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Can We Rely on Open-Source Energy System Optimization Models? The TEMOA-Italy Case Study

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Abstract: Energy system models have become crucial to assess the effectiveness of possible energy policies in pursuing the declared environmental objectives. Among bottom-up models, the tools most widely used by researchers and institutions to perform scenario analyses and policy evaluations rely on commercial software and closed databases, limiting the transparency of the studies. The purpose of this work is to demonstrate that open-source tools, relying on open databases, can be used as a valid alternative to commercial tools, getting equivalent results not only for simple case studies as done so far, but also for complex (national, regional, or multi-regional) reference energy systems. Working on the already available open TEMOA optimization framework, a bottom-up technology-rich model is developed here for the Italian reference energy system on an extended TEMOA version, comparable in detail and complexity to the equivalent TIMES framework. The accuracy of the novel TEMOA-Italy model in a business-as-usual scenario is assessed, showing that the average relative differences with respect to the consolidated TIMES-Italy results are in the order of few percent. The open-source model, available on Github, is now ready for the test and implementation of new optimization paradigms, which was not possible in the TIMES framework.

Keywords: energy system modeling; open-source model; open database; optimization models; TEMOA

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1. Introduction

Long-term energy planning is crucial in the definition of energy programs for governments worldwide and keeps proving itself as a valuable tool to assess the effectiveness of energy transition strategies [1]. In the current framework, where human activity is globally recognized as the main cause responsible for climate change and its related effects, an informed policy making based on accredited energy models is fundamental to try and assess the most compelling pathway for the mitigation of those problems [2].

This work aims at proving that energy models developed in open-source frameworks can be used to perform scenario analysis with results equivalent to those obtained through well-accepted and widely used commercial software. This step of verification is necessary for the long-term goal of overcoming the typical economic optimization paradigm (currently the only one performed by bottom-up energy system optimization models, ESOMs [3]) and, e.g., to effectively introducing a sustainability accounting/optimization component. This goal requires the availability of open and reliable tools, guaranteeing at the same time the accessibility to the source code and a verified robustness of the optimization algorithm compared to more widely used tools.

While open-source frameworks, such as the Tools for Energy Model Optimization and Analysis (TEMOA [4]), for instance, are available in principle for the implementation of new objective functions, their embedded description of the reference energy system (RES) is not fully comparable and compatible with the one implemented in commercial tools such as the TIMES model generator [5], so that a one-to-one comparison on models developed in the two frameworks on a large RES (at national level) has never been performed to the best of our knowledge. Since the reliability of an energy model is essential, before moving to the shift of the objective function to include sustainability features, an open framework is here selected, enhanced, and extended to a level that the tool becomes comparable to TIMES. The capability of the resulting open-source framework and tool to replicate the TIMES framework and tool is assessed by a rigorous benchmark. A test case is built for the Italian energy system, and a business-as-usual scenario is analyzed both with TEMOA-Italy and with a well-established TIMES-Italy model, currently used for the quarterly analysis of the Italian energy system [6].

TIMES and Open-Source Energy System Optimization Modeling Frameworks

Among the wide range of existing ESOMs [7], bottom-up models can take advantage of a detailed description of the energy technologies involved in each step of the considered RES. They work with a high disaggregation level, thus needing extensive database of technical and economic data to support the characterization of each component [3]. One of the most relevant examples [8] of bottom-up, technology-rich energy modeling framework is represented by the TIMES model generator [5] (and its ancestor MARKAL [9]). TIMES combines a technical engineering approach to macroeconomic ingredients, using a linear programming formulation to produce the least-cost optimized composition of the energy system under exam over a medium-to-long term time scale under the assumption of partial equilibrium of competitive markets in a perfect foresight approach [10]. Specific combinations of different policies and developments of the energy system allow the definition of different scenarios, which provides a set of constraints on technologies, commodities, or driver evolution. The basis of the TIMES models lay in the identification and description of a RES, i.e., a network of the interconnections of all the commodities and technologies composing the energy system under study [11], and of the end-use demands. A complete RES encompasses, from one side, the description of the main energy consumption sectors, namely the residential, the commercial, the agriculture, the transport and the industry sectors, and from the other side the supply sectors (upstream and power sector) for the extraction and transformation of primary energy sources and electricity and heat production. Working over a long-term time scale, the RES typically includes not only the existing technologies, but also a set of new technologies to be integrated into the energy mix by the optimization algorithm to satisfy given end-use demands, based on their techno-economic characterization. Two examples of the required characterization for TIMES technologies are presented in [12] for the industrial sector and in [13] for the transport sector. End-use demands can either be estimated through exogenously specified arrays of values obtained from external sources or by computing them [2]. Methodologies for the calculation of the demands can be either based on general equilibrium models (e.g., GEM-E3 [14]) or on simpler autoregressive models as in [15].

Among 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 [16]. At the global level, the TIMES framework is at the basis of the analyses carried out by the International Energy Agency (IEA) for the periodical publication of the Energy Technology Perspectives (ETP) [17], first issued in 2006, to assess the future role of low-carbon energy generation. Although some of the (technology) database used in the JRC-EU TIMES Model and ETP are open and publicly available, the TIMES generator requires the use of commercial software to read the input data, solve the optimization problem, and postprocess the results.

Recently, a growing awareness is spreading in the scientific community about open science, i.e., the possibility to freely disseminate data and results of scientific research, increasing responsiveness and spreading knowledge regardless of the economic status of the recipients [18]. The importance of that issue is so relevant that it falls within the priorities of the European Commission [19]. In particular, the open science purpose can be realized in the field of energy modeling providing open access to both models and data, leading not only to higher quality, reliability, and recognition of the results of energy projection tools [20], but also to the spread of attempts of shaping the energy system according to non-economical paradigms.

While TIMES model instances cannot be currently defined part of an open modeling environment, several open-source tools or frameworks have been developed in the recent years for the energy system optimization and analysis, with some focusing on the optimization of the electricity system alone, e.g., Balmorel [21], pyPSA [22], and Switch [23], and some others referring to the overall energy system. Two main tools fall in the second category, namely the Open-Source Energy Modelling System (OSeMOSYS [24]) and the TEMOA [4], aimed at replicating the TIMES optimization algorithm using linear programming techniques to minimize the system-wide cost of energy supply by optimizing the deployment and utilization of energy technologies over a user-specified time horizon to meet end-use demands [25]. So far, however, any of those tools has been developed to allow use of different objective functions, which would identify the most suitable configurations of the energy systems meeting a target or paradigm different from the minimum cost of the system [26].

As of today, OSeMOSYS has been used to develop a large body of model instances used for deterministic scenario analyses to assess optimal energy transition pathways at different national and international scales. The tool has been adopted as a support for several research questions. For instance, the OSeMOSYS-SAMBA has been developed and used for the analysis of energy security issues in South American countries [27]. Models based on OSeMOSYS have been developed for the analysis of future electrification pathways in Tanzania to decarbonize the power sector and ensure universal energy access [28] or for the study of the integration of renewable energy sources in the power system in Tunisia [29]. An interesting attempt to expand the OSeMOSYS formulation is shown in [30], where power plant retrofitting is modeled expanding the mathematical equations of the source code considering, for instance, possible change of plant (or operation) characteristics, or lifetime extension, with an application to the Korean RES. Another attempt for the expansion of the model formulation is presented in [31], where the potential of different demand-response strategies in the balance between electricity supply and demand is assessed for the case of the Portuguese power system in three scenarios. Note, however, while no applications of OSeMOSYS have so far attempted the adoption of objective functions different from the one implemented in TIMES, the only attempt to compare the two tools on the same case study is limited just to the power sector [32].

On the other hand, the set of publications involving applications of TEMOA to real case studies is still quite poor. The main focus of works concerning TEMOA is devoted to the presentation of the modeling framework [4] and its uncertainty analysis tool for multi-stage stochastic optimization [33]. An example of application of TEMOA for the analysis of the United States energy system is presented in [34], where the US is presented as a single region and projections are drawn from 2015 to 2040 to assess the impact of the absence of federal climate policies, in response to the withdrawal of the US government from the Paris Agreement, first announced in 2017, then formalized in 2020 [35] and finally revoked after the settlement of the President Biden administration at the beginning of 2021 [36]. The dataset used in the cited work is based on the United States Environmental Protection Agency (EPA) MARKAL model [37] and represents the basis for the Open Energy Outlook (OEO) project. The OEO is a non-policy biased analysis for the assessment of possible U.S. energy futures to inform future energy and climate policy efforts [38]. Another TEMOA-based application explores South Sudan electricity planning strategies using stochastic optimization to produce a near-term hedging strategy on a time horizon of 20 years from 2017 on [39]. So far, no comparison of the results of a TEMOA-based model have been compared to the results of an equivalent TIMES model for the sake of benchmarking of TEMOA.

The paper is structured as follows. In Section 2, the motivations for the selection of TEMOA as the open modeling framework are discussed, together with the procedure followed for the RES database construction, the implementation of drivers and constraints and the optimization problem which is solved, highlighting the integrations done with respect to the standard TEMOA framework. Section 3 presents the main features of the case study at hand, devoted to the Italian energy system. In Section 4, the results obtained from TIMES-Italy and the new TEMOA-Italy are compared to ensure their correspondence, and the accuracy of the TEMOA model replicating the TIMES framework algorithm is assessed. Eventually, the conclusions and the policy implications of the work are presented in Section 5.

2. Methodology

The following sections present the development of the TEMOA-Italy model, from the selection of the open-source framework for the model implementation to the construction of the RES and the implementation of drivers and constraints to the already-available TEMOA framework. Note that, with respect to the original tool, several technical parameters and procedure were developed and added to the TEMOA source code, not yet implemented in the published version of the framework [40], as they were necessary to fully replicate the parameters used in a TIMES-based model such as the TIMES-Italy. To keep track of all the changes made to the TEMOA source code, a detailed guide has been issued, allowing to obtain the version in use of the framework starting from the available one on GitHub. This guide and the resulting integrated open-source tool are available at [41], on GitHub.

2.1. Selection of the Open-Source Framework

Based on [26], for the implementation of an ESOM with at least the very same potentialities of TIMES from an open-source framework, two tools have been taken into consideration: OSeMOSYS [24] and TEMOA [4].

Table 1 presents an overview of the main features of the OSeMOSYS and TEMOA open tools against TIMES. Concerning the input data entering system, OSeMOSYS provides the Model Management Infrastructure (MoManI), an open-source browser-based platform which allows model development and the editing and update of the underlying OSeMOSYS equations [42]. Moreover, TEMOA provides an online user interface for model creation and management. Anyway, the input dataset for any TEMOA model instance can be constructed either as a text file or a relational database (preferred in case of larger datasets). Relational databases for TEMOA include the structure of the different tables filled with input data for the model and are stored in a text file in .sql format. Once the .sql text file is complete, it is converted into a .sqlite database in order to be interpreted by the TEMOA source code. Finally, the TIMES input data system is articulated over two passages: the set of Excel files containing input data for the model, built following a precise structure and syntax (the number and complexity of the Excel database can increase a lot with model size and degree of detail) are fed to the VEDA Front-End [43] model user interface that recalls the TIMES source code and the solver. OSeMOSYS and TEMOA, differently from TIMES, in their standard formulation share the infeasibility to set interpolation rules for the future evolution of parameters.

Concerning the possibility to modify the model structure (possible with OSeMOSYS and TEMOA), the TIMES source code can be downloaded for free after having signed a Letter of Agreement and requested credentials [44]. More in detail, 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 redefined to include, for instance, sustainability parameters [45] independent on costs or to shift to a multi-decision algorithm [46,47] without the ETSAP approval (that obtains the intellectual property of any approved changes [48]).

The source code for the three modeling frameworks under analysis is based on high-level programming languages: among them, OSeMOSYS alone provides three different versions of the source code in GNU [49], Python [50], and GAMS [51], while TEMOA is only written in Python and TIMES in GAMS. In particular, the choice of Python, with its verbosity, its easy access to a rich ecosystem of supporting modeling tools and the support of a wide user community and documentation is deemed as the most appropriate choice to reduce the learning curve for new modelers [4].

Table 1. Comparison of available tools for macro-scale energy system optimization.

