted by the Piedmont Region [23], representing the median population growth scenario. The growth rate for the regional GDP is taken from the predictions made by the General Confederation of Italian Industry (Confindustria in Italian) [33]. The remaining drivers mostly relative to the industry sector (both past and future trends) are adopted from TEMOA-Italy which in turn were updated to establish the effects of the COVID-19 pandemic [34].

In the energy modelling field, attributing adequate elasticities to demands presents an important challenge and has always been place of debates [35]. In the absence of the region-specific data, the demands elasticities are adopted from TEMOA-Italy. Fig. 4 shows the historical trends and the future evolutions of the drivers of the model, highlighting up to 2014 the impact of the financial crisis started in 2008 and of COVID pandemic in 2020, especially on industrial production and gross domestic product (GDP). The commercial (service) added value is expected to increase significantly in the future, while the population, although following the median scenario [23], is expected to decrease.

2.1.3. The supply side

The only conventional energy commodity in the power sector of Piedmont is natural gas which is predominantly imported and also extracted in limited quantities within the Region, as indicated in the annual reports of the National Mining Office for Hydrocarbons and Georesources [36]. Similarly, the same resource indicates limited local oil extraction in the Val Sesia area, but the majority is imported via northern pipelines or through the Savona and Genoa terminals, both located outside the Region. The final consumption of crude oil in the Region is very limited and according to the reports of the Ministry of

Table 3
Source and assumptions adopted for the characterization of fuels and electricity trade in TEMOA-Piedmont [41].

	Energy commodity	Period 2011–2022	Future projections
Import	*Coal, oil, natural gas, liquefied natural gas (LNG)*	World Bank annual commodity prices [42]	2022–2030: World Bank forecasts [43,44] 2030–2050: World Energy Outlook 2022 projections [45]
	Coal and oil products	Scaling factors from [46]	Same future trends as coal and oil, respectively
	Solid biomass	Values for Italy from [46]	Projections for Italy from [46]
	Bioethanol and biodiesel	Global and European prices from [45,47]	Same future trends as gasoline and gas oil
	Electricity	Average prices, based on [47,48]	Same trend as natural gas
Export	*Fuels**	Scaling factors from [46]	
	Electricity	Average national single prices, based on [47,48]	Same trend as natural gas

**Fuels* include all the traded commodities excluding electricity.

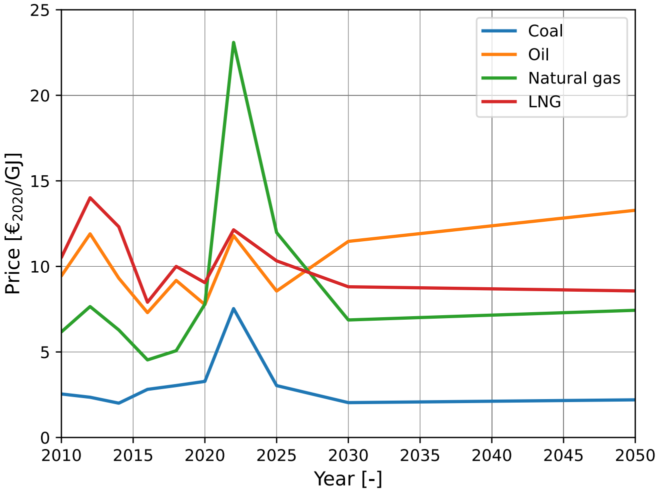

Fig. 5. Import prices of coal, oil, natural gas, and liquified natural gas (LNG) modeled in TEMOA-Piedmont.

Environment and Energy is in declination [37]. Crude oil, after being processed in the Trecate refinery, is distributed throughout the Region and in Italy. Likewise, the use of coal and coke in different sectors in the Region is quite limited and has a decreasing trend as well [38]. The local fossil fuels reserves, both for natural gas and crude oil, are considered by the model with devoted constraints taken from report of National Mining Office for Hydrocarbons and Geo-resources [36].

The main renewable energy sources of the Region are hydroelectric, solar and wind. Because of the geological structure, geothermal electricity generation is absent [22] and there is just a negligible capacity for heat generation from geothermic resources [38], thus this resource is not included in the base year of the model. The implementation of solid biofuels in the residential sector, despite being a diffuse resource, is under restriction because of the air pollution control measurements [39].

According to TERNA [22], the regional electricity production, although increasing, was in deficit when in 2013 underwent an overrun for the first time in 60 years and again after a few years of deficit reached autonomy in 2017.

The trade of refined fuels and electricity is modeled through import and export fictitious processes, characterized by trade prices and assuming regional prices of Piedmont equal to the national Italian prices [40]. In this regard, the sources and adopted assumptions are summarized in Table 3, while the import prices for the main fossil fuels are shown in Fig. 5: the price spikes due to the 2022 energy crisis are accounted for. Electricity imports are excluded from 2017 on, in order to guarantee the region self-sufficiency achieved in 2017 [26]. The complete sets of data implemented in TEMOA-Piedmont upstream sectors are available on GitHub [41].

Besides the main resources mentioned above, some data has been obtained in fragmented mode making use of the occasionally published statistics on various reports. The following reports are: reports of the Regional Environmental Protection Agency (Agenzia Regionale per la Protezione dell'Ambiente – ARPA – in Italian) [49]; the Italian Institute for Environmental Protection and Research (Istituto Superiore per la Protezione e la Ricerca Ambientale – ISPRA – in Italian) [50] report on solid biomass, biogas and sustainable bioliquids consumption in the electricity sector, and the report on solid biomass in residential and non-residential sectors by National Energy Service Manager (Gestore dei Servizi Energetici – GSE – in Italian) [38].

An overview of the existing technologies of the power sector is provided in Table 4. The installed capacities related to different hydro plants (basin, reservoir, and flowing) were taken from TERNA [22]. In addition, the hydroelectric park of the model also includes the pumping sites.

For renewable sources, besides TERNA data, further cross-checking was carried out referring to data from GSE [51] and regional environmental agency ARPA-Piedmont [49], which led to the identification of biofuel (bioliquids, biogas and biomass) and municipal waste plants.

Given the peculiarity of the Region and the city of Turin in the presence of the district heating network, this characteristic was included in the power sector by selection of combined heat and power plants. Data for these plants was sourced from information published by the region's primary electricity producer, IREN [52]. The techno-economic characterization of the plants, both for existing (see Table 4) and new technologies was taken from TEMOA-Italy [16].

Because of the absence of coal, oil, geothermal and offshore power plants within the Piedmont context, they were also excluded from the technology portfolio. Concerning the new technologies, the same techno-economic modelling adopted in TEMOA-Italy [16] was integrated into TEMOA-Piedmont.

The capacity factors important to define the productivity of renewable energy sources are calculated using Europe's Joint Research Center (JRC)'s "European Meteorological derived High Resolution RES

Table 4
Techno-economic characterization of existing technologies in the TEMOA-Piedmont power sector.

Category	Resource	Efficiency (%)	Existing Capacity (GW)	End of Life	Fixed O&M Cost (M€$_{2009}$/GW)	Variable O&M Cost (M€$_{2009}$/PJ)	Capacity Factor (%)
Power Plants	**Natural Gas**	≈ 44	4.46	≈ 2035	18.4	0.79	≈ 36
	Biofuels	≈ 29	0.12	≈ 2030	12.5	0.36	
	Hydroelectric		4.46		22.6	0.08	≈ 32
	Solar		1.07	≈ 2025	30.8	13.89	≈ 12
	Wind		0.01	≈ 2020	34.0		≈ 17
CHP Plants	**Natural Gas**	≈ 71	2.89	≈ 2035	29.1	0.61	≈ 47
	Biofuels	≈ 35	0.05	≈ 2030	220.5	0.83	

Table 5
Sub-sectors, technologies, final energy consumption and final demands of the transport sector in 2011.

Sub-sector	Category	Technology	Final Energy Consumption (PJ)						Demand	
			Diesel Fuel	Gasoline	LPG	Natural Gas	Jet Kerosene	Electricity		
Road	**Passengers**	**Cars**	39.47	25.60	3.96	0.92			22.70	Bvkm[a]
		Buses	2.09						0.11	
		Two Wheelers		3.53					4.31	
	Freight	**Light Commercial Trucks**	19.70	0.94					5.06	
		Medium Trucks	6.07						0.54	
		Heavy Trucks	14.00						0.62	
Rail	**Passengers & Freight**	**Trains**	0.58					1.51	2.09	PJ
Aviation	**Passengers & Freight**	**Aircrafts**					2.22		2.22	
Other								1.57	1.57	

[a] Bvkm (billion vehicle kilometres) is a measurement unit which accounts for the distances travelled by a specific category of vehicles.

generation time series (EMHIRES)" dataset [53], the past yearly regional capacity factors of wind and PV power plants by TERNA [26] were disaggregated into hourly format. Moreover, the monthly capacity factor of hydropower technologies in Piedmont was estimated by rescaling the national monthly values proportionally to the regional average capacity factor in the 2012–2021 period compared to the national ones, from TERNA, [26] and [22] respectively.