Feature \ Tool	OSeMOSYS	TEMOA	TIMES
Features of the input data entering tool	Several steps are required for the definition of the time scale, space-scale, and technological characterizations, but allows a prompt visualization of the RES network	Complexity increases with the complexity of the energy system, but the code formulation makes it straightforward	Complexity increases with the complexity of the energy system (especially with the number of regions), due to the large number of Excel files to be managed
Future evolution of parameters	The required values must be declared at each desired time-step	The required values must be declared at each desired time-step	The required values must be declared at each desired time-step, with the possibility of assigning different interpolation rules
Type of programming language	High-level	High-level	High-level
Programming language(s)	GNU open-source Python open-source GAMS commercial	Python open-source	GAMS commercial
Optimization software (solver)	GLPK for GNU open-source GLPK for Python open-source CPLEX for GAMS commercial	GLPK for Python open-source CPLEX for Python commercial (but can be run on an external server) Gurobi for Python commercial (but available with free academic license) COIN-OR CBC open-source [1]	CPLEX for GAMS commercial
Features of the optimization software	Suitable for simple energy systems if using-open-source solvers	Suitable for large-scale energy systems	Suitable for large-scale energy systems
Possibility to modify/improve the code	Possible	Possible	Possible, but it requires the ETSAP approval
Possibility to perform stochastic optimization	Impossible at present state, but an extension can be formulated	Possible with an already implemented Python module	Possible, but time-consuming and complex due to the difficult data handling

[1] Not available for Windows.

On the other hand, one of the main differences between OSeMOSYS and TEMOA regards the availability of open-source solvers, thus the complexity of the energy system that can be optimized by the model. Indeed, using the freely available GLPK [49] solver coupled with OSeMOSYS, only relatively simple energy systems can be optimized with acceptable computational cost. On the contrary, with TEMOA there is the possibility to use freely also solvers allowing the optimization of larger-size energy systems, such as CPLEX [52] or Gurobi [53] (GLPK can be nevertheless used for simpler study cases). TIMES, instead, requires a commercial license in order to use CPLEX or other solvers. The other important difference between OSeMOSYS and TEMOA is that the latter is provided with an extension of the deterministic code that allows performing a stochastic optimization. This allows conducting uncertainty analysis with large and complex models to evaluate the accuracy of the obtained results.

All in all, the OSeMOSYS and TEMOA open-source tools have already proved to be mature enough to be comparable to TIMES, even though the continuous extension of their functionalities (which is also partly taken on in this work concerning TEMOA) would be beneficial to increase their reliability [20].

In this work, the choice of TEMOA for the development of the case-study, i.e., an open-source model for the Italian energy system, is mainly due to three reasons: (1) the possibility to use freely powerful open-source solvers as CPLEX and Gurobi; (2) the use of Python, allowing to rely on numerous software packages and libraries developed in that programming language; and (3) the possibility to model large-scale energy systems.

2.2. Enhancement of the TEMOA Framework

This section presents the improvements to the TEMOA framework developed to empower the capability to model a complex RES and become then comparable to a TIMES model of the same energy system.

The main sectors composing a generic RES and the connection between its different sections are shown in Figure 1. The system is composed of three demand-side sectors (buildings, transport, and industry) and two supply-side sectors (upstream and the power sector). While the demand-side sectors consume energy to satisfy final energy service demands, the supply-side sectors produce the energy commodities consumed by the demand-side (namely: fossil fuels, primary renewable potential, electricity, and heat). For the correct description and optimization of the energy system, a complete energy system modeling framework should be structured to include the techno-economic description of the technologies, the drivers for the demand projection, and a set of constraints. Eventually, a proper objective function (to be maximized or minimized in a linear programming problem) should be identified.

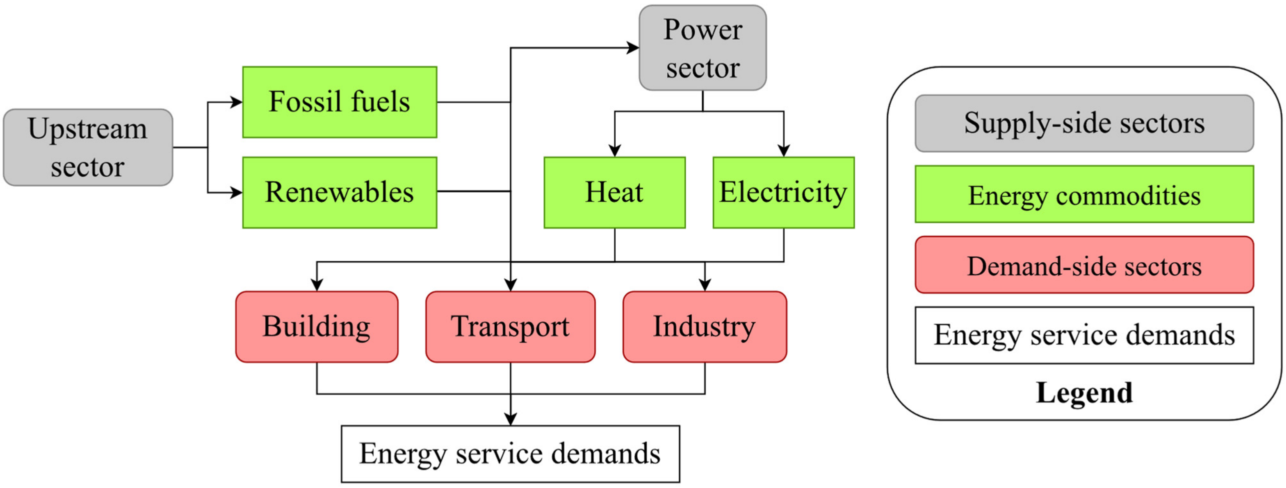

Figure 1. Schematic representation of the general reference energy system of a bottom-up energy system optimization model.

As shown in Figure 2, the essential items for the definition of the RES structure are the commodities (labeled as physical, emission, or demand commodities), the technologies, and the respective efficiency, connecting commodities and technologies to define the technology chain from extraction of natural resources to the final service demands. The commodities labeled as "demand commodities" must be the output commodities of at least one technology and the demand level must be specified in the "Demand" table per each milestone year labeled as "future" year. The demand and the emission commodities can only be output commodity for a technology, while the physical commodities (energy or materials) can be both produced and consumed by different technologies. Then, other very important parameters are those related to the cost of the technologies, being directly used in the formulation of the objective function to be minimize (the total cost of the system).

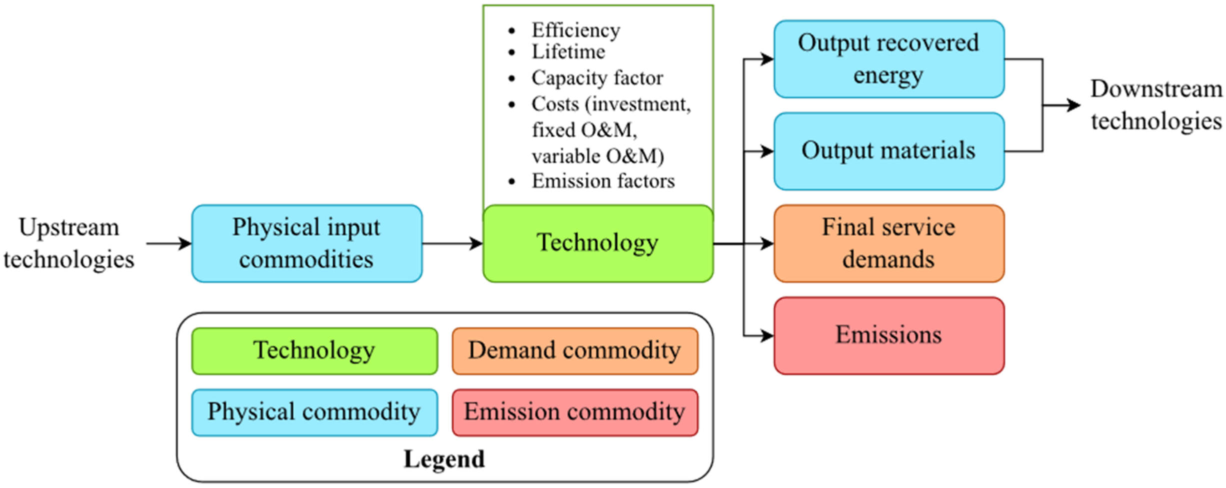

Figure 2. Schematic representation of the different commodity categories in the RES construction.

A list of the main parameters involved in the construction of the database containing the techno-economic characterization of the Italian RES in the TEMOA model is provided in Table 2, reporting the parameters description and their names in TEMOA. In particular, 3 categories of parameters are included in the TEMOA formulation:

- **Labels** used for internal database processing identify the different kinds of commodities (physical, demand, emissions) and technologies ("supply-side" or "demand-side" sectors), and the belonging of each time period to the set of "existing" or "future" years. More in detail, existing (historical) periods represent a base for the model where the energy system configuration at a certain point in time can be defined and has no freedom neither associated investment costs as the existing technologies are already present in the energy system when the analysis begins. Existing periods are also used to calibrate the energy-use features of the technologies included in the model, based on energy statistics. Future periods, on the other hand, represent the optimization horizon in which the total cost of the system has to be minimized.
- **Sets** associate definite entities to the labels mentioned above. In TEMOA there are mainly four kinds of sets: periods, sub-annual "time slices", technologies, and energy commodities. Periods require to assign the definition of the milestone years considered as representative of each period. Then, sub-annual time slices subdivide each period into portions of the day (day, night, and peak) and seasons of the year in order to better tune the model of the supply part of the RES under exam. Indeed, production features of some technologies (e.g., renewable plants) can strongly vary according to the seasonal or daily time slices in which they operate. The technologies set contains the definition of all the possible energy technologies that the model can build, and the commodity set contains the definition of all the input and output forms of energy that the different technologies consume and produce.
- **Parameters** can be used to define processes or constraints, thus, to assign techno-economic features, or to assign upper or lower bounds for technologies' evolution.

The detailed technical discussion of the new parameters and equations added to the TEMOA framework and of the parameters which formulation has been modified with respect to the original version of the code is provided in Appendix A. The main aspects concern the implementation of an annual capacity factor in the framework (in addition to already available time-slice specific capacity factors), the development of new constraints for technology groups and the development of an automatic database preprocessing for the data interpolation/extrapolation along the time, the computation of emission factors, and the demands projection in time according to driver and elasticity values.

Table 2. Main items included in the TEMOA database. New parameters introduced within this study and parameters whose formulation has been modified with respect to the original TEMOA version are highlighted in bold.

Category	Description	TEMOA Name
Labels used for internal database processing	Commodity category	commodity_labels
	Technology category	technology_labels
	Time period labels	time_periods_labels
Sets	Commodity names	commodities
	Technology names	technologies
	Milestone years	*time_periods*
	Seasons of the year	*time_season*
	Time periods of the day	*time_of_day*
Parameters used to define processes	Discount rate	*GlobalDiscountRate*
	Demands	*Demand*
	Efficiency	*Efficiency*
	Existing capacity	*ExistingCapacity*
	Capacity factors	*CapacityFactor* *CapacityFactorTech* *CapacityFactorProcess*
	Capacity to activity	*Capacity2Activity*
	Fixed O&M cost	*CostFixed*
	Investment cost	*CostInvest*
	Variable O&M cost	*CostVariable*
	Emission factors	*CommodityEmissionFactor* *EmissionActivity*
	Economic lifetime	*LifetimeLoanTech*
	Technical lifetime	*LifetimeTech* *LifetimeProcess*
Parameters used to define constraints	Minimum capacity constraint	*MinCapacity*
	Maximum capacity constraint	*MaxCapacity*
	Minimum activity constraint	*MinActivity*
	Maximum activity constraints	*MaxActivity*
	Minimum activity for technology groups	*MinGenGroupTarget*
	Maximum activity for technology groups	*MaxGenGroupLimit*
	Maximum production across time periods	*MaxResource*
	Share of input commodity	*TechInputSplit*
	Minimum commodity input share for technology groups	*MinInputGroup*
	Maximum commodity input share for technology groups	*MaxInputGroup*
	Share of output commodity	*TechOutputSplit*
	Maximum commodity output share for technology groups	*MaxOutputGroup*

Despite the new constraints added or further developed in TEMOA to allow a fair comparison to TIMES, there are differences in the set of equations implemented within the two frameworks, and in the formulation of the optimization algorithm. As an example, Equations (1)–(3) show the different formulation of the relationship between the total flow of output commodity of a certain technology and its installed capacity in TIMES [54] and TEMOA [55], respectively. Given the relevance of the relationship between activity and capacity for the construction of the optimized RES, as they directly determine its cost, we present here its different implementation in the two modeling frameworks. The two equations are intended to model the same concept, namely the constrain on the total flow of output commodities to the capacity multiplied by a conversion factor. However, the TIMES formulation (Equations (1) and (2)) is far more detailed and complex than the TEMOA one (Equation (3)).

$$TOT_{OUT} = \begin{cases} \sum FLO & if\ commodity\ does\ not\ contribute\ to\ ACT \\ \sum ACT & if\ commodity\ contributes\ to\ ACT \end{cases} \quad (1)$$

$$\begin{aligned} TOT_{OUT} &= (NewCAP + OldCAP - RetCAP - OfflCAP) \times \\ &\times (CapacityFactor \times Capacity2Activity \times DTS \times FAC) \end{aligned} \quad (2)$$

$$\sum ACT + \sum CUR \leq CAP \times (CapacityFactor \times Capacity2Activity \times DTS \times FAC) \quad (3)$$

In Equation (1) in the TIMES framework, the contribution of a commodity to the total commodity output TOT_{OUT} includes commodities contributing or not to the process activity ACT. As a matter of fact, the summation $\sum ACT$ is the total activity of a technology and the summation $\sum FLO$ is the total commodity production not contributing to the process activity. This distinction is not present in TEMOA, where a single term is sufficient to represent the total commodity production of a technology, and namely $\sum ACT$ in Equation (2). In addition to the global flow of output commodity $\sum ACT$, the term $\sum CUR$ is used in TEMOA to represent the total curtailment of energy production (useful for scenarios with high renewable penetration). Note that curtailments (equivalent to commodity overproduction) are not allowed in TEMOA by default but only if explicitly set by the modeler, while in TIMES overproduction is generally possible if specific constraints are not used to avoid this.

Moving now to the right-hand side of Equations (1) and (2), the available capacity is computed by TIMES and TEMOA in two different ways. TIMES allows distinguishing among the (positive) contributions of new installations ($NewCAP$) and residual capacity from past periods ($OldCAP$), and the (negative) contributions of the retired capacity ($RetCAP$) and the started-up, shut-down, and off-line capacities ($OfflCAP$). On the other side, the total capacity is instead represented in TEMOA (Equation (2)) with a single variable (CAP), including the new, old, and retired capacities.

Concerning the parameters composing the conversion factor from capacity to activity they are the same in the two formulations and, namely: *CapacityFactor*, *Capacity*2*Activity*, the Duration of the Time Slice (DTS), and the Fraction of Available Capacity (FAC). Those and similar differences in the implementation of the two frameworks justify minor discrepancies between the results from the two models, as it will be commented more deeply in Section 4.

3. Case Study: The Italian Energy System

In the context of energy system models belonging to the TIMES family, the TIMES-Italy model instance for the analysis of the Italian energy system has been developed throughout the last years by the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA). TIMES-Italy has gained high policy relevance as it was used to support the Italian National Energy Strategy (SEN) [56] and is currently used for the periodic quarterly analysis of the Italian energy system by ENEA [6]. For those reasons, the TIMES-Italy model has been chosen as reference for the development of the novel TEMOA-Italy model. The TEMOA-Italy is the implementation of the updated TIMES-Italy in the TEMOA framework, and it includes in the time horizon only a single existing year, corresponding to the "base year" in the TIMES-Italy model (set in 2006). For that reason, all the existing technologies are installed at the base year and their capacity is maintained for their entire lifetime, while their activity is constrained to a linearly decreasing trend (as explained in Appendix A.3). The choice of keeping 2006 as the base year is not only motivated by the necessity to fully replicate the existing TIMES-Italy model, but also by the possibility to perform a validation of the model comparing the results obtained for the historical period 2006–2020 with the actual statistical data in terms of energy consumption and demands evolution. Such a model validation is beyond the scope of this paper and will be addressed in the future. TIMES-Italy is a single-region model, thus the relationship between Italy and the countries related to it via commercial and energy trade is defined using import-export parameters. The model serves as a tool for energy projections up to 2050 and has been recently re-calibrated (i.e., it matches the actual energy statistics provided by the national energy balances, see for instance [15] for the industrial sector) on 2006 historical data, provided by the International Energy Agency [57]. The tool contains a detailed description of the Italian energy system in 2006, from the extraction and import of primary energy source to the transportation, buildings, industrial, and agricultural sectors final energy use.

The RES under analysis for the Italian region [58], summarized in Figure 3, is subdivided into five sectors (three demand-side sectors and two supply-side sectors). The demand-side sectors are buildings (including the agriculture, commercial, and residential sectors), transport, and industry. The supply-side sectors are the power sector and the upstream sector. Each sector includes a set of technologies, characterized by several techno-economic parameters (see also below), used to produce all the commodities necessary to ensure the production of the required final energy service demands. The upstream sector is reported in the upper part of the diagram (orange boxes): it includes fossil fuels extraction, production, and transformation technologies and renewable energy sources production technologies (i.e., fictitious technologies that transform renewable energy potential in energy commodities). The output commodities of the upstream sector (along with fuel imports) are inputs for the power sector and the demand-side sectors. Power sector technologies (yellow boxes) allow further processing of energy commodities, and in particular for electricity (centralized and distributed) and heat production. Imports from abroad also contribute to the electricity availability. The demand-side sectors transform energy commodities from the power and upstream sectors into energy service demands, and they are sketched in the red boxes in the bottom part of the diagram.

Figure 3 also reports the number of technologies included in the energy system, per energy sector (transport, industry, buildings, and power) and subsectors (each sector can satisfy a set of different demands relative to different subsectors). The existing technologies (at least one final technology per each energy subsector) are those involved in the base year calibration of the model to reproduce the base year technology chain consuming energy to satisfy the associated final energy service demand. To match the energy consumption in the timesteps after the base year, two options are available: to keep the existing technologies in service, accounting for their postulated increasing efficiency with time, or to constraint their availability as time goes by, to allow their substitution them with new technologies. The first option is simpler but does not allow to consider any relevant technology change. The second requires including in the database the techno-economic description of the available new technologies; it is more precise and allows the optimization to choose among a larger number of available options. Concerning the new technologies included in the TEMOA-Italy, a higher level of detail (corresponding to a larger number of technologies included in the dataset) is available for those demand categories presenting a higher energy consumption (for example, residential and commercial space heating or cooling, chemical, or iron and steel in the industry sector, and road transport). This is reasonable, because it increases the computational efficiency of the optimization, having a higher accuracy in the technology description only for the sectors characterized by a higher impact on the total energy consumption. Eventually, focusing on the power sector, a larger number of renewable energy technologies, with respect to the fossil fueled technologies, are described in the model, expecting a higher penetration of renewables in the energy mix for the future. The current stage of the model does not include nuclear power plants, given that there are no prospects for the development of the nuclear sources in Italy due to the unambiguous political choices [59]. The techno-economic characterization of the technologies included in the TIMES-Italy and TEMOA-Italy models is available at [60]. The detailed input files for the construction of the Italian RES, as shown in Figure 3, are available in [41]. Among the many existing and new technologies implemented in the model for the different sectors, the detail of the techno-economic characterization for the three most energy-consuming demand-side subsectors and namely chemical industry, road transport cars, and residential space heating is reported in Tables A2–A4 (in Appendix B.2), respectively. Investment and fixed O&M costs have not been reported for existing technologies, since their installed capacity and their availability in time comes only from the base year calibration and the associated constraints, i.e., it does not depend on the optimization performed by the model. For parameters varying in time (e.g., increasing efficiency or decreasing costs), the minimum and the maximum values have been reported.

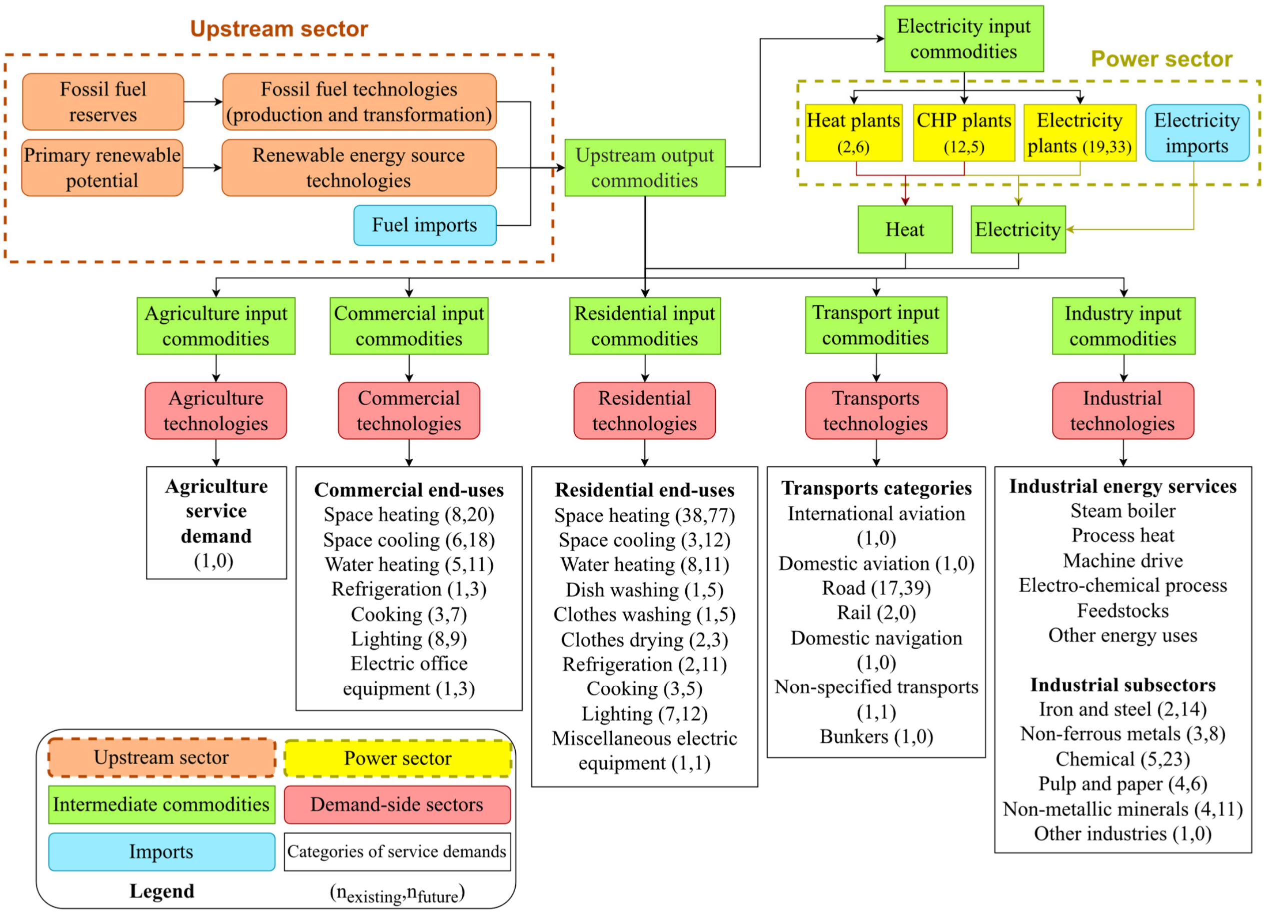

Figure 3. Schematic structure of the TEMOA-Italy reference energy system, connections between the different sectors and number of the described technologies.

In order to perform future projections in the different sectors, the model relies on a database of existing and innovative technologies (both at commercial and research and development stage), while future service demands in each sector of the economy (e.g., driven distance by car or truck, residential/commercial space heating, industrial production of steel or paper, etc.) are projected according to a set of drivers and demand elasticities and must be satisfied by the model at each time step. Future projections are articulated over several time steps. For the work presented here, the selected time periods are set in 2007, 2008, 2010, 2012, 2014, 2016, 2018, 2020, 2022, 2025, 2030, 2040, and 2050. The time periods resolution is chosen to be less refined by the end of the time horizon because of the higher degree of uncertainty about the projections of drivers (see Appendix B.1 for details).

While the annual value of each final service demand of the model is known at the base year and projected along the time with exogenous drivers and elasticities, the intra-annual distribution of the demand is also important to consider seasonal and daily variations of environmental conditions that affect the energy demands. The division of the milestone year into more refined time-slices is performed in TEMOA-Italy (as in TIMES-Italy) with four seasons (spring, summer, fall and winter) and three times of day (day, night and peak), leading to 12 time slices per year. A percentage of the total time of the year is assigned to each time-slice, as reported in Table 3. The time repartition among the seasons is uniform (25% of the total time of year per season), while it reflects the different duration of day and night in summer and winter.

Table 3. Percentage subdivision of total time of the year among the time-slices (in TIMES-Italy and TEMOA-Italy) [58].