2.1.4. Transports

The principal data resources used in the development of this sector have been statistics of the Automobile Club of Italy (ACI) [54] in different years, TERNA statistics [26], Oil bulletin [55] and the analysis of energy consumption and emission reduction report by Piedmont Region [56].

The energy mix of the transport sector is reported in Table 2. The main fuel in the sector is diesel followed by gasoline, electricity, and LPG. Electricity comprises also the consumed amount relative to non-transport purposes of the sector. Starting from that level of detail, further steps were required to disaggregate the energy carriers among different services performed in the sector and also to identify the relative installed capacities of the existing technologies, necessary for the model calibration.

The first step was the identification of the transport modes (sub-sectors) in the Region. The sector does not include navigation, being in the hinterland. Regarding aviation, Piedmont is served by two civil airports situated in Caselle (in the province of Turin) and Levaldigi (in the province of Cuneo). Furthermore, a military airport is located in the province of Novara. Due to the limitation of detailed data, the aviation sub-sector of the model encompasses domestic, international, passenger and freight in one service.

The land transport sub-sector is divided into road and rail categories. Similar to aviation, the latter encloses both domestic and international passengers and freight transport within a single service. In contrast, the passenger and freight are included as two separate services of road transportation. Since these services may be carried out using several technologies (i.e., cars, buses and two-wheelers), it was necessary to determine the main categories and allocate energy consumption to each. To this end, the statistics of ACI [54] were consulted. These statistics brought to the further breakdown of the road transport services into the technologies reported in Table 5. Moreover, three-wheelers do not constitute a significant transport method in the Region.

Fuel attribution was started from the main categories (visible under the sub-sectors column in Table 5). The ACI statistics were also used to identify the fuels of the technology categories. Because of the negligible number of electric road vehicles in 2011, all the electricity consumed in the transport sector has been attributed to "rail" and "Other electricity uses". The electricity consumed by rail was obtained from the TERNA statistics [22], while the rest has been assigned to the "Other electricity uses". Concerning gasoline, it was completely allocated to road transport, as also stated by the Regional Environmental Agency report [49] and cross-checked with the TEMOA-Italy transport sector, developed based on the International Energy Agency (IEA) energy balance for Italy [57]. The sector consumed fuels per technology type is reported in Table 5.

The fuels disaggregation was performed on the basis of the mileages (travelled kilometres) of the specific technologies in 2011 in Piedmont, their efficiency, and the composition of the fleet (number of vehicles by technology) compared to the structure of the TEMOA-Italy transport sector in the same year. The average mileages of road transport in the Region were calculated referring to the Italian mileage and consumed commodities in 2006 (both known from TEMOA-Italy [58]) and those in 2011. While the structure of the Regional transport sector in the same two years i.e., 2006 and 2011 taken from ACI statistics in these two years ([59;60], respectively).

The final distribution of the different energy commodities among the base year technologies is shown in Table 5, highlighting the major role of cars in the transport and of diesel as the most relevant fuel. In particular, diesel vehicles dominate the existing road freight fleet which is similar to the Italian fuel shares in the transport sector of TEMOA-Italy [61].

According to Piedmont's PEAR [39] in 2011 the Region's transportation sector consumed 124.7 PJ, while the total final energy consumption resulting from the calculation and reported in Table 5 equals 122.2 PJ. The individual service demands per fuel type are calculated by multiplying the final energy consumption for each technology (see Table 5) by the respective efficiencies taken from TEMOA-Italy [58], assuming that the national values are also representative of the average performances of the Piedmont vehicles fleet. Ultimately, the final

Table 6
The main techno-economic parameters of the vehicles new technologies in the model.

Category	Technology	Efficiency (Bvkm/PJ)		Investment Cost (M€/Bvkm)		Fixed O&M Cost (M€/Bvkm)	Lifetime
		2020	2050	2020	2050		
Cars	**Diesel**	0.80	0.98	3090	3060	62.63	12
	Gasoline	0.31	0.42	2860	2830	62.63	12
	LPG	0.29	0.29	3060	3060	64.37	12
	Natural Gas	0.15	0.20	3060	3060	64.37	12
	Full Hybrid	0.40	0.69	3585	2830	61.76	12
	Plug-in Hybrid	0.76	1.03	5380	3740	60.00	12
	Electric	1.15	1.37	5520	3730	51.33	12
	Fuel Cells	0.50	0.94	11,590	5140	70.03	12

demands are obtained by summing up all the service demands belonging to the same transportation method (see Table 5).

Table 6 shows the main techno-economic parameters used to model new technologies in the TEMOA-Piedmont cars sub-sector. While the characterization of diesel, gasoline, LPG, and natural gas technologies in 2020 is based on [62], the exogenous technology learning (efficiency improvements and cost decrease) and the parameters for electric, full hybrid and fuel cell cars are estimated by applying the same proportionality factors provided by Europe's JRC-EU-TIMES [63].

2.1.5. Buildings

The buildings in the TEMOA-Piedmont model include those dedicated to housing purposes defined as the residential sector, buildings used for business and service purposes forming the commercial and agriculture sectors.

2.1.5.1. Residential. The energy vectors present in the base year of the residential sector of the model are shown in Table 2. The main resources of the data can be listed as TERNA [26] for electricity, natural gas bulletin [64], oil bulletin [55], "Analysis of Energy Consumption and Achievable Emission Reductions" report [56], natural gas distribution report by ARPA [65].

The final service demands of the sector are space heating and cooling, water heating, lightning, cooking, dish and cloth washing, cloth drying, refrigerating and other electricity uses as also listed in Table 13. Based on these final services to get fulfilled, the energy carriers needed to be further disaggregated.

A dataset of almost 50′000 Energy Performance Certificates (Attestato di Prestazione Energetica – APE – in Italian) which provide mostly the space heating features of individual dwellings in the Region is used to develop this subsector of the residential sector. In fact, the APE certificates are also provided with a section relative to the cooling systems of households which, being optional, is usually not filled in by people. The use of this dataset brought some modification of the space-heating sub-sector of the model with respect to that of TEMOA-Italy [61]. Consequently, the relative commodities were modified accordingly and were divided following the methodology applied in TEMOA-Italy and explained in the following.

Table 7
Residential energy commodities, final fuels consumption (E^{f}_{agg}) and their shares ($f_{\%}$) in 2011.

		Total Energy E^{f}_{agg} – (PJ)	Space Heating ($f_{\%}$)	Space Cooling ($f_{\%}$)	Water Heating ($f_{\%}$)	Refrigeration ($f_{\%}$)	Cooking ($f_{\%}$)	Dishwashing ($f_{\%}$)	Clothes Washing ($f_{\%}$)	Clothes Drying ($f_{\%}$)	Lighting ($f_{\%}$)	Other Electricity Uses ($f_{\%}$)
Energy fuels	**Natural Gas**	72.73	89.5 %		7.5 %			3 %				
	Diesel Fuel	2.06	90 %		10 %							
	Heavy Fuel Oil	0.37	94 %		6 %							
	LPG	3.92	78 %		7 %			15 %				
	Electricity	17.91	3 %	4 %	11.5 %	18 %	0.5 %	4.5 %	9.5 %	6.5 %	28.1 %	14.4 %
	Biomass	25.27	96 %		4 %							
	Heat	8.16	87 %		13 %							

Equation (1) is used to disaggregate the energy commodities present in the sector among the service demands, where ($f_{\%}$) is the fuels shares in each service and E^{f}_{agg} is the aggregated total energy shown in column "Total Energy" of Table 7.

$$E^{f}_{end} = f_{\%} \times E^{f}_{agg} \tag{1}$$

Table 8 reports the disaggregated energy consumption by the residential service demands in the base year of the model. As mentioned before, the configuration of the space heating has been modified to take more advantage of region-specific data of the APEs. In TEMOA-Italy, the residential buildings comprise four categories: single and multiple family buildings, by turn divided into old and new. As in the APEs, there were no indications of such features of dwellings, and considering the energy classifications A1-A4, B, C, D, E, F and G, the buildings were divided into three new categories: Low-Consuming enclosing A1-A4 classes, Medium-Consuming involving classes B, C, D and High-Consuming comprising E, F and G classes.