Seasons / Times of Day	Spring	Summer	Fall	Winter
Day	11.5%	12.5%	11.5%	10.5%
Night	12.5%	11.5%	12.5%	13.5%
Peak	1.0%	1.0%	1.0%	1.0%

Final service demands could be distributed among the time-slices according to different proportions with respect to those shown in Table 3 to consider their possible significant dependence on environmental conditions. For instance, that is crucial for lighting and thermal energy in buildings, being lighting demand influenced by the time of day and space heating and cooling strongly dependent on the season of the year [58]. Such an unbalanced time distribution of demands among the time-slices implies that an overcapacity of technologies producing them is installed, since the energy system must be able to satisfy the demand even in all the time-slices. While those aspects are fully considered in the TIMES-Italy model for the interested service demands, at the current state of development of TEMOA-Italy all the demands are annual. This is because introducing non-annual demands significantly affects the TEMOA computational cost (as discussed in Section 4.1) and, for this reason, the intra-annual optimization has been reserved only to the power sector at the moment.

For what concerns the supply-side, the intra-annual representation of energy production is mainly relevant for renewable energy plants in the power sector, as their production is strongly influenced by weather conditions (e.g., the model must consider that the solar resource is not available during the night). Those phenomena are modeled (both in TIMES-Italy and TEMOA-Italy) through a variable capacity factor in the different time slices of the year, used to represent the uneven availability of the resource during the year for each renewable plant.

4. Comparison of Results

In this section, the results obtained from both TIMES-Italy and TEMOA-Italy models are compared in a business-as-usual scenario. The scenario is characterized by:

- Medium level-costs for import of primary sources [58].
- No subsidies to renewable electricity production.
- Neither CO_2 emission limits, nor carbon tax applied.
- No carbon capture, utilization, and storage technologies.

4.1. Computational Cost

The first general result to be compared concerns the computational costs associated to the optimization processes performed by the two tools. This is a relevant aspect to evaluate the performances of an open tool compared with a commercial competitor, especially dealing with models that allow also stochastic optimization. A rigorous evaluation of that parameter is quite difficult, being it dependent on the performances of the machine where the model is installed. Usually, the most time-consuming phases of an ESOM run are the construction of the model instance and the resolution of the optimization problem. A qualitatively evaluation of the computational costs is in the order of 1 min for TIMES-Italy resolution (few seconds due to the construction of the model instance and the remaining due to the optimization) and 10 min for TEMOA-Italy resolution (5 min for both phases). The non-negligible computational cost required to solve a complex model such as TEMOA-Italy is the main weakness of TEMOA if compared to TIMES and an important limitation to possible studies based on stochastic optimization. Moreover, the TEMOA optimization time is strongly affected by the number of intra-annual technologies and non-annual demands included in the energy system (for which an optimization on each time-slice is required and it is not sufficient to optimize the annual production of output commodities).

4.2. Aggregated Results

Figure 4 describes the optimal primary energy consumption (by energy source) in 2030, in terms of: imported energy from abroad (including fossil fuels and electricity); fossil fuels produced in Italy; and renewable energy sources (such as solar, hydroelectric, biofuels, geothermal and wind). The results show a very good agreement between the two models with a swap of 2–3% in the fossil fuel consumption. While the lower natural gas consumption in TEMOA-Italy is also highlighted in the electricity mix (Figure 5) and will be discussed in the following, the difference in oil consumption it is not reflected in the power sector, and it is due to the demand-side. Being oil products mainly consumed in transports, the investigation of this discrepancy is reported in Section 4.3.2, dedicated to the transport sectorial results.

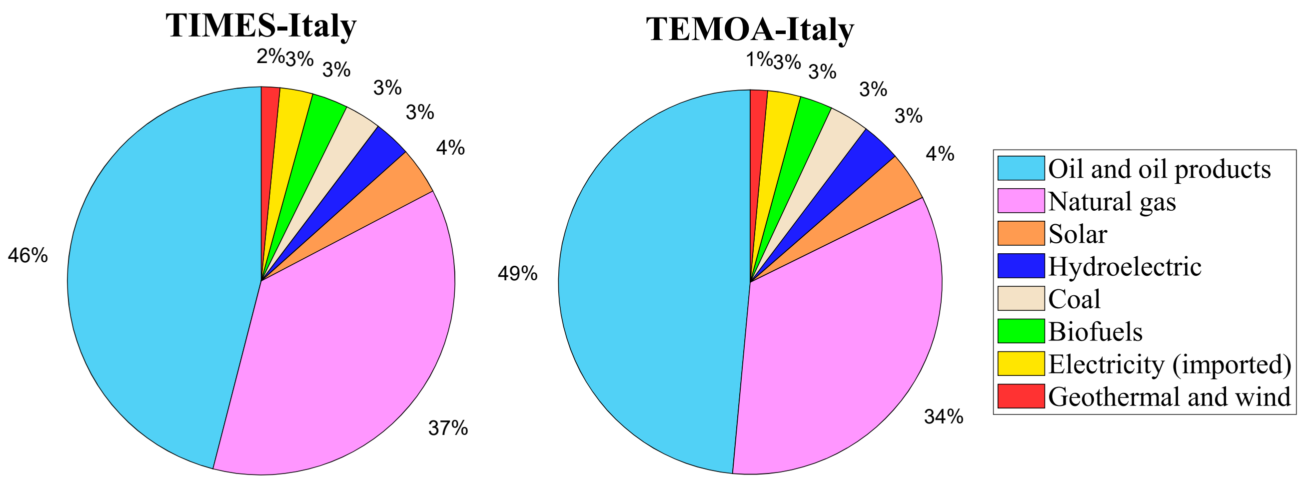

Figure 4. Comparison of the optimal overall energy mixes in 2030.

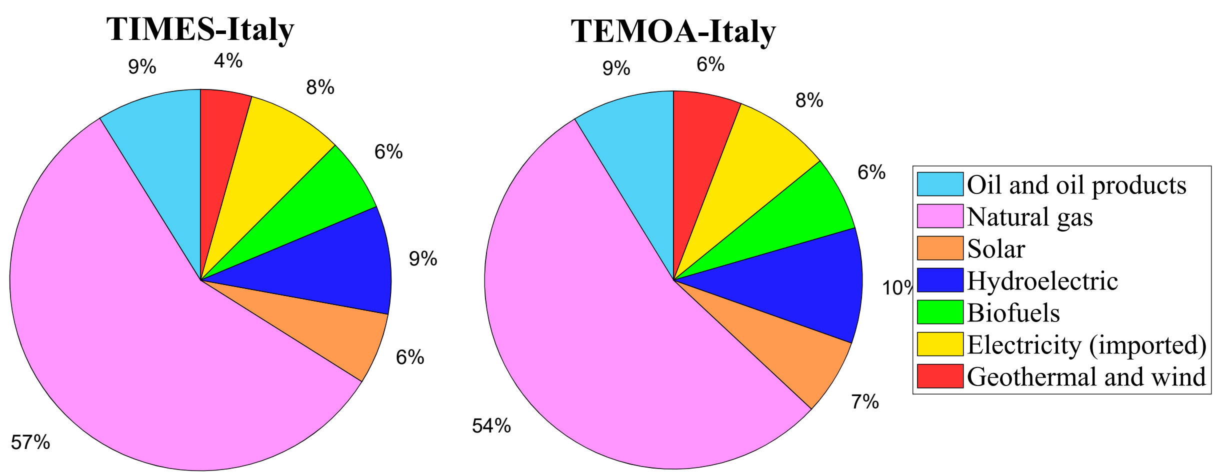

Figure 5. Comparison of the optimal energy mixes for electricity production in 2030.

Figure 5 shows the optimal resource consumption for electricity production in 2030. The share of oil and oil products in the power sector is the same, suggesting that the difference in the primary energy consumption shown in Figure 4 is due to the demand-side of the energy system. The natural gas consumption reflects the difference already shown in Figure 4 for the primary energy consumption (lower in the TEMOA results) and it is compensated by some of the renewable sources (geothermal and wind, hydroelectric and solar). Since a significant fraction of the natural gas consumption in the power sector is due to CHP plants (producing both electricity and heat) in the studied scenario, the adopted characterization strategy to model this kind of plants is perfectible. A typical information involved in modeling CHP plants is the ratio between heat and electricity produced. While that is implemented in TIMES-Italy with a dedicated technical parameter i.e., the coefficient of heat to power ratio (CHPR) that usually represents an upper limit, in TEMOA-Italy the ratio between heat and electricity is fixed.

4.3. Disaggregated Results

The output data of an energy model optimization consist of several types of results. The detailed comparison between the two models has been carried out here focusing on three main aspects:

- The contribution of each final technology to the production of each demand commodity and its evolution along the time horizon (technology mix).
- The consumption of each energy commodity, disaggregated by sector, and its contribution along the time horizon (energy mix).
- The associated costs to the selected technologies along the time horizon.

The quantification of the accuracy of the results is evaluated through the relative differences between the TIMES-Italy and the TEMOA-Italy outputs. The level of detail on which the analysis is performed is crucial to determine its validity in benchmarking the TEMOA results. In other terms, to have a precise evaluation of the open model accuracy, the discrepancies should be calculated at a sufficient disaggregation level. For that reason, the evaluation is carried out comparing the results for the single technologies production, sectorial energy consumption, and costs. The relative difference between the two sets of results is then calculated according to Equation (4), where x^i is the commodity production, consumption, or cost associated to the i^{th} technology and $diff^i$ is the calculated relative difference.

$$diff^i = \frac{x^i_{TEMOA} - x^i_{TIMES}}{x^i_{TIMES}} \tag{4}$$

The resulting evaluation of the accuracy for the single technology is very important to guarantee a detailed assessment but should be complemented by more synthetic indexes at an aggregated level for entire energy subsectors and sectors of the RES to give an overall estimation of the open model performances. To achieve that goal, two procedures have been adopted. The first one targets the evolution of the relative difference $diff_{avg}$ between the two models results along the entire time horizon for different portions of the RES (namely an energy subsector or demand-side sector). The value of $diff_{avg}$ is obtained for each milestone year according to Equation (5), where f^i is the associated weighting factor to the x^i_{TIMES} data and is equal to the ratio between the contribution of the i^{th} commodity and the total commodity production, consumption, or cost of the selected subsector or sector (x_{TIMES}). The weighting is based on TIMES-Italy results, coherently with the approach of taking them as the reference results. In Equation (5), the absolute value operator prevents the compensation of positive and negative differences.

$$diff_{avg}[\%] = \sum_{\mathrm{i}} \left| diff^i \right| \cdot f^i = \sum_{\mathrm{i}} \left| diff^i \right| \cdot \frac{x^i_{TIMES}}{x_{TIMES}} \tag{5}$$

A summary assessment of the overall results accuracy along the entire time horizon is also useful to have the possibility to represent with single numbers the precision of the modeling of entire energy subsectors and sectors. Such evaluation is performed deriving the cumulative commodity production or consumption (x^i_{cum} for the i^{th} commodity, Equation (6)) by single technologies along the time horizon (from 2006 to 2050 in the case study) and evaluating the relative differences and the average relative difference on the cumulative results, see Equation (7).

$$x^i_{cum} = \sum_{j=t_0}^{t_{end}} x^i \cdot \Delta t_j = \sum_{j=2006}^{2050} x^i \cdot (t_{j+1} - t_j) \tag{6}$$

$$diff_{cum}[\%] = \sum_i diff^i_{cum} * f^i_{cum} = \sum_i \left| \frac{x^i_{cum,TEMOA} - x^i_{cum,TIMES}}{x^i_{cum,TIMES}} \right| * \frac{x^i_{cum,TIMES}}{x_{cum,TIMES}} \tag{7}$$

In the following sections, the benchmark results are reported, per each demand-side sector included in the RES (industry, transport, and buildings).

4.3.1. Industry

Comparing now the resulting technology mixes from the two models (TIMES-Italy and TEMOA-Italy) and according to Equations (4) and (5), a weighted average error curve is derived for each industrial subsector, as shown in Figure 6.

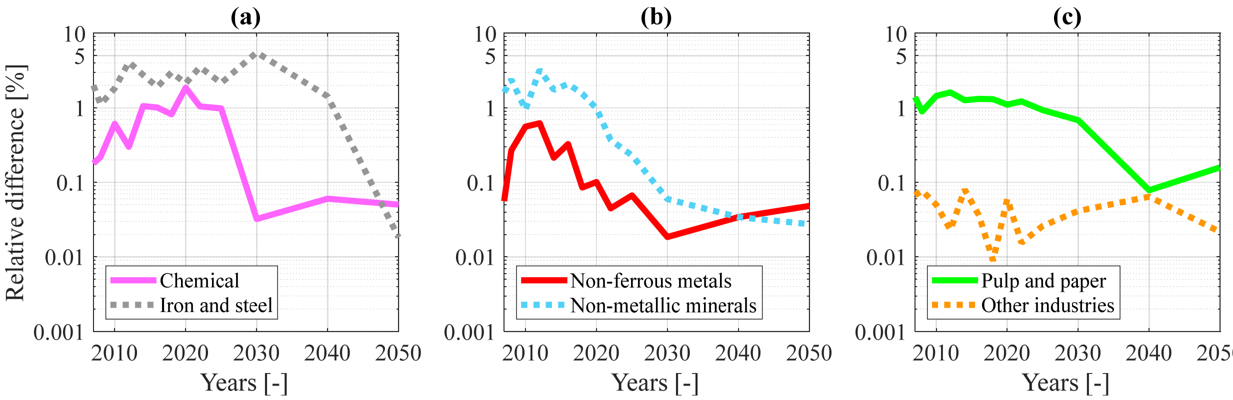

Figure 6. Average relative difference curves associated to the optimal technology mix for: (**a**) chemical and iron and steel sectors; (**b**) non-ferrous metals and non-metallic minerals sectors; (**c**) pulp and paper and other industries.

The average relative difference is lower for the subsectors with a simple structure, and namely the non-ferrous metals subsector (Figure 6b) and the so-called other industries (Figure 6c). The general trends of the curves are characterized by higher errors associated to the first milestone years and decreases along the time. That decreasing trend is more pronounced for the chemical subsector (Figure 6a), non-ferrous metals (Figure 6b), and non-metallic minerals (Figure 6b). The explanation of that behavior is linked to the compresence of existing technologies (installed since the base year) and new technologies (see also the detailed data reported in Appendix C). Indeed, as reported in Appendix A.3, the capacity of the base year technologies is bounded to progressively reach 0 at a certain milestone year, which in TIMES-Italy and for the industrial sector is usually 2030, to simulate the disposal and the consequent substitution with new capacity of the existing technologies. The number of active technologies is higher for time steps characterized by the concurrent operation of base year technologies (in subsectors including those disposal constraints), increasing the system complexity and consequently decreasing results accuracy. Moreover, the complexity of the system amplifies even small discrepancies in the results due to differences in the implementation of the model equations (as discussed in Section 2). This explanation of the global trend is confirmed by the case of the "other industries", where a quite constant relative error is found throughout the entire time horizon, since the final production of this sector is modeled by a single existing technology with increasing efficiency and without any substitution by a new technology.

A more synthetic evaluation of the model ability to reproduce the optimal technology mix is given by the average relative difference on the cumulative activity of final technologies, obtained according to Equation (7). The results are reported in Table 4. In this case, lower discrepancies are associated to the simplest structured subsectors (such as other industries and non-ferrous metals), while the values increase for the other more complex industrial subsectors.

Table 4. Average relative difference between TIMES-Italy and TEMOA-Italy results in cumulative activity for industrial technologies.

Industrial Subsector	$\mathbf{diff_{cum}}$ [%]
Chemical	0.31
Iron and steel	2.57
Non-ferrous metals	0.07
Non-metallic minerals	0.62
Pulp and paper	0.86
Other industries	0.02

Passing to the analysis of the energy consumption, Figure 7a shows a stacked diagram comparing the resulting industrial energy mix in 2030. Figure 7b shows the curve of average relative error along the entire time horizon (weighted on the consumption of each commodity with respect to the total energy consumption of the sector per each milestone year, derived according to Equation (5)).

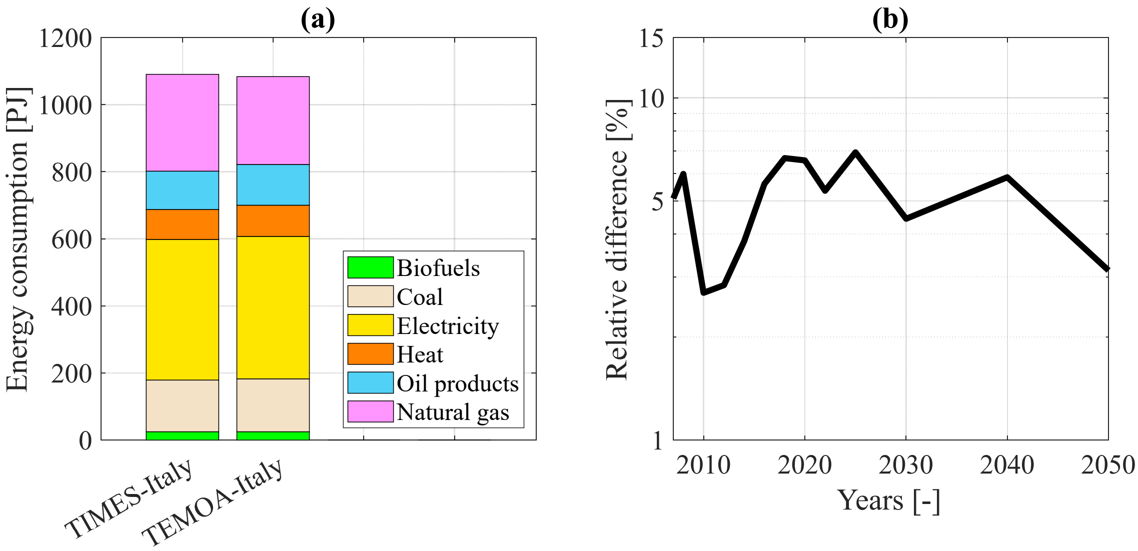

Figure 7. Comparison between the optimal industrial energy mix: (**a**) composition in 2030; (**b**) average relative difference curve along the time.

The average error curve associated to the industrial energy consumption is characterized by higher values with respect to the curves representing the accuracy of the subsector technology mixes. That phenomenon is partially due to the higher complexity of the whole industrial sector, that also includes intermediate industrial service production technologies (such as technologies to produce steam, machine drive, process heat, etc.) in addition to end-use commodity production technologies [58]. Furthermore, going up the production chain, several parameters contribute to determine the consumption of each energy commodity, inevitably leading to an amplification of the margin of error. Indeed, while for the evaluation of the cheapest technological combination (satisfying the demand and respecting the constrains set) the model establishes the final technology mix (being this choice mainly due to the cost of the available technologies), several parameters (with their accuracy) are involved in the construction of the associated energy mix. For instance, the efficiency of each selected technology, the minimum/maximum shares of every input/output commodity could amplify the error passing from the technology to the energy mix. The resulting accuracy of the industrial energy mix, shown in Figure 7, includes yearly errors between a minimum of 2.89% in 2010 and a maximum of 6.93% in 2025, with a cumulative relative difference representative of the energy consumption accuracy of the entire time horizon of 3.96% (evaluated according to Equation (7)).

Concerning the resulting costs associated to the industrial technologies, Figure 8a compares the percentage distribution by subsectors of the cumulative industrial sector cost and Figure 8b shows the time evolution of the total cost of industrial technologies, without any significant difference between the two models results. This is also confirmed by the average relative difference between the cumulative industrial costs from the two models, equal to 2.06% (evaluated according to Equation (7)).

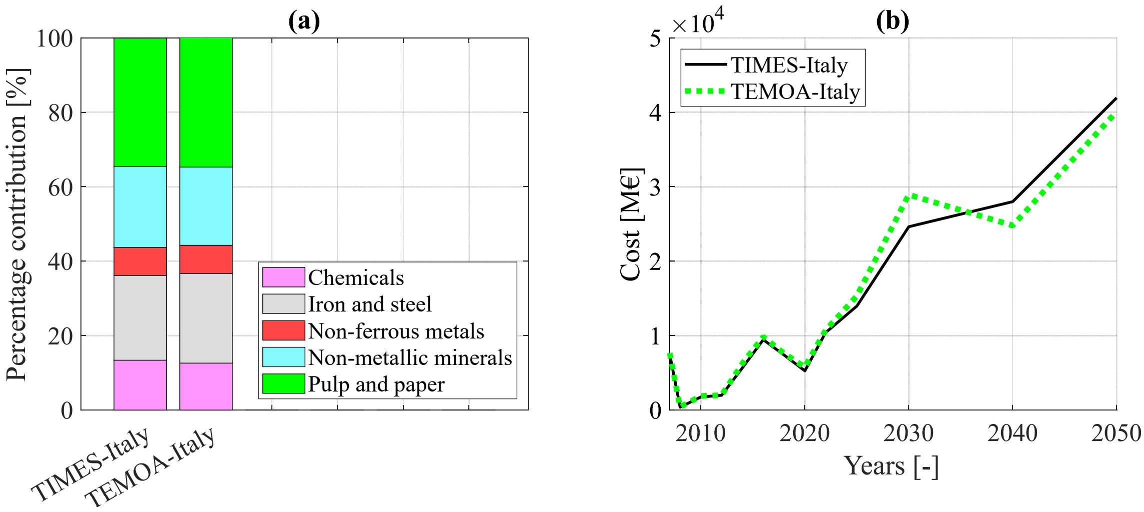

Figure 8. Comparison between the cumulative total cost of the industrial sector: (**a**) percentage sub-sectorial contributions; (**b**) evolution in time.

Detailed results for the industrial technology mix producing the final service demands for the industrial sector are reported Table A5 (in Appendix C), where the activity (total output commodity flow) of each final technology and milestone year, evaluated from both the TIMES-Italy and the TEMOA-Italy models, are reported as well.

4.3.2. Transport

The analysis of the results for the transport sector is focused on the road transport categories with a higher degree of detail with respect to the other transportation modes (aviation, navigation, trains) in view of the higher number of available technologies for road transport in the RES (and the consequent higher complexity and discrepancies in results associated to this subsector with respect to non-road), as reported in Figure 3. This choice is also supported by the fact that most of the energy consumption in transport sector is associated to the road technologies (approximately the 82% at the base year).

The curves of the average relative difference of the technology mix for road transport modes and for the other transport subsectors (aviation, navigation, rail, and other transports) are shown in Figure 9. As already commented comparing simpler with more complex industrial subsectors, results of the average relative differences associated to the non-road transportation modes (Figure 9b) is at least one order of magnitude lower than the difference related to the road transportation modes (with many technologies involved in the modeling and a very high number of constraints). The results for the transport sector lead also to an evaluation (Equation (7)) of the average relative difference between the cumulative activities of the selected technologies of 0.75% for road and 0.07% for non-road.

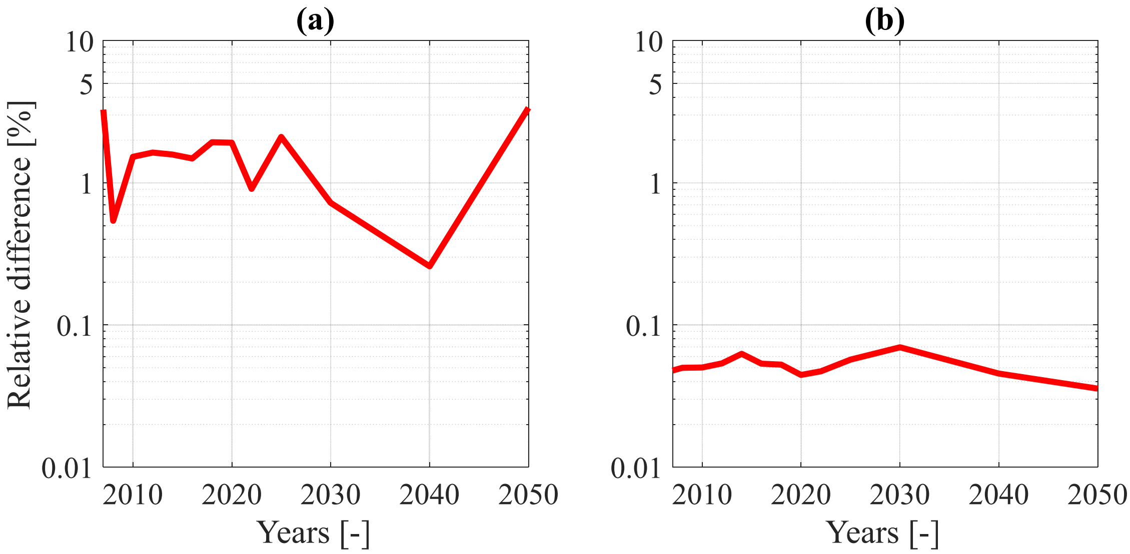

Figure 9. Average relative difference curves associated to the optimal technology mix for: (**a**) road transport categories; (**b**) non-road transport categories.