The shares of different classes from the energy vectors ($k^{j}_{\%}$) are obtained by elaborating the records of the dataset and are reported in Table 9. As can be seen, heavy fuel oil is absent in the low-consuming buildings. These shares are used to split further the space heating fuels (E^{f}_{end}) among energy classes. ($E^{k_j}_{end,i}$) which is the fuel i consumed in buildings class j , is obtained applying Equation (2).

$$E^{k_j}_{end,i} = k^{j}_{\%} \times E^{f}_{end,i} \tag{2}$$

Other parameters updated elaborating the APEs were the efficiencies

Table 8
Final energy consumption (E^{f}_{end}) per service demand.

		Space Heating	Space Cooling	Water Heating	Refrigeration	Cooking	Dishwashing	Clothes Washing	Clothes Drying	Lighting	Other Electricity Uses
Final Energy Consumption (PJ)	**Natural Gas**	65.10		5.45		2.18					
	Diesel Fuel	1.86		0.20							
	Heavy Fuel Oil	0.35		0.02							
	LPG	3.06		0.27		0.59					
	Electricity	0.54	0.72	2.06	3.22	0.81	1.16	1.70	0.09	2.58	5.03
	Biomass	22.10		3.20							
	Heat	7.85		0.303							

Table 9
Fuels shares (%) in meeting space heating demand in various energy classes of buildings (k^{j}).

Fuel	Energy class ($k^{j}_{\%}$) Low-Consuming	Medium-Consuming	High-Consuming
Natural Gas	0.3 %	8.8 %	90.9 %
Diesel Fuel	0.1 %	6.4 %	93.5 %
Heavy Fuel Oil		4.8 %	95.2 %
LPG	0.4 %	7.9 %	91.7 %
Electricity	28.4 %	18.5 %	53.1 %
Biomass	0.6 %	11.7 %	87.7 %

of space heating reported alongside the final energy consumption per building class in Table 10.

Useful Energy (*UE*) was calculated referring to Equation (3) and reported in Table 12 for Low Consuming buildings. Where necessary, the consumed energy is further split between the technologies (t) which use the same commodity (i) using shares ($S_{i,t}$) taken from TEMOA-Italy and the relative efficiency $Eff_{i,t}$. Wherever the service is met by unique technology, the share $S_{i,t}$ will be 1 (e.g., Deisel boilers). Moreover, the efficiencies which were not updated using APEs as well as all shares are adopted from TEMOA-Italy [61].

$$UE^{k}_{end,i,t} = E^{k}_{end,i} \times S_{i,t} \times Eff_{i,t} \tag{3}$$

Ultimately, service demands are calculated by multiplication of the useful energy and the conversion factor. These conversion factors, obtained again from the APEs are the inverse weighted average of the consumed energy for unit area and per energy class and are reported in Table 11 for all building categories.

These conversion factors remain the same for the space heating technologies belonging to the same building category. These parameters convert the consumed energy (PJ) into the final service demands expressed in millions of square meters (Mm^2).

Ultimately, each final demand (D_j) of the sector is calculated by summing up their parts ($SD_{i,t,j}$) met by different technologies according to Equation (4).

$$D_j = \sum_{i,t} SD_{i,t,j} \tag{4}$$

Table 12 shows technological and technical details of the space heating subsector of the low consuming buildings. For the sake of brevity, the same parameters are shown just for the water heating subsector. All final service demands of the residential sector together with their unit are visible in Table 13.

2.1.5.2. Commercial buildings. The commercial sector comprises offices and buildings dedicated to economic and service activities. The energy mix of the sector reported in Table 2, was obtained from TERNA statistics for electricity [26], natural gas bulletin [64], oil bulletin [55] and TEMOA-Italy [61]. The main two energy carriers of the sector are natural gas followed by electricity. The different final service demands of the sector, very similar to those of the residential sector, are reported in Table 14.

The fuel shares ($f_{\%}$) to disaggregate and distribute fuels among service demands in order to obtain useful energy are taken from TEMOA-Italy [61] and are reported in the upper part of Table 14. The application of these shares led to the fuel distribution shown in the lower part of Table 14. Similarly, the efficiencies of the commercial technologies are assumed to be well represented by the national average values and are adopted from TEMOA-Italy [61]. Eventually, the final demands (as reported in the last row of Table 14) of the sector are calculated by multiplying the final energy consumption by their relative efficiency. As shown in Table 14, the measurement unit of all final demands in the commercial sector is PJ. Thus, they do not require any further conversion factor like residential space heating.

2.1.5.3. Agriculture. The energy mix of the agriculture sector is reported in Table 2. Natural gas, diesel and electricity are respectively the

Table 11
Space heating conversion factors per building category.

	Low Consuming	Medium Consuming	High Consuming
Conversion factor (Mm^2/PJ)	7.93	3.36	2.27

Table 10
Final energy consumption in space heating and the efficiency of relative technologies.

	Low-Consuming Energy Consumption (PJ)	Efficiency (%)	Medium-Consuming Energy Consumption (PJ)	Efficiency (%)	High-Consuming Energy Consumption (PJ)	Efficiency (%)
Natural Gas	0.19	77	5.75	73	59.10	69
Diesel Fuel	0.01	79	0.12	76	1.74	70
Heavy Fuel Oil			0.02	82	0.33	75
LPG	0.01	83	0.24	70	2.80	69
Electricity	0.15	55	0.10	60	0.29	63
Biomass	0.13	77	2.59	76	19.40	66

Table 12
Space heating fuels and technologies in low consuming buildings.

	Energy vector	Technology description	Consumed energy $E^{k}_{end,i}$ − (PJ)	Shares $S_{i,t}$	Efficiency $Eff_{i,t}$ − (−)	Useful Energy $UE^{k}_{end,i,t}$ − (PJ)	Conversion factor (Mm2/PJ)	Service demand per fuel $SD_{i,t,j}$ − (Mm2)	Space heating demand in LC buildings D_j −(Mm2)
Low Consuming	Natural gas	Natural gas boiler	0.19	0.99	0.77	1.42E-01	7.93	1.13E + 00	3.50
		Natural gas heat pump		0.01	1.19	2.05E-03		1.63E-02	
	Diesel	Distillate boiler	0.01	1.00	0.79	1.38E-03		1.09E-02	
	Heavy fuel oil	Heavy fuel oil boiler	–	–	–	–		–	
	LPG	LPG boiler	0.01	1.00	0.83	1.04E-02		8.26E-02	
	Electricity	Resistance	0.15	0.84	0.55	1.26E-01		9.97E-01	
		Electricity heat pump		0.16	2.13	4.89E-02		3.88E-01	
	Heat	District heating	0.01	1.00	0.76	8.76E-03		6.94E-02	
	Biomass	Biomass boiler	0.13	1.00	0.77	1.02E-01		8.06E-01	

Table 13
Residential sector final demands and their units.

Sub-sectors		Final service demands	Unit
Space Heating	**Low Consuming**	3.50	Mm^2
	Medium Consuming	23.70	Mm^2
	High Consuming	0.01	Mm^2
Space Cooling		0.03	Mm^2
Water Heating		6.73	PJ
Refrigeration		0.66	Gl
Cooking		2.03	PJ
Dishwashing		0.20	Glav
Clothes Washing		0.44	Glav
Clothes Drying		0.01	PJ
Lighting		60.60	Glm
Other Electricity Uses		5.03	PJ

three most consumed energy commodities in the sector. Similar to TEMOA-Italy's [61] agriculture sector, also TEMOA-Piedmont does not include distinct technologies in competition with each other. The energy vectors enter a single technology to meet the single final demand of the sector which amounts to 36.80 PJ, equal to the total final energy consumption of the sector assuming unitary efficiency.

2.1.6. Industry

The energy carriers consumed by the industrial sector are shown in Table 2. The most consumed energy vector in this sector is electricity 47.4 PJ followed by natural gas 43.4 PJ and heavy fuel oil placing diesel in the fourth place. It is important nothing again that the energy balance is obtained by making assumptions on the shares of the fuels as reported in Table 2, in Section 2.1.1. Besides the reported energy vectors, some indications of small amounts of pet coke and coal were found in the GSE monitoring report [38] and were attributed to the sector.

Like other sectors of the model, also the industry is composed of different sub-sectors as listed in Table 15. Besides the usual sub-sectors, a part of the electricity entering the sectors is assigned to a new sub-sector relative to water treatment energy needs amounted to 5.61 PJ, as stated in TERNA statistics [22]. This decision was made to enable the development of the water sector of the model in future updates. For now, the demand of this sub-sector is linked to unitary driver and elasticities, assuming a constant trend.