A slightly lower accuracy of road transport results is justified by the absence of detailed constraints on the technology mix in the TEMOA framework at the current state of development. For that reason, some of the constraints on the future composition of the fleet of vehicles, expressed in TIMES-Italy in terms of contribution of a certain vehicle category (e.g., diesel cars, hybrid cars, etc.) to the satisfaction of its transport demand, have been replied in TEMOA-Italy with equivalent constraints on the energy mix, with a conversion through an average efficiency of the fleet of vehicles. The adoption of such an average efficiency is of course an approximation that could be avoided with the introduction of a new constraint typology with respect to the already implemented ones (as also discussed in Section 5). The detailed optimal technology mix for cars is reported in Table A6 (in Appendix C).

Concerning the analysis of transport energy consumption, Figure 10a shows the optimal energy mixes in 2030 split by fuels (derived from the two models) and Figure 10b shows the curve of average relative error along the entire time horizon (weighted on the consumption of each commodity with respect to the total energy consumption of the sector per each milestone year, derived according to Equation (5)). The transport sector energy mix results to be more accurate with respect to the industrial mix, coherently with the simpler structure of the transport sector with respect to the industrial technology chain. While industrial technologies include intermediate commodities for the industrial energy services and technologies producing them, the transport sector is composed only by technologies consuming energy to directly produce the final transport demands. This leads to an average relative difference curve between a minimum value of 0.23% in 2008 and a maximum of 3.65% in 2020, with an average value on the cumulative fuel consumption along the entire time horizon of 1.51% (see Equation (7)). As shown in Figure 10a, the transport energy mix in 2030 is mainly composed of oil products (with an almost negligible contribution from electricity and natural gas), and the associated average relative difference of 1.11% in 2030 partially explain the difference in the overall oil and oil products consumption, also highlighted by Figure 4.

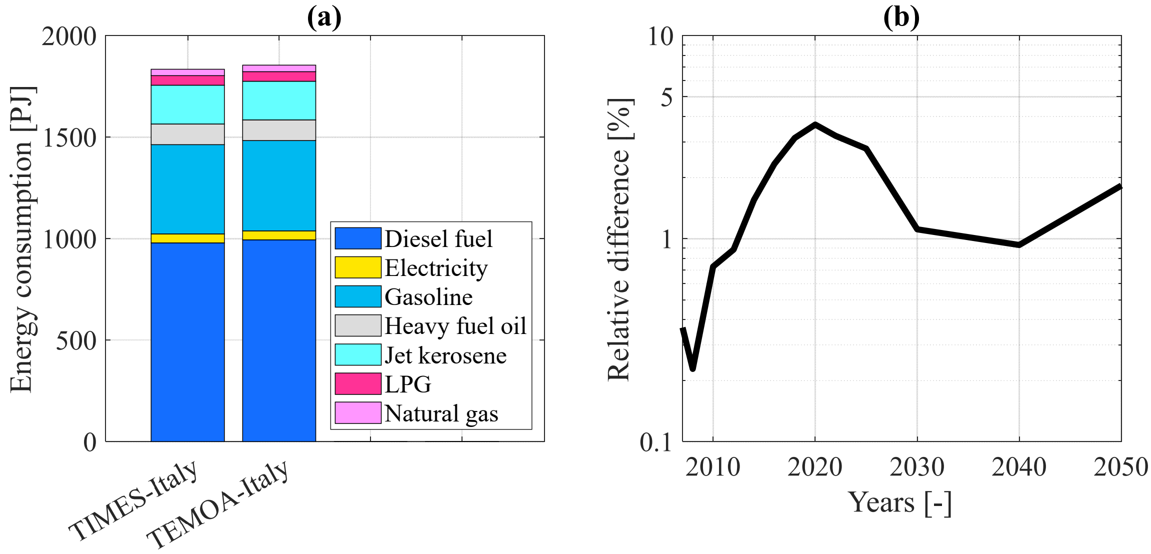

Figure 10. Comparison between the optimal transport energy mix: (**a**) composition in 2030; (**b**) average relative difference curve along the time.

Concerning the resulting costs associated to the transport technologies, Figure 11a compares the distribution of the subsectors to the cumulative cost of the sector and Figure 11b reports the time evolution of the total cost of the present technologies, showing an accordance between the two cost trends. This is also confirmed by the average relative difference between the cumulative transport costs of the models, equal to 2.37% (evaluated according to Equation (7)).

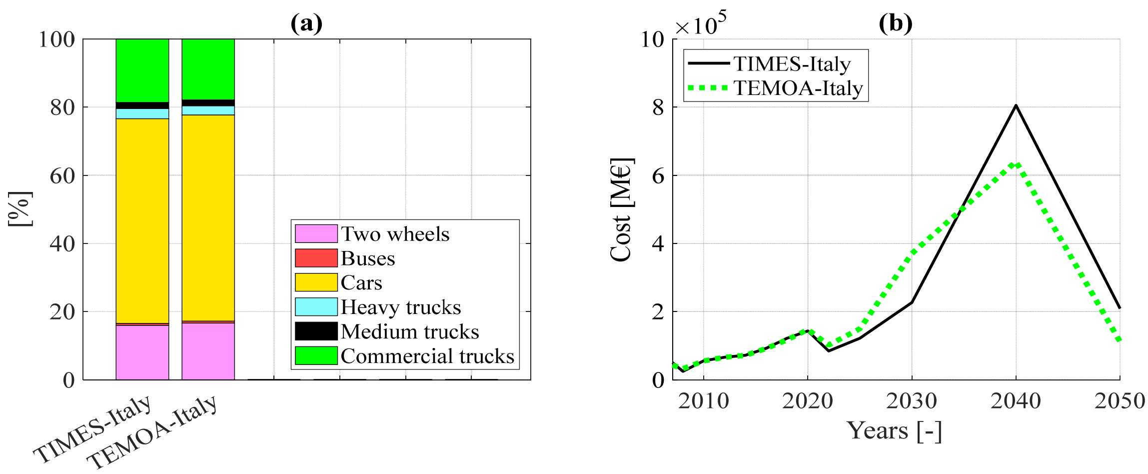

Figure 11. Comparison between the cumulative total cost of the transport sector: (**a**) percentage sub-sectorial contributions; (**b**) evolution in time.

4.3.3. Buildings

Results related to the buildings sector (residential, commercial, and agriculture) are reported in this section. Since several units of measurement are used to quantify the final service demands of the sector, used to express properly the different end-uses, it is not possible to compute an average difference curve synthetically representing the accuracy of the technology mixes selected by the tools (as it has been done for the other sectors). For that reason, to quantify the accuracy of the final service demands production and according to Equation (8), the percentage of maximum value of difference between the total production of each final service demand of TIMES-Italy and TEMOA-Italy models was calculated.

$$\text{diff}_{\max}[\%] = \max\left(\frac{\left|x^i_{\text{TEMOA}} - x^i_{\text{TIMES}}\right|}{x^i_{\text{TIMES}}}\right) \tag{8}$$

The resulting curve is shown in Figure 12a. To provide a higher detail for the most energy consuming end-use of the buildings sector, i.e., residential space heating, the average relative difference comparing the optimal technology mixes is also reported in Figure 12b. While Figure 12a is useful to compare the accuracy of the demands level (being the evaluated relative difference less than 1% with the only exception of 2010 value), Figure 12b shows (as for the other demand-side sectors) the precision in replicating the selected technology mix for a single end-use category. The residential space heating end use has been chosen because of being the most energy consuming in the buildings sector (accounting alone for 62% of the total residential, commercial, and agriculture energy consumption at the base year). Along the time horizon, the average relative difference varies from ~2% up to ~7% for the intermediate years (i.e., between 2014 and 2030), while a decreasing trend for the average relative difference seems to occur for the last time steps of the time horizon (namely, 2040 and 2050). The detailed optimal technology mix for residential space heating is reported in Table A7 (in Appendix C).

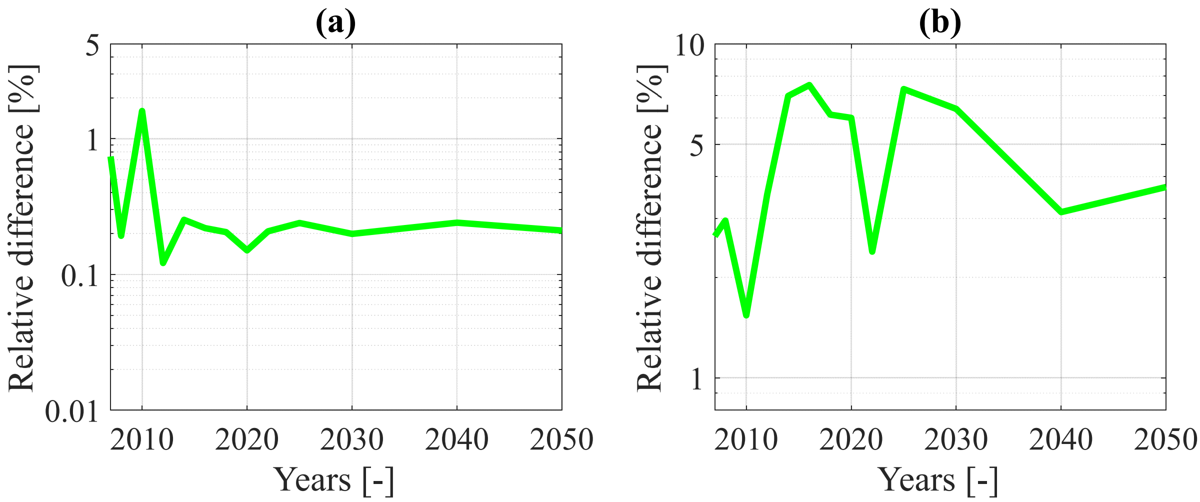

Figure 12. (**a**) Maximum relative difference associated to the total production of residential, commercial and agriculture final service demands. (**b**) Average relative difference associated to the optimal technology mix for residential space heating.

It should be also noticed that the optimal technology mix for residential space heating is affected by the annual representation of all the final service demands in TEMOA-Italy, different from the intra-annual approach adopted by TIMES-Italy (as already explained in Section 3).

Focusing now on the evaluation of the resulting energy mix for the buildings sector, Figure 13a shows the comparison of the optimal energy mixes in 2030 split by fuels and Figure 13b shows the weighted average relative error along the entire time horizon according to Equation (5). Lower discrepancies between the two models are associated to the time steps close to the base year (up to 2010), with higher differences appearing from 2014 on. That is consistent with the fact that at the beginning of the time horizon the technology mix is defined as equal to the base year statistics and consequently the results are constrained to those values, with higher accuracy. Figure 13a qualitatively shows a rather equivalent energy mix for the two sets of results in 2030. The accuracy of the sectorial energy mix is represented by an average relative difference on the cumulative energy consumption of each fuel along the entire time horizon of 4.11% (evaluated according to Equation (7)).

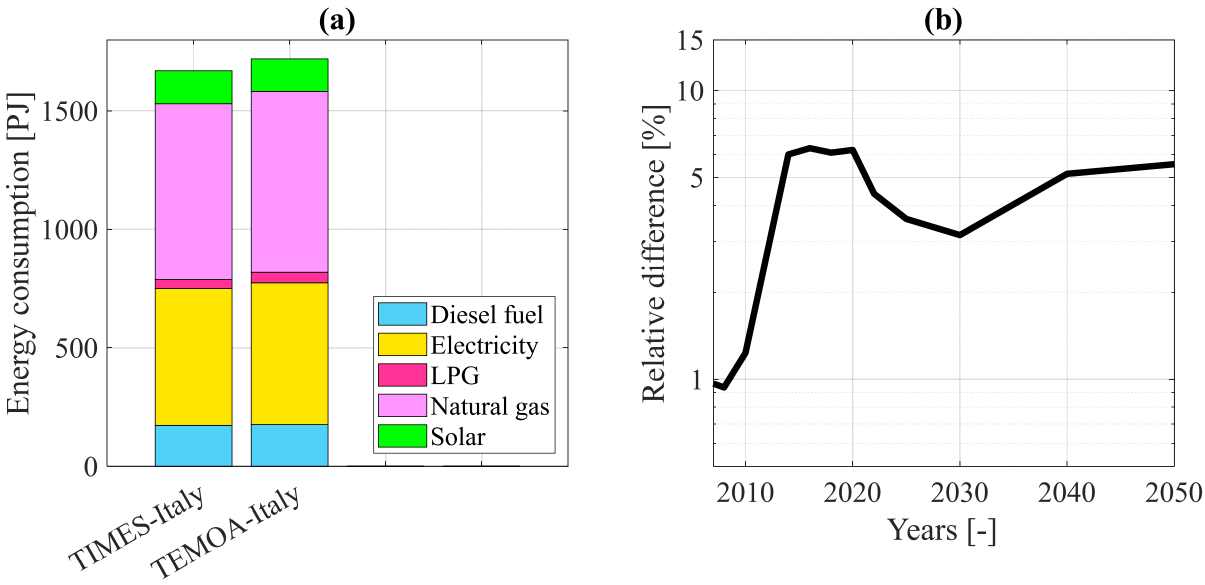

Figure 13. Comparison between the optimal buildings energy mix: (**a**) composition in 2030; (**b**) average relative difference curve along the time.

Concerning the resulting costs associated to the residential and commercial technologies, Figure 14a compares the percentage distribution of the cumulative buildings costs (agriculture sector is not included in the cost comparison, since it is modeled with a single existing technology without any associated cost) by subsectors, while Figure 14b reports the time evolution of the total cost associated to the buildings technologies. Figure 14a shows a similar cost distribution between the different residential and commercial subsectors, with higher differences for residential space heating and the other residential subsectors. The average relative difference between the cumulative costs from the two models evaluated according to Equation (7) is 4.71%.

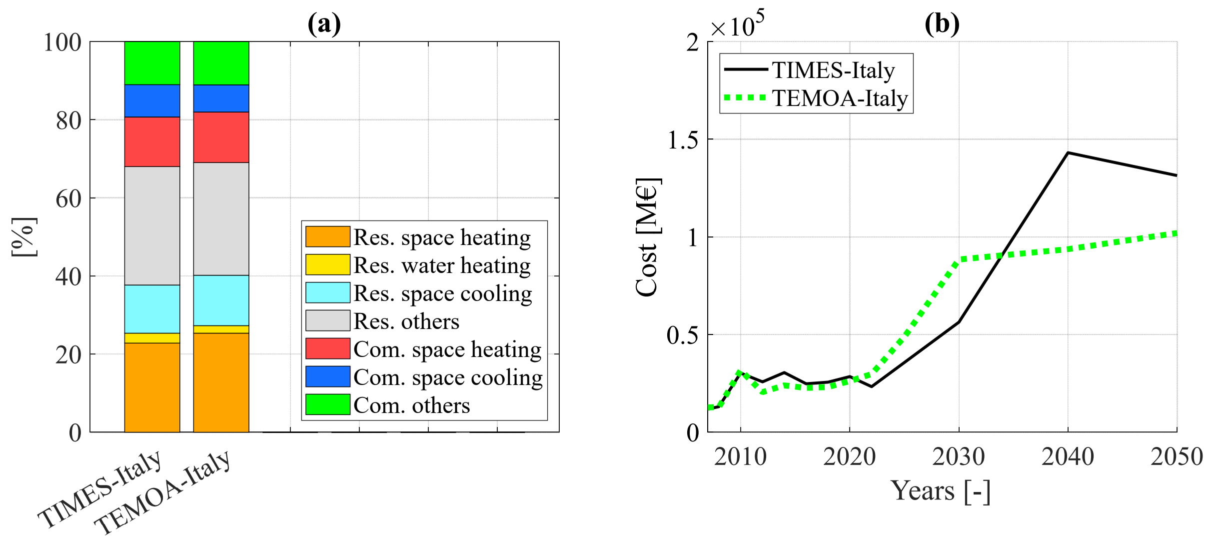

Figure 14. Comparison between the cumulative total cost of the buildings sector: (**a**) percentage sub-sectorial contributions; (**b**) evolution in time.

5. Conclusions and Perspective

Open tools in the framework of partial-equilibrium energy system optimization models can boost the research, identification, and test of novel set of constraints or optimization paradigms to achieve, for instance, sustainability targets, which do not follow the mere economical paradigm of targeting the minimum cost of the energy system. Aiming at demonstrating that open modeling tools can be adopted as a valid alternative to commercial tools, the TEMOA framework, already available in an open-source form, was significantly extended to include functionalities and parameters to allow modeling a complex and realistic reference energy system, and then applied to a case study—the Italian energy system. The novel open-source TEMOA-Italy has been presented in this paper and compared on a fair basis to the TIMES-Italy model, used by ENEA as the basis for the Italian Energy Strategy.

The assessment of the accuracy of the open model, benchmarked with the reference TIMES-Italy model, demonstrates that the novel tool, when applied to the same reference energy system in a business-as-usual scenario, is capable to reproduce the main features of the reference model with an accuracy within few percent (up to 4% concerning the resulting energy mix) of discrepancy. The accuracy depends strongly on the complexity of the structure of the analyzed energy systems; the lower the complexity of the technology chain required to produce the final service demands consuming primary resources, the higher the accuracy of the novel tool.

Summarizing the comparison of the results from the two tools, a general good agreement has been shown, with some residual discrepancies.

As mentioned in Section 4, the first possible improvement regards CHP plants, producing both electricity and heat. The amount of heat produced with respect to electricity is defined in TIMES by a dedicated parameter (CHPR), usually implemented as an upper limit. This means that, once the electric efficiency of the plant is defined, the model can evaluate the optimal amount of heat produced. TEMOA does not include such a parameter, and the heat production form CHP plants is currently modeled with a fixed proportion with respect to electricity. The integration of a similar parameter in the tool will allow a more precise modeling of CHP plants in TEMOA and will help refining results in the power sector, devoted to the production of heat consumed by the demand-side.

Constraints on minimum and maximum shares of input and output commodities for a technology or a technology group have been discussed in Section 2. Similarly, the TIMES framework also allows to set constraints on the consumption or production share of a certain commodity by a technology or technology group. For instance, this is useful in road transport to set constraints on the evolution of the technology mix without the adoption of equivalent constraints on the energy mix (as discussed in Section 4.3.2).

In addition, Appendix A.3 describes the strategy adopted to model the disposal of existing capacities in TEMOA-Italy, through the derivation of an equivalent constraint on the technology activity. The drawback of the adopted approach is that the installed capacity resulting by the model (constant and equal to the existing capacity for a period of time equal to the technology lifetime) for the involved technologies will not correspond to the actual residual capacity (linearly decreasing). This complicates the results post-processing if the installed capacities need to be studied. A proper parameter could be developed and integrated in the code to model the progressive reduction of available capacity starting from the existing capacity at the base year and avoiding relying on an equivalent constraint on the technology activity.

A precise validation of the model results on the historical period 2006–2020 will increase the reliability of the models results for the future milestone years. Furthermore, the intra-annual description of non-annual final demands (such as space heating and lighting) should be implemented in TEMOA-Italy, identifying proper strategies to minimize the impact of this on the computational time of the tool.

In perspective and for a wider and more challenging set of scenarios including aggressive decarbonization where the adoption of new technologies, such as those proposed in [12], is crucial, the TEMOA-Italy will be further tested in benchmark to the TIMES-Italy. In the framework of open-science and transparency and accessibility of data and tools, the new tool is already available to the scientific community. This eases third party verification of the input assumptions, adopted methodology, and results, increasing the reliability and the robustness of the results themselves. The targeted transparency will be also an asset for an independent evaluation of the effectiveness of the energy policies adopted by policy makers (governments and international organizations) in pursuing the declared objectives of environmental sustainability.

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Appendix A. Enhancement of the TEMOA Framework

Appendix A.1. Description of the Technologies in the RES

This section presents the parameters involved in the techno-economic description of technologies in the developed TEMOA-based framework, together with the associated equations defining their role within the optimization algorithm. The analysis has been concentrated on the main integrations performed with respect to the original TEMOA formulation [40].

The first new parameter and the associated equation implemented in the TEMOA model formulation is the annual *CapacityFactor*, used to connect the technology capacity (*Cap*) to its activity (*Act*), according to Equation (A1). The *Capacity2Activity* factor, representing a conversion factor from capacity to activity unit of measurement, is also included in the evaluation.

$$(CapacityFactor \cdot Capacity2Activity) \cdot Cap \geq Act \tag{A1}$$

While the activity represents the total flow of output commodities of a technology (e.g., the activity of a power plant is the energy produced during the year [PJ], the activity of industrial facilities is the total periodical production in terms of demand commodity and by-products [Mt], . . .), the capacity of a technology can be defined as its nominal production capability as if it was continuously operated at full load. The capacity of a power plant is for instance its nominal installed power [GW] while the activity corresponds to the actual electricity output [PJ]; on the other hand, the capacity of industrial facilities is the maximum production capability [Mt], while the activity is the actual production output, always accounted for in [Mt]. The capacity factor *CapacityFactor* is used to account for the unavailability periods of technology, due to unavailability of its input energy resources or to maintenance. Figure A1 graphically shows the relation between the capacity (nominal installed power) and the activity (annual energy produced) for a power plant. The average annual capacity factor can be evaluated as the annual energy produced over the product between the nominal installed power and the duration of the year and its value is graphically represented in Figure A1 by the ratio between the yellow area and the sum between the yellow area and the green area. The *Capacity2Activity* factor, for the example under analysis of a power sector technology, usually represents the maximum annual energy producible [PJ_a] if the plant were constantly operated at its nominal power [GW], and it is evaluated according to Equation (A2).

$$Capacity2Activity = 8760\left[\frac{\text{h}}{\text{y}}\right]\cdot 3600\left[\frac{\text{s}}{\text{h}}\right]\cdot 10^{-6}\left[\frac{\text{PJ}}{\text{GJ}}\right] = 31.536\left[\frac{\text{PJ}_\text{a}}{\text{GW}}\right] \quad \text{(A2)}$$

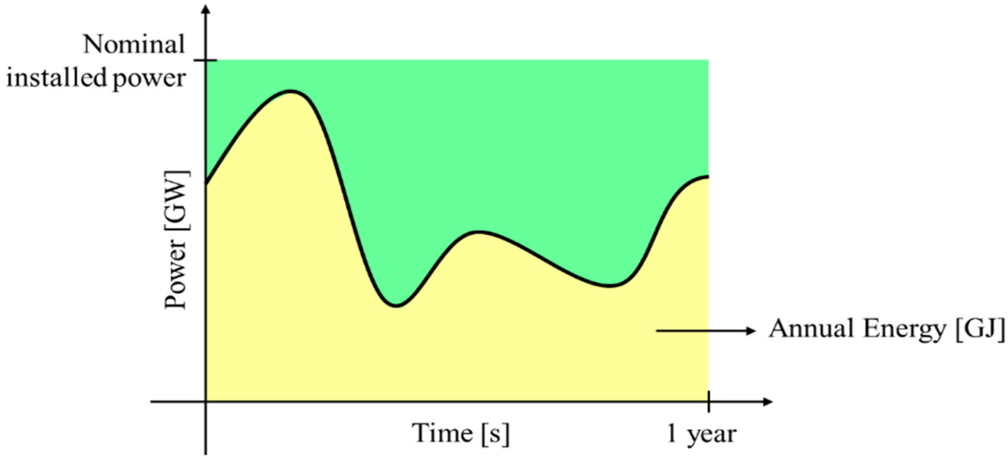

Figure A1. Relation between the nominal power, the actual power and the annual energy produced, for a power sector technology.

As reported in Table 2, TEMOA already included two parameters representing the capacity factor, namely the *CapacityFactorTech* and the *CapacityFactorProcess*. The motivation behind the introduction of a new formulation for this parameter is the simplification of the data handling. Indeed, the *CapacityFactor* is indexed by time period (with a single value per technology and milestone year), while the *CapacityFactorTech* (already included within the TEMOA parameters) is indexed in the TEMOA formulation by time slice (season and time of the day, which can be assigned to different values within the same milestone years), and the *CapacityFactorProcess* is indexed both by time slice and time period. The new *CapacityFactor* parameter allows a simpler modeling of the relation between the activity and the capacity of a technology and is especially useful to account for the availability of certain types of processes when not depending on the particular time slice (e.g., to account for maintenance of plants or holidays). The new parameter, however, does not substitute the other two, being them necessary to define variable capacity factor for different time slices.

The *LifetimeTech* (constant along the time) and the *LifetimeProcess* (indexed by time period) parameters are used to define the lifetime of a technology, while the *LifetimeLoanTech* is used to separate the loan lifetime from the useful life of a process.