The disaggregation of the energy vectors among the sub-sectors was performed differently from other sectors of the model: in the absence of detailed regional information, an iterative method departing from the existing capacities of the TEMOA-Italy [61] technological inventory has been adopted. The initial existing capacities were obtained by adjusting the national ones proportional to the regional over national added values [32] of the most similar activity sectors. The following step was the calculation of the consumed fuels applying the input shares, existing capacities (obtained before by rescaling), and efficiencies of TEMOA-Italy [61].

Each iteration consisted of the determination of final fuel consumption based on the installed capacities in that iteration. The energy mix obtained in each iteration was compared with the sector's energy mix and in case of differences, the existing capacities were further modified to reach a closer energy mix to the assigned one (shown in Table 2). The most relevant capacity modifications were applied to the technologies with the simplest commodity flow i.e., the "other" categories. This choice was made because some technologies have output commodities that are used as input of other technologies (for instance machine drives). Consequently, changing the capacity of such technologies acts on a group of fuels and not just on one.

In Table 16, the existing and new technologies present in the Iron and steel sub-sector of the model, their input commodities, commodity input shares and some other characterization parameters are shown. More detailed information about the sector's structure and features of the sectors can be accessed from the model via GitHub [41].

After reaching the energy mix close to that of assigned to the sector,

Table 14
Demand levels by commercial end-uses and final energy consumption by fuels and commercial end-uses in 2011.

		Total Energy E^{f}_{agg} – (PJ)	Space Heating	Space Cooling	Water Heating	Lighting	Cooking	Refrigeration	Electric Office Equipment
Fuel shares ($f_{\%}$)	**Natural Gas**	43.64	88 %	5 %	3 %		4 %		
	Gasoline	0.66	82 %	8 %	10 %				
	LPG	0.55	67 %		25 %		8 %		
	Electricity	25.13	8 %	13 %	5 %	30 %	1 %	7 %	36 %
	Heavy fuel oil	0.37					100 %		
			Final Energy Consumption (PJ)						
Natural Gas			38.4	2.18	1.31		1.75		
Gasoline			0.54	0.05	0.07				
LPG			0.37		0.14		0.04		
Electricity			2.01	3.27	1.26	7.54	0.25	1.76	9.04
Heavy fuel oil							0.37		
			Sector Demands D_j						
(PJ)			60.63	31.4	14.6	2.12	0.43	1.28	1.76

Table 15
Industrial sub-sectors, products, and demand levels in 2011.

Sub-sectors		Demands
Chemicals	**Olefins**	1.20 Mt
	Aromatics	
	Ammonia	
	Methanol	
	Chlorine	
	Other chemicals	
Iron and steel	**Basic oxygen furnace**	2.68 Mt
	Electric arc furnace	
	Other technologies	
Non-ferrous metals	**Aluminium**	1.13 Mt
	Copper	
	Zinc	
	Other non-ferrous metals	
Non-metallic minerals	**Wet cement kilns**	2.25 Mt
	Dry cement kilns	
	Lime	
	Glass	
	Ceramics	
Pulp and paper	**Chemical pulp**	0.61 Mt
	Mechanical pulp	
	Recycled pulp	
	Paper mill	
Other	**Other industries**	27.80 PJ
	Other non-energy uses	5.80 PJ
	Other non-specified	4.05 PJ
Water uses	**Electricity in water uses**	5.62 PJ

it has been possible to obtain the final demands by application of the conversion factors which enable the conversion of the used energy to final energy demands (similar to what is explained in buildings section). Like other techno-economic parameters of the sector, also the conversion factors of technologies are adopted from the TEMOA-Italy model [61]. The final energy demands of the sector are shown in Table 15. As it can be seen, all sub-sectors have a single final demand, with the exception of "Other industries" which has three different final demands according to the consumed commodity..

The development of this sector has been an indirect indication to the value of the regional energy models. It demonstrates that how data rescaling (performed as the initial step of the sector development) fails to capture the characteristics of the target region. This is, in part, due to the interdependence of commodities across and between sectors, as well as the specific structural and techno-economic features of each territory. Inadequate approximations can lead to significant inaccuracies in evaluations and results. Should more precise and region-specific data become available, the industry sector will be subject to updates.

2.1.7. Hydrogen

TEMOA-Piedmont includes a simple hydrogen module, comprising the traditional technology methods producing this energy carrier. At the moment, the module encompasses two centralized and one decentralized steam methane reforming technologies, the first two available from 2020 and the latter from 2025, a heavy oil partial oxidation technology available from 2020 and an electrolysis technology from 2025. The techno-economic characterization of these technologies is adopted from the Europe's JRC-EU-TIMES hydrogen generation module [63] available on GitHub [41].

2.1.8. The emission factors

TEMOA-Piedmont considers two types and four emission commodities (namely CO_2, CH_4, N_2O and SO_X) [66]. The two emission types implemented in the model and discussed in detail in [67,68] are commodity-related and process-related. The former accounts for emissions due to the combustion of fuels and represents the carbon content of the fuels while the later represents emissions due to the activity of specific technologies such as chemicals production or vented emissions in upstream. With the aid of adequate conversion factors embedded into the model, it is also possible to compute or constrain the CO_{2EQ} emissions. Table 17 reports the CO_2 emission factors of the most relevant energy commodities and processes of the model, while the complete set of emission factors is available through the model on GitHub [41].

As biofuels are assumed to be carbon neutral, specific negative emission factors are used to compensate for the emissions associated with their consumption in the demand side of the system, discussed widely in [68].

2.2. The storylines

In order to further examine the robustness of TEMOA-Piedmont and inspired by the regional energy and transport policies, two different storylines were implemented in the model. Besides coherence with the regional plans, the choice of scenarios tries to evaluate the response of the model to predictable restrictions. In the case of the emission scenario, the model is expected to install fewer polluting technologies and use less-emitting fuels. The hydropower scenarios instead, are thought to study the model's behavior when adopting a certain technology at different levels.

A schematic representation of the storylines is shown in Fig. 6. Both stories take as reference the *Baseline scenario "BL"*. The *"BL"* represents the state of the model according to past years calibration and its evolution following the least cost criteria, without introducing any policy or restriction. Fig. 7 shows the trends of the targeted parameters in the "*BL*" scenario (in blue), compared to the same parameter under the constraints implemented in the "*ET*", "*LH*" and "*PEAR2022*" scenarios.

As mentioned before, the first storyline targets emissions in the

Table 16
Iron and steel sub-sector technologies and other techno-economic characterization.

Type	Technology	Existing capacity (Mt)	Input commodities	Input share	Efficiency	Investment cost (M€/Mt)	O&M cost (M€/Mt)	Lifetime (years)	Capacity Factor
Existing	**Basic oxygen furnace**	1.11	Steam	3 %	0.08			30	
			Machine drive	6 %					
			Other energy use	2 %					
			Feedstock	41 %					
			Natural gas	40 %					
			Coal	3 %					
			Blast furnace gas	0 %					
			Heavy fuel oil	2 %					
			LPG	1 %					
	Electric arc furnace	1.87	Steam	2 %	0.23			30	
			Machine drive	25 %					
			Other energy use	7 %					
			Feedstock	8 %					
			Natural gas	8 %					
			Coal	3 %					
			Electricity	46 %					
			Refined petroleum products	0 %					
New	**Blast furnace-Basic oxygen furnace**		Blast furnace gas	100 %	0.31	128.0	3.2	30	0.85
			Feedstock	58 %					
			Machine drive	5 %					
			Coal	36 %					
	Direct reduced iron-Electric arc furnace		Electricity	70 %	0.18	458.0	17.4	20	0.85
			Feedstock	22 %					
			Natural gas	7 %					
	Hydrogen direct reduction		Electricity	22 %	0.12	634.0	17.4	20	0.85
			Hydrogen	60 %					
			Natural gas	5 %					
			Machine drive	13 %					
	HIsarna-Basic oxygen Furnace		Natural gas	1 %	0.07	440.0	14.5	30	0.85
			Electricity	5 %					
			Coal	94 %					
	Ulcowin		Coal	6 %	0.06	6940.0	20.2	20	0.85
			Natural gas	14 %					
			Electricity	80 %					
	Ulcolysis		Electricity	92 %	0.06	6720.0	17.0	20	0.85
			Natural gas	8 %					

Table 17
Commodity and process CO_2 emission factors.

Sector	Commodity/Process	Emission Factor	Unit
Different sectors	**Natural Gas**	56.1	kt/PJ
	LPG	63.1	
	Gasoline	69.3	
	Jet Kerosene	71.5	
	Diesel	74.1	
	Heavy Fuel Oil	77.4	
	Municipal Waste	85.9	
Upstream	**Refinery**	1.6	
Industry	**Dry clinker (existing)**	484.5	kt/Mt
	Wet clinker (existing)	484.5	
	Dry clinker (new)	505.2	
	Wet clinker (new)	505.2	
	Lime production	392.5	

transport sector. Piedmont is part of the Po Valley, known for suffering from high [69] and persistence [70] air pollution. Thus, studying plans which lead to the air pollution reduction of the area is crucial. The *Emissions Transport "ET"* scenario is adopted from the Region's most recent transport plan dated back to 2018 [71]. The plan sets limits on $CO_{2,EQ}$ emissions in 2020, 2030 and 2050 with respect to the 2010 value (9.7 Mt/year). Due to the plan, the maximum allowable emissions for the mentioned milestone years should decrease and be respectively 9.5, 7.8 and 3.5 (Mt/year). Because such upper limits are applied as the reduction percentages referring to 2010 values, this leads to an initial point (see Fig. 7a, orange line) slightly higher than the $CO_{2,EQ}$ emissions of the "*BL*" scenario (blue line). The reduction percentages are −2% in 2020, −20 % in 2030 and −64 % in 2050 and are implemented as the maximum $CO_{2,EQ}$ emissions of the whole transport sector.

The hydroelectric storyline unfolds two different (and somehow contrary) trends. Hydropower is the second largest electricity generation method in Italy lying behind thermoelectric. Almost 63 % of the total 23.2 (GW) installed hydroelectric capacity of the country belongs to the four northern regions Lombardy, Piedmont, Trentino-Alto Adige and Aosta Valley [22]. Accounting for 17 % of the national installed capacity, Piedmont is the nation's second largest capacity holder. In the past years, thanks to the construction of small-scale plants, the regional installed capacity showed an increasing trend from 2.6 (GW) in 2012 to 2.8 (GW) [22].

The most recent energy plan of Piedmont, the PEAR [39], dating back to 2022 foresees an increase of 940 (GWh) in the regional electricity generation via hydropower, from 2015 to 2030. The first studied scenario, "*PEAR2022*" replicates this policy: the generated hydropower in 2015 (8210 GWh) was added to the planned growth to obtain the 2030 forecast (9150 GWh). As the plan goes no further than 2030, using these two values a trendline has been fitted and is assumed to project the values for 2035, 2040 and 2050 to be implemented into the model.

On the other hand, affected by the past droughts, the electricity generation from hydroelectric in 2022 in Italy experienced a decreasing trend reaching its lowest historical level [22], a 36 % reduction with respect to 2021. The same resource shows that despite capacity extension, a similar decreasing trend was observed also in the regional hydropower generation. Thus, the scenario *Low Hydroelectric "LH"* is studied following such decline.

$$E_{HYD}(PJ) = -0.82\left(\frac{PJ}{year}\right)\bullet year + 1.69\bullet 10^{3}(PJ) \tag{5}$$

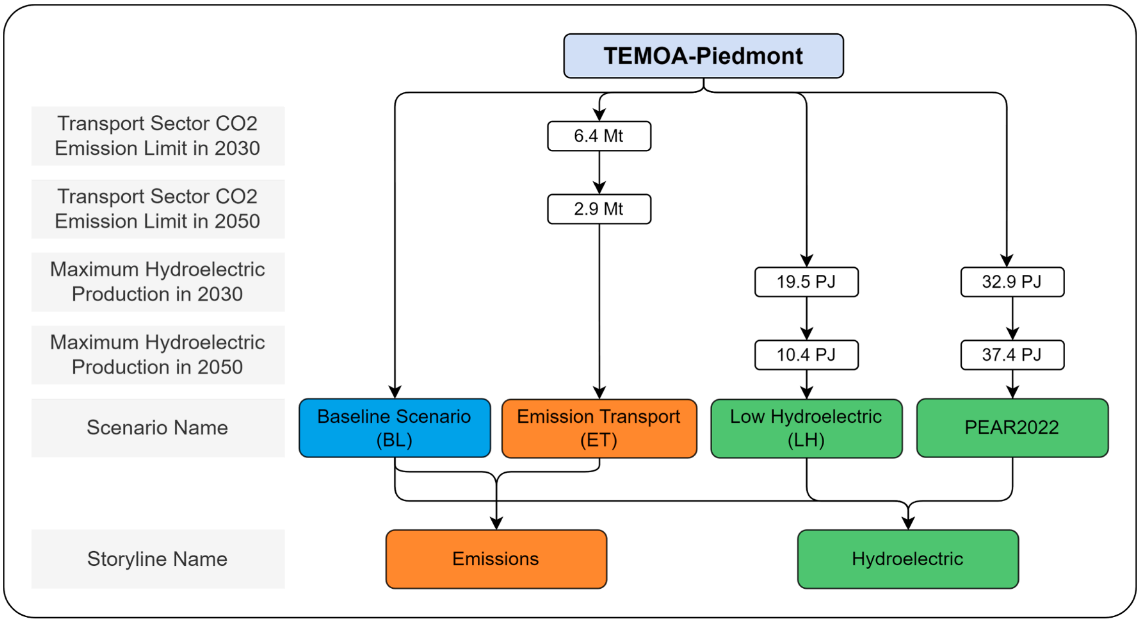

Fig. 6. Storylines and scenarios implemented in the TEMOA-Piedmont.

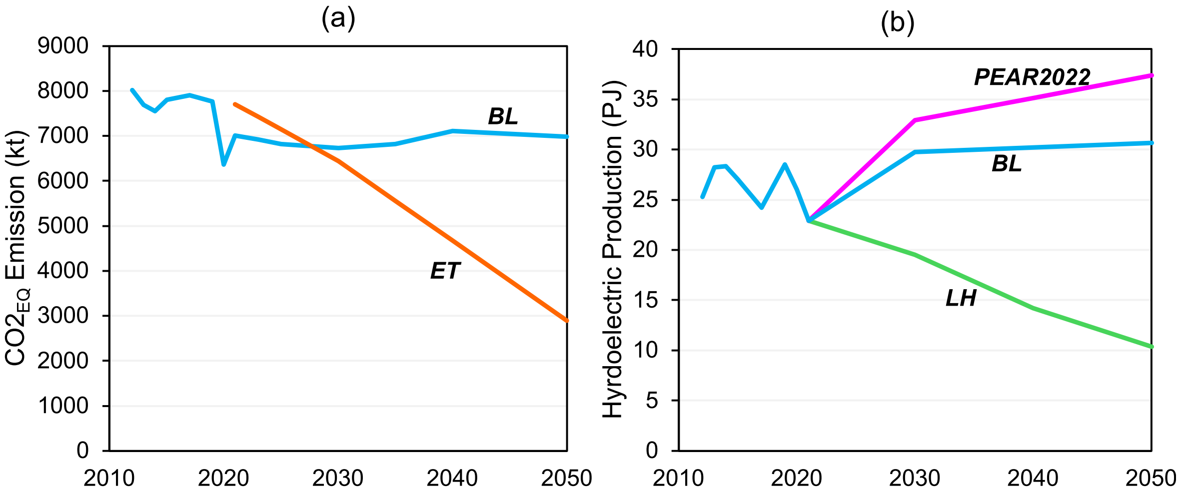

Fig. 7. Applied scenarios on (a) emissions in transport, (b) hydroelectric. The red curve in the figure b shows the historical trend of the hydroelectric generation while the blue curve is how it is in the model.

At the first step, the trendline of the historical generation represented by Equation (5) is obtained. Then, the decline percentage for a 10-year period (the time between two representative years 2012 and 2022) (equal to −27 %) is evaluated. The same percentage is used to calculate the upper limit for 2030, 2040 and 2050 (10 years periods). These values are implemented as maximum activity for the technologies of hydropower.

Fig. 7b shows the discussed “*PEAR2022*” and “*LH*” scenarios respectively in magenta and green, together with the baseline (blue) trends.

3. Results and discussion

This section presents the results of the implemented scenarios along with the corresponding discussion. The associated results of the *“BL”* scenario, emissions and hydroelectric storylines will be given in Sections 3.1, Sections 3.2, and Sections 3.3, respectively.

3.1. *Baseline*

In Fig. 8 the *“BL”* scenario results are shown, representing the reference state of the TEMOA-Piedmont as said before. Regarding the primary energy, with a significant difference, natural gas is the most consumed energy source followed by oil and oil products (Fig. 8a). This trend seems to be also economically convenient as it stays the same in the energy mix of future years. The second most consumed energy carriers in the region are oil products (i.e., diesel, gasoline, heavy fuels oil, jet kerosene and oil). In the 2019–2021 period, the effect of the COVID-19 pandemic is more evident in the transport sector through fuel consumption decrease. Biofuels and hydroelectric, occupying third and fourth places in the final energy mix, keep the same past trends also in the future years with a slight reduction against natural gas. The share of coal, although very limited, reduces further in the future periods, reaching stationary consumption due to the industry uses mainly (see Fig. 8a). In this scenario, as expected, the limited shares of solar and wind disappear in the future due to lack of economic competitiveness and their low-capacity factors.

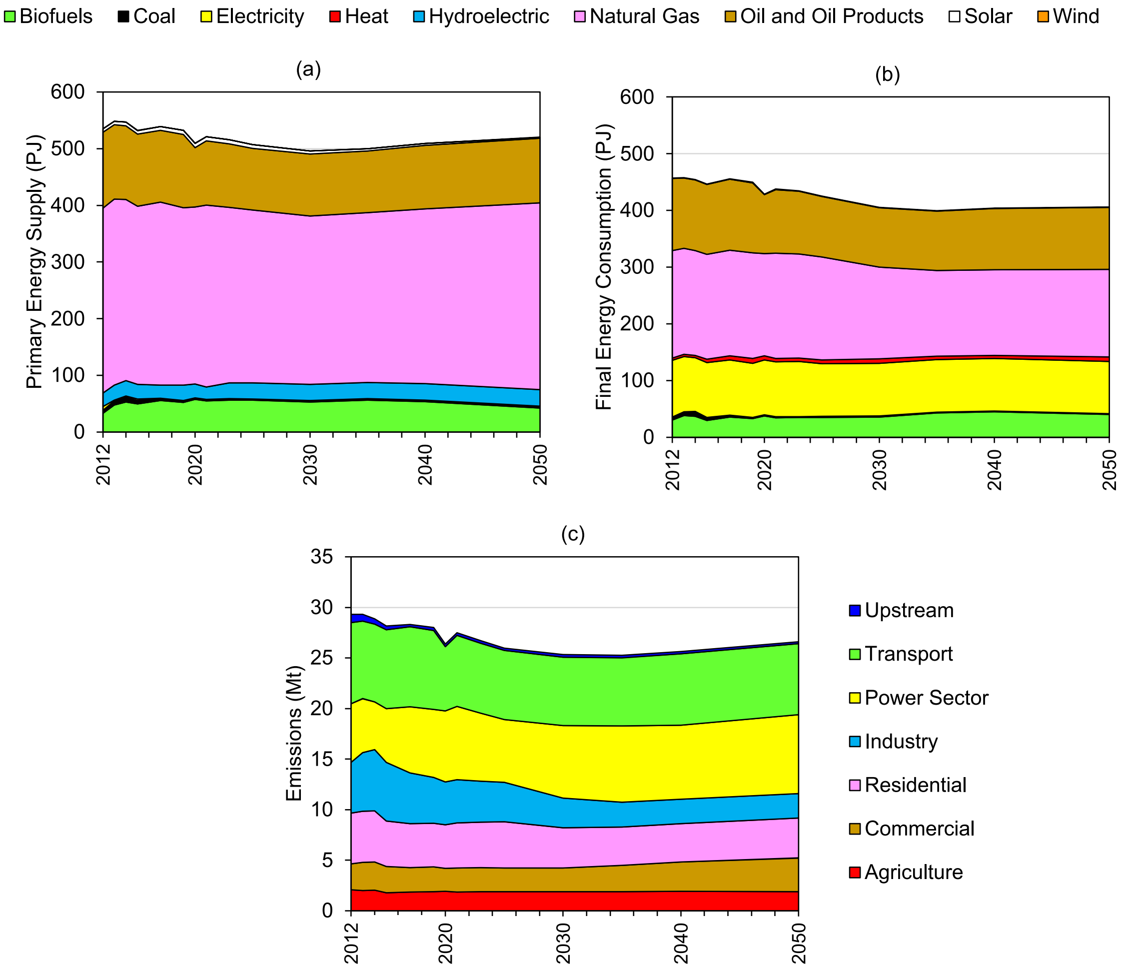

Fig. 8. Primary energy supply (a), final energy consumption (b) and sectorial breakdown of the emissions (c) for the Baseline scenario.

Table 18
Sectorial breakdown of the cumulative investment costs for the 2023–2050 time interval in *BL* scenario.

Sector	Investment Cost (B€)
Commercial	3.38
Residential	3.91
Industry	1.83
Power Sector	1.25
Transport	125.42

Natural gas and oil products are the most consumed final energy followed by electricity and biofuels (see Fig. 8b) and keep the same past configuration in the future, despite a slight reduction. Like its primary energy supply, coal consumption decreases until it reaches a steady state, while heat consumption shows an increase in the first modelling years before getting into a stationary phase.

The comparison of Fig. 8a with Fig. 8b indicates a decrease in the final energy resources consumption against almost the same levels of primary ones. This originated in the increased efficiency due to the new technologies penetration in the demand side sectors.

Considering the emissions in the *"BL"*, shown in Fig. 8c, in the initial years, the transport sector stays in the first place with a relatively high difference comparing with other sectors. Because of the substitution of existing industrial technologies with less emissive options, the emissions in the industry sector occupying the second position in initial modelling years tend to decrease, changing their place with the power sector. The emission increase in the power sector is attributed to the local generation starting to cover all the electricity demand without dependency on imports from outside region happening in 2017 [26]. The slight reduction visible in the overall emission over the past years is attributed both to lesser consumption and performance improvements of the technologies. The emissions in all sectors except the commercial sector reach a plateau from 2030 on. This behavior is due to the higher growth expected in this sector, imposed by the sector's driver. Like the last two graphs also in this graph the effect of COVID-19 is visible, especially in the emissions of the transport sector.

Coming to the costs, Table 18 shows cumulative investment costs from 2023 to 2050. As it can be seen, the transport sector manifests the highest investment cost being considerably ahead of others. In addition to the elevated costs, this could be explained by the overall shorter lifespan of the technologies and higher units of technologies (limited capacity per unit) required to meet the sectors demands.

Residential is the second most capital expending sector followed by the commercial sector with just over a half B€ less. Also, in these cases, technologies with lower lifetimes and reduced capacity per unit required to meet the final demands could explain the higher costs.

3.2. *Model validation*

The reliability of a model depends on the quality of input data, otherwise said data calibration and the validation of the output. While calibration is performed during the development phase and is meant to ensure the quality of the input data, to guarantee the performance, it is necessary to validate the ability of the model in replicating the measured data [72]. The purpose of this chapter is to present a comparison of the

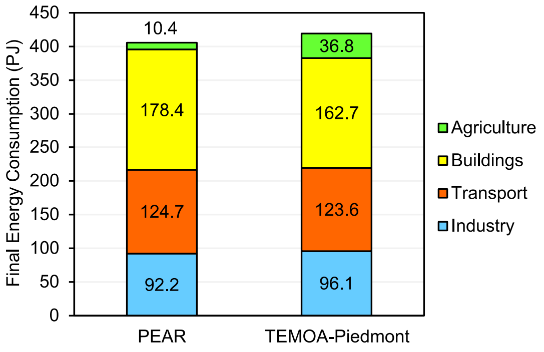

Fig. 9. Comparison of the final energy consumption mixes in the base year of the model and PEAR data.

model outputs with historical time series. The outputs of the transport and power sectors will be discussed in detail as they are used to implementing the storylines.

The overall energy mix was compared with the aggregate data published on the official energy document of the region, namely the Regional Energy and Environmental Plan (Piano Energetico Ambientale Regionale – PEAR – in Italian) [39] was performed and is visible in Fig. 9. As can be seen, the model shows a representative trend with some marginal discrepancies. Overall, the model exceeds by 3 % the regional energy mix (corresponding to around 14 PJ). The situation varies in sectors: while in the transport and industry, the differences are very small and negligible, almost 1 (PJ) and 4 (PJ) respectively, in the civil sector, composed of residential and commercial sectors, the difference increases to 15.7 (PJ) for the model being in deficit. Note that a source of difference is related to the different categorization of the PEAR compared to the model. More precisely, the presence of "other" as an individual category in PEAR, absent in the model in that way. In fact, this category exists as a subsector within each sector, but not as an independent category. Moreover, the data of different authorities (for instance TERNA for electricity [26] and Ministry of Environment and Energy Security for oil and gas products [36]) showed intrinsic mismatches. Indeed, and as mentioned in Section 2.1, because the energy balance was constructed fuel by fuel and as the data provided in the PEAR is in aggregated format, it was not possible to spot the exact origin of the misalignments of the two energy balances.

In the absence of time series for transport sector, a point-to-point

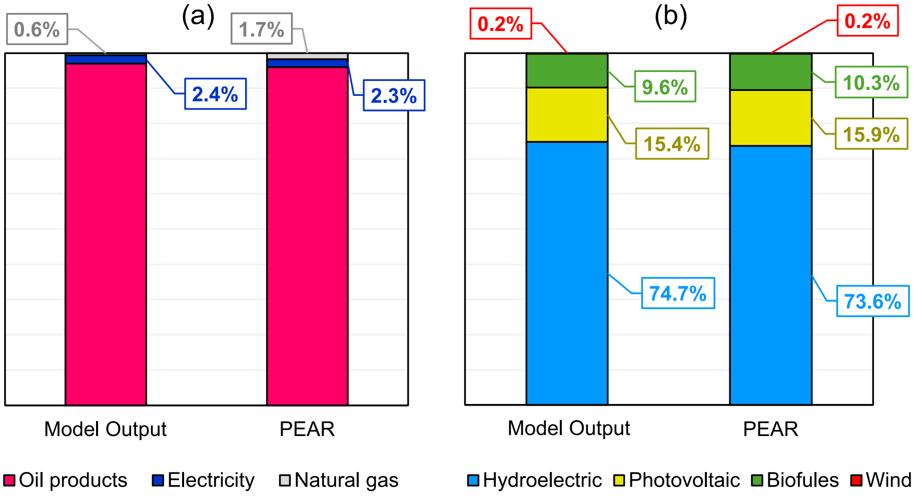

Fig. 10. Model outputs comparison with data from PEAR in 2014 for (a) final energy consumption of the transport sector and (b) renewable electricity production.

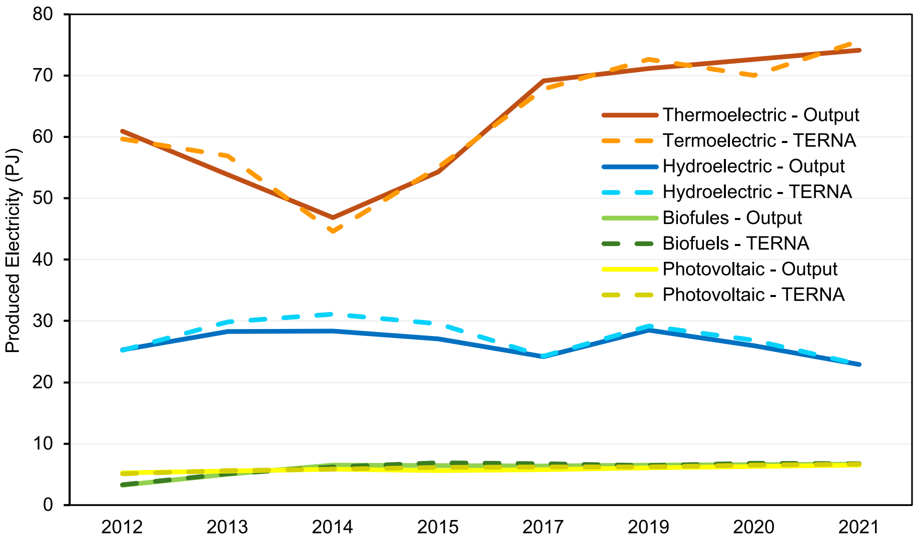

Fig. 11. Comparison of the model outcomes for the electricity production evolution from 2012 to 2021 with statistics of TERNA, for the most relevant sources of the Piedmont power sector.

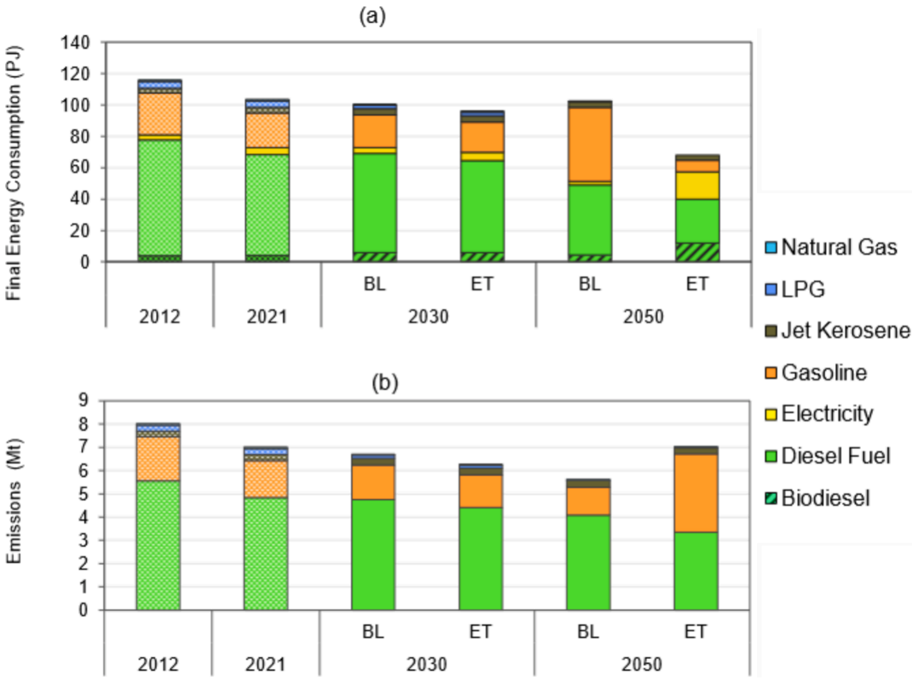

Fig. 12. Breakdown by energy commodity of final energy consumption (a) and the $CO_{2,EQ}$ emissions (b) of the TEMOA-Piedmont transport sector in 2012, 2021, 2030 and 2050, in the “Baseline” and “Emissions Transport” scenarios.

validation of the outcomes with respect to PEAR [39], relative to the 2014 was performed and is shown in Fig. 10a. This validation demonstrates the perfect alignment of the transport sector with the measured data. Similarly, a point-by-point assessment of the shares of renewable resources in the model in 2014, with the data published in the PEAR [39] is shown in Fig. 10b. It can be observed that also in this single year, the model shows a perfect alignment with the registered data.

Fig. 11 shows the output of the electricity generation by method compared to the historical series of TERNA. As visible, the results – particularly for thermoelectric and hydropower plants, which account for the majority of electricity generation – are almost identical to TERNA’s data [26].

3.3. Emissions storyline

Fig. 12 shows the comparison of the evolution of the transport sector’s final energy consumption (a) and $CO_{2,EQ}$ emissions (b) in the *Baseline “BL”* and *Emissions Transport “ET”* scenarios in four representative years 2012, 2021, 2030 and 2050. The first two years, illustrated by faded patterns are relative to the historic years, identical in both scenarios as the restrictions are not applied to them. In 2030, the *BL* scenario shows a similar energy mix to that of *ET* because of the vicinity of the emission levels in the two scenarios. Diesel fuel is the most consumed commodity followed with a marked difference by gasoline. The same trend is also visible in the emissions sources Fig. 12b.

In 2050 in *BL* scenario and in the absence of any restriction, the penetration depends on pure economic convenience thus the presence of fossil commodities, and in particular gasoline, increases. However, still a significant amount of gas oil is required to meet the sector’s final demands. Concerning the *ET* scenario in the same year, as expected, a higher penetration of biodiesel and a significant penetration of electricity in the energy mix is evident. The presence of electric technologies contributes to increasing the average efficiency of the sector and, consequently, reducing the total final energy consumption of the sector (around 70 PJ) which compared to more than 100 PJ in the *BL* scenario shows a –33 % decrease. The consumption of LPG and natural gas in both scenarios decreases, being more pronounced in *ET*. While in *BL* this reduction has a cost-related criterion, their drop in *ET* is attributed to their emissions. The restrictions of the *ET* scenario do not have any effect on the consumption of jet kerosene and consequently, its emissions, as it is the only fuel consumed in the aviation subsector of the model.

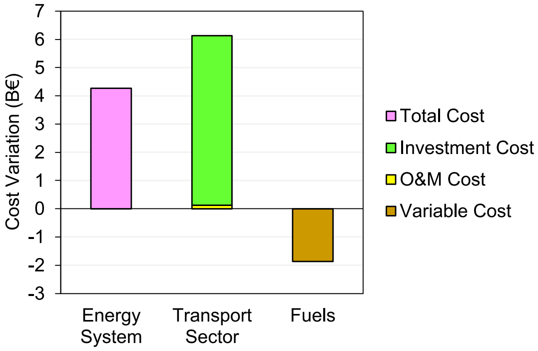

Fig. 13. Variation in the different cost components for the whole energy system, the transport sector and the cost for fuels. The compared costs are cumulative for the entire time horizon up to 2050. The variation in the O&M cost component for the transport sector both includes fixed and variable O&M costs.

As mentioned before, in 2050 the emissions, shown also in Fig. 7a, are significantly lower in the *ET* scenario than *BL*. Residual emissions are mostly due to fossil fuels consumption (see Fig. 12) specifically diesel. The penetration of biodiesel contributes to abating the emissions, being considered carbon neutral in the emissions accounting methodology implemented in the model, as discussed in Section 2.1.8.

Over the 2023–2050 period, compared to *BL*, in the *ET* scenario, some 4.2B€ additional investment costs due to the deployment of electric vehicles are estimated. However, comparing the total system cost in the two scenarios leads to a lower cost difference (2.6B€), thanks to the savings in the fuel cost which partially compensates for the higher investment cost associated with electric vehicles. These outcomes could be further investigated in dedicated analyses with a specific focus on the assumptions made for the technology hurdle rates, as discussed in [73].

Examining the costs dimension, Fig. 13 reports the cost variations over the whole time horizon from the *BL* to *ET* scenarios for the entire

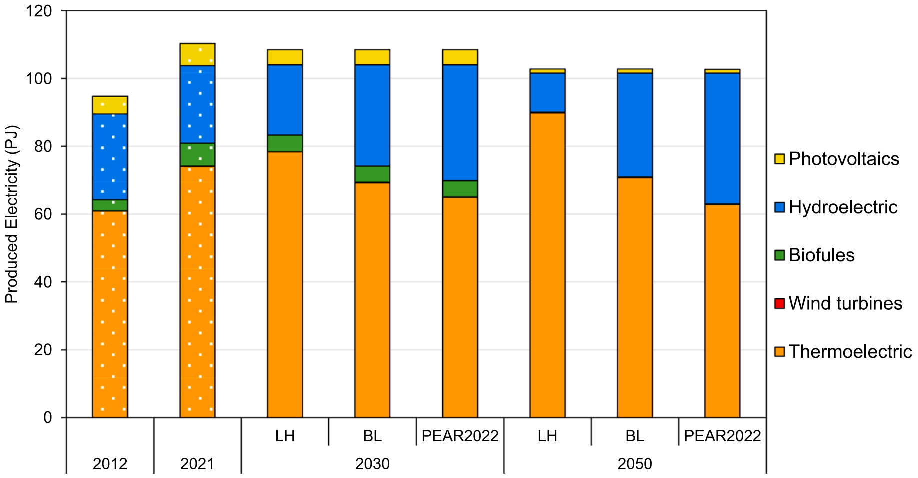

Fig. 14. The electricity mix evaluated by TEMOA-Piedmont compared with TERNA statistics in 2012 and 2021, and the future evolution in the *Low Hydroelectric "LH"*, *Baseline "BL"*, and *"PEAR2022"* scenarios.

energy system, the transport sector and the consumed fuels. The *ET* scenario exhibits a 6B€ of additional cost with respect to *BL*, mainly for investments in innovative vehicles needed to respect the emissions constraint. Looking at system level the additional cost is around 4B€ less thanks to the 2B€ savings in the cost of fuels. This is due to the lower consumption of gasoline and diesel fuel shown also in Fig. 12.

The verification of the reduction of the emissions and the increment of the costs serves to confirm the reliability of the TEMOA-Piedmont in modeling the future policies and transition plans.

3.4. Hydroelectric storyline

As discussed in Section 2.2, this storyline was chosen first of all because hydropower is the most exploited renewable energy source of the region and additionally to assess the model's performance under two series of restrictions affecting the same subsector. Moreover, these scenarios in one case (*PEAR2022*) mirror the energy policy direction and in the other (*LH*), show the restrictions posed by climate conditions on the electricity generation despite the increased capacity of hydropower.

Fig. 14 presents the electricity mix in four representative years 2012 (the first calibrated year of the model), 2021 (the last calibrated year) patterned filled, 2030 and 2050 solid filled. The overall electricity generation in the region showing a growing trend till 2021, starts decreasing mostly due to the efficiency improvement of the end-use technologies in different demand sectors, decreased population and lesser industrial needs. As expected, the share of hydroelectric increases in PEAR2022, shrinks in the *LH* scenario, while the *BL* stays in the middle of the two. This implies a lower and higher penetration of electricity from natural gas, respectively. The other resources are negligible according to the economic optimization performed by the model.

In *LH*, although the share of hydroelectric shrinks, the renewable resources are not coming in play automatically: the existing solar plants (yellow slices) after getting retired, are not substituted because of their cost. The wind turbines (in red, almost not visible) disappear because of low capacity factors, and high cost. The same situation happens for the biofuel power generation (in green). The most economically convenient technologies to cover the electricity demand are thermoelectric power plants (in orange) which are in fact natural gas plants. The same happens in *PEAR2022*, hydroelectricity forced to increase, tends to substitute the renewable energy resources instead of conventional technologies showing the importance of economic incentives in the green energy policies. Another key point is that to achieve a resilient energy transition, besides adoption of renewable resources requires accounting also climate change implications.

In this storyline and as expected, the technology configuration of the *BL* lies between the two upper and lower bounds formed respectively by *LH* and *PEAR2022*. In the *LH* other technologies were supposed to take the place of hydroelectric electricity while in *PEAR2022* hydropower was expected to grow.

4. Conclusions and perspectives

Although regional models are not still widespread, their potential role in showing the region-specific characteristics and giving support to energy planning aimed at realizing the energy transition and decarbonization policies still needs to be investigated. To cover the gap between macro-scale energy system optimization models and territory specific features, and following the open-science principles, the present work introduced the Energy System Optimization Model of Piedmont developed within the TEMOA open-source framework (TEMOA-Piedmont). Besides further proving the maturity and reliability of the open-source models and specifically TEMOA, this study showed the potential of this framework to model energy systems over reduced spatial scales.

The adopted methodology for data collection and for model calibration provides an example of how it is possible to deal with the limited data availability compared to the typical situation for national model instances. At the same time, a valuable framework for future research and practical applications in similar contexts is provided. Although the granularity level of the data and the commodity in question requested different disaggregation methodologies and assumptions varying also from sector to sector, the point-by-point comparison of the model with best available data demonstrates consistency of the adopted approach.

The space-heating subsector of the residential sector was characterized by referring to a Regional database of Energy Performance Certificates (APEs). This database allowed to update the technical parameters of the dwellings as well as the efficiencies of the space heating technologies. The development of the industrial sector of the model began by downscaling the national values taken from TEMOA-Italy. However, further adjustments were required, revealing that the downscaling approach cannot adequately capture the characteristics of a region, underscoring the importance of region-specific models.

The overall resulting final energy consumption of the Region showed an excellent alignment with PEAR (419.2 vs 405.7 PJ for model exceeding by 3 %), particularly in transport (123.6 vs 124.7 PJ) and industry (96.1 vs 92.2 PJ) sectors. The buildings sector presents a higher misalignment (162.7 vs 178.4 PJ) as encompasses residential and commercial sectors. The higher mismatch was relative to the agriculture (10.4 vs 36.8 PJ). The transport sector's fuels repartition in 2014 reflected almost perfectly the PEAR data on consumed fuels (97 % vs 96 %

oil products, 2.4 vs 2.4 % electricity and 0.6 vs 1.7 % natural gas).

To monitor the behavior of the model under restrictions, the model was then used to analyze long-term scenarios in transport and power sectors declared, showing to be a handy tool to implement policies. TEMOA-Piedmont is a significant step towards the extension of open framework energy modelling into regional context and despite being the first ESOM of Piedmont, succeeded in replicating the in-hand statistics of Piedmont Region.

Given the high data-intensity of ESOMs and significant dependency on the available data and their format, the main weakness of the proposed methodology resides in its reproducibility. The model will be subject to enhancement in future releases by of the existing hydrogen module, inclusion of carbon capture and sequestration technologies and amplifying the energy dimension with water and land.

Data availability

The TEMOA-Piedmont model is accessible on GitHub [41], also the TEMOA source code used for the optimization process is available on GitHub [74].

CRediT authorship contribution statement

Farzaneh Amir Kavei: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matteo Nicoli:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Conceptualization. **Francesco Quatraro:** Supervision. **Laura Savoldi:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

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

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Supplementary material

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