Moreover, some operations required to be automated to guarantee a manageable database compilation, namely: the data interpolation/extrapolation and the computation of the emission factors. An automatic algorithm has been then developed (available at [41]) to perform a preprocessing on the .sql database, (manually compiled), including all the descriptive parameters of the RES. The new functions to automatically preprocess the data to obtain the desired RES description consist of:

- An automatic interpolation and extrapolation process (totally missing in the original TEMOA version [40], that requires the manual specification of the parameters for all the time periods included in the optimization process), performing the same operations encompassed in, e.g., the TIMES framework. This feature, including the option of setting different interpolation and extrapolation rules for different parameters in the Excel files, is automatically executed by the software. In particular, it is possible to assign interpolation/extrapolation options to the parameters included in the TEMOA database to set: (1) the interpolation type (linear or log-linear); (2) whether interpolation only or also extrapolation should be operated; and (3) whether extrapolation should be performed backward, forward, or both [54]. The most-common interpolation rule is the linear one, with constant extrapolation forward and, this is the general rule developed for the case-study presented here, with few exceptions. Table A1 lists the parameters for which interpolation and extrapolation are required, specifying the applied rule. Notably, the three main selected rules are: piecewise constant interpolation (implemented only for the lifetime parameter); piecewise linear interpolation (for all the parameters except for the lifetime); and constant extrapolation forward (for all the parameter except for constraint on technology groups' activity). For the technology lifetime, a piecewise constant interpolation curve has been chosen, to maintain an integer value for the parameter. Note that the constraints applied to technology groups (rather than to single technologies) are only linearly interpolated, but not extrapolated forward, as it happens for the other parameters. It should be noted that a constant extrapolation forward could also be easily obtained for all the constraints on technology groups, simply repeating the last value of the interpolation in the last time step of the time horizon, without the necessity to change the preprocessing algorithm. This integration strongly simplifies the database construction and its modification, allowing the energy modeler to build databases representing large and complex RES.

Table A1. Interpolation/extrapolation rules implemented in the preprocessing Python script.

Parameter	Interpolation/Extrapolation Rule		
	Piecewise Constant Interpolation	**Piecewise Linear Interpolation**	**Forward Constant Extrapolation**
LifetimeProcess	X		X
Efficiency		X	X
TechInputSplit		X	X
TechOutputSplit		X	X
EmissionActivity		X	X
CostInvest		X	X
CostFixed		X	X
CostVariable		X	X
MaxActivity		X	X
MaxGenGroupLimit		X	
MaxCapacity		X	X
MinActivity		X	X
MinGenGroupTarget		X	
MinCapacity		X	X
MaxInputGroup		X	
MaxOutputGroup		X	
MinInputGroup		X	
CapacityFactor		X	X
CapacityFactorProcess		X	X
CapacityCredit		X	X

- The automatic evaluation of the technology-based emission factors, which are implemented in TEMOA through the dedicated parameter *EmissionActivity*, proportional to the technology activity. Being the *EmissionActivity* parameter indexed by region (index r), emission commodity (index e), input commodity (index i), technology (index t), year (index v), and output commodity (index o), the filling of the database would be very complex without an automatic computation of the emission factors. Furthermore, the emissions associated to the consumption of fossil fuels are usually equal for the same fuel (being dependent on its chemical composition). For that reason, a parameter representing the emission factors per unit of commodity consumed (*CommodityEmissionFactor*) has been added to the database, indexed by the input commodity to which the emission is associated and the emitted emission commodity. The operation performed in the preprocessing script (reported in Equation (A3)) is the sum of the contribution of the Commodity-based Emission Factor $CEF_{i,e}$, divided by the efficiency of the technology $(Efficiency_{r,i,t,v,o})$ to obtain the correspondent emission factor per unit of output, with the Technology-based Emission Factor $TEF_{r,e,i,t,v,o}$ (usually adopted to model process-related emissions) possibly manually inserted in the *EmissionActivity* table of the database, before being preprocessed. The output of the algorithm is the preprocessed database, with the complete *EmissionActivity* table.

$$EmissionActivity_{r,e,i,t,v,o}\left[\frac{\text{kt}}{\text{act}}\right] = \frac{1}{Efficiency_{r,i,t,v,o}\left[\frac{\text{act}}{\text{PJ}_\text{i}}\right]}\cdot CEF_{i,e}\left[\frac{\text{kt}}{\text{PJ}_\text{i}}\right] + TEF_{r,e,i,t,v,o}\left[\frac{\text{kt}}{\text{act}}\right] \quad \text{(A3)}$$

Appendix A.2. Drivers for the Energy Service Demands

In ESOM models, the expected levels of energy service demands are projected along the analyzed time horizon according to socio-economic drivers. The future projection of energy service demands is performed according to Equation (A4), where $Demand_t$ and $Demand_{t-1}$ and the service demand levels at time step t and $t-1$, respectively, δ_t and δ_{t-1} are the driver values at time step t and $t-1$, respectively, and e_t is the elasticity associated to the time step t.

$$Demand_t = Demand_{t-1} \times \left[1 + \left(\frac{\delta_t}{\delta_{t-1}} - 1\right) \times e_t\right] \quad \text{(A4)}$$

Elasticities are usually adopted to correct demand projections in order 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 [10].

The driver projections along the entire time horizon (exogenously provided to the model and usually taken from studies of statistical institutes such as the European Eurostat [61] and the Italian ISTAT [62] for the test case described in this paper) have been implemented in the TEMOA formulation and included in the database preprocessing script, available at [41]. The operation is performed on the basis of the base year demands (manually inserted in the database) and the associated drivers and elasticities. The demands are then projected according to Equation (A4).

Appendix A.3. Constraints

Constraints are typically used in ESOMs for two different purposes: (a) defining the configuration of the existing energy system at the base year and its progressive disposal along the time; (b) implementing technical, economic and environmental constraints for the future evolution of the energy system.

As far as the residual capacity of an existing technology (installed at the base year) is concerned, the existing capacity of a certain technology at the base year should be set, together with its residual capacity evolution in time. The evolution in time of that capacity is generally linear starting from the base year value and goes to zero after a certain time interval to model the disposal of the existing technology in time (according to their lifetime) and to allow the substitution by new technologies. To mimic a linear decrease of the existing technologies in the energy mix, a constraint on the maximum activity *MaxActivity* (linearly decreasing along the time) has been introduced to all the existing technologies of the subsectors for which new technologies are included in the database. The constraint is built from the residual capacity *ResidualCapacity*, given as an input parameter, with the contribution of the *Capacity2Activity* factor and of the *CapacityFactor*, as shown in Equation (A5).

$$\begin{aligned} &MaxActivity\ [\text{act}] \\ &= CapacityFactor\cdot Capacity2Activity\left[\frac{\text{act}}{\text{cap}}\right]\cdot ResidualCapacity\ [\text{cap}] \end{aligned} \quad \text{(A5)}$$

To allow the definition of the maximum available resources of fossil fuels in the region under investigation, for the extraction technologies in the upstream sector, the parameter *MaxResource* has been redefined. The original formulation of the parameter imposed an upper bound to the summation of the resulting activity of a technology for each time period. In the summation operator, the multiplication by the length of each time period has been added to correctly account for the relative weight of each milestone year to the total cumulative activity (Equation (A6)).

$$\sum_{\mathrm{i}=t_{first}}^{t_{last}} Act_{\mathrm{i}} \cdot \Delta t_i \leq MaxResource \tag{A6}$$

New constraints on technology groups have also been implemented in the TEMOA framework. The maximum total activity is used to set an upper bound to the total activity of a group of technologies (Equation (A7)) in the new constraint is $MaxGenGroupLimit$, developed similarly to the analogous minimum constraint $MinGenGroupTarget$, already included in TEMOA. Moreover, new constraints on commodity shares have been developed to set the minimum ($MinInputGroup$, Equation (A8)) or maximum ($MaxInputGroup$, Equation (A9)) percentage that can be assigned to a certain commodity in input to a technology group ($\mathrm{commodity}_{\mathrm{IN,group}}$) or the maximum ($MaxOutputGroup$, see Equation (A10)) in output from a technology group ($\mathrm{commodity}_{\mathrm{OUT,group}}$). Those constraints are very similar to the already implemented *TechInputSplit* and *TechOutputSplit* constraints, with the difference that they are applied to technology groups, while *TechInputSplit* and *TechOutputSplit* are applied to single technologies, imposing a minimum share to their input and output commodities.

$$\sum_{\mathrm{tech\ in\ group}} Act_{\mathrm{tech}} \leq MaxGenGroupLimit_{\mathrm{group}} \tag{A7}$$

$$\frac{\mathrm{commodity}_{\mathrm{IN,group}}}{\sum_{\mathrm{i}} \mathrm{commodity}^{\mathrm{i}}_{\mathrm{IN,group}}} \geq MinInputGroup \tag{A8}$$

$$\frac{\mathrm{commodity}_{\mathrm{IN,group}}}{\sum_{\mathrm{i}} \mathrm{commodity}^{\mathrm{i}}_{\mathrm{IN,group}}} \leq MaxInputGroup \tag{A9}$$

$$\frac{\mathrm{commodity}_{\mathrm{OUT,group}}}{\sum_{\mathrm{i}} \mathrm{commodity}^{\mathrm{i}}_{\mathrm{OUT,group}}} \leq MaxOutputGroup \tag{A10}$$

Appendix A.4. The Optimization Problem

The optimization problem solved by the TEMOA is fully comparable to that of the standard TIMES-models [54], based on the minimization of the objective function, which expresses the total cost of the energy system C_{tot}. The total cost is computed in Equation (A11), based on the discount factor *DiscountFactor* (discounted value to the beginning of the time horizon of a unitary payment, based on *GlobalDiscoutRate* [55]) and the cost values of the single technologies selected in the optimal technology mix. Three parameters used in the technology modeling are crucial for the computation of the objective function, and namely, the investment cost *CostInvest* [M€/cap.], the fixed O&M cost *CostFixed* [M€/cap.], and the variable O&M cost *CostVariable* [M€/act.] of the technology [55], see Table 2. While the investment cost and the fixed O&M cost are proportional to the installed capacity ($Cap_{\mathrm{r,t,v}}$) of a technology, the variable O&M cost is proportional to the total Flow of Output commodities ($\mathrm{FO}_{\mathrm{r,p,s,d,i,t,v,o}}$). The $LA_{\mathrm{r,t,v}}$ is the annualization factor used to annualize the investment cost of a technology, based on the process-specific loan length and the process-specific discount rate. Those economic parameters are used to evaluate the optimal configuration of the system that guarantees to minimize C_{tot}, resulting from the sum of the total investment cost (C_{loans} [M€/cap.]), fixed O&M cost (C_{fixed} [M€/cap.]), and variable O&M cost

($C_{variable}$ [M€/act.]), to satisfy the final service demands production complying with the applied constraints.

$$\begin{aligned} C_{tot} = C_{loans} + C_{fixed} + C_{variable} = \\ &= \sum_{\mathrm{r,t,v}} (CostInvest_{\mathrm{r,t,v}} \cdot LA_{\mathrm{r,t,v}} \cdot \mathrm{DiscountFactor} \cdot Cap_{\mathrm{r,t,v}}) \\ &+ \sum_{\mathrm{r,p,t,v}} (CostFixed_{\mathrm{r,p,t,v}} \cdot \mathrm{DiscountFactor} \cdot Cap_{\mathrm{r,t,v}}) \\ &+ \sum_{\mathrm{r,p,t,v}} \left(CostVariable_{\mathrm{r,p,t,v}} \cdot \mathrm{DiscountFactor} \cdot \sum_{\mathrm{s,d,i,o}} \mathrm{FO}_{\mathrm{r,p,s,d,i,t,v,o}} \right) \end{aligned} \tag{A11}$$

Appendix B. The Italian Energy System

Appendix B.1. Drivers for Demand Projection in Future Years

TEMOA-Italy adopts driver projections from the Italian Integrated National Energy And Climate Plan (PNIEC) [63], which in turn uses projections taken from the EU Reference Scenario 2016 [64]. Note that, in the case of the industrial sector, drivers are based on a Vector Auto Regressive (VAR) analysis described in [15] and formulated to consider the effects of the COVID-19 pandemic and taking into account historical data up to 2020.

Figure A2 shows the historical growth rate for all drivers considered in the model, normalized with respect to the initial value in 2006 and obtained using Equation (A4). Concerning the period 2006-2018, the PNIEC drivers offer good performances following the historical trends. In particular, the drastic drop of Gross Domestic Product (GDP), see Figure A2a, and industrial demand, see Figure A2a, and industrial demand, see Figure A2b, consequent to the 2008 financial crisis and the subsequent period of economic stagnation are evident in the left part of the figure. Moreover, the effects of COVID-19 are evident in some industrial subsectors, whereas for agriculture and commercial value added, population, and GDP, the PNIEC forecasts (developed on the basis of historical data up to 2018) do not consider the effects of the 2020 pandemic and follow a constantly increasing trend (though at different rates) from 2018 on.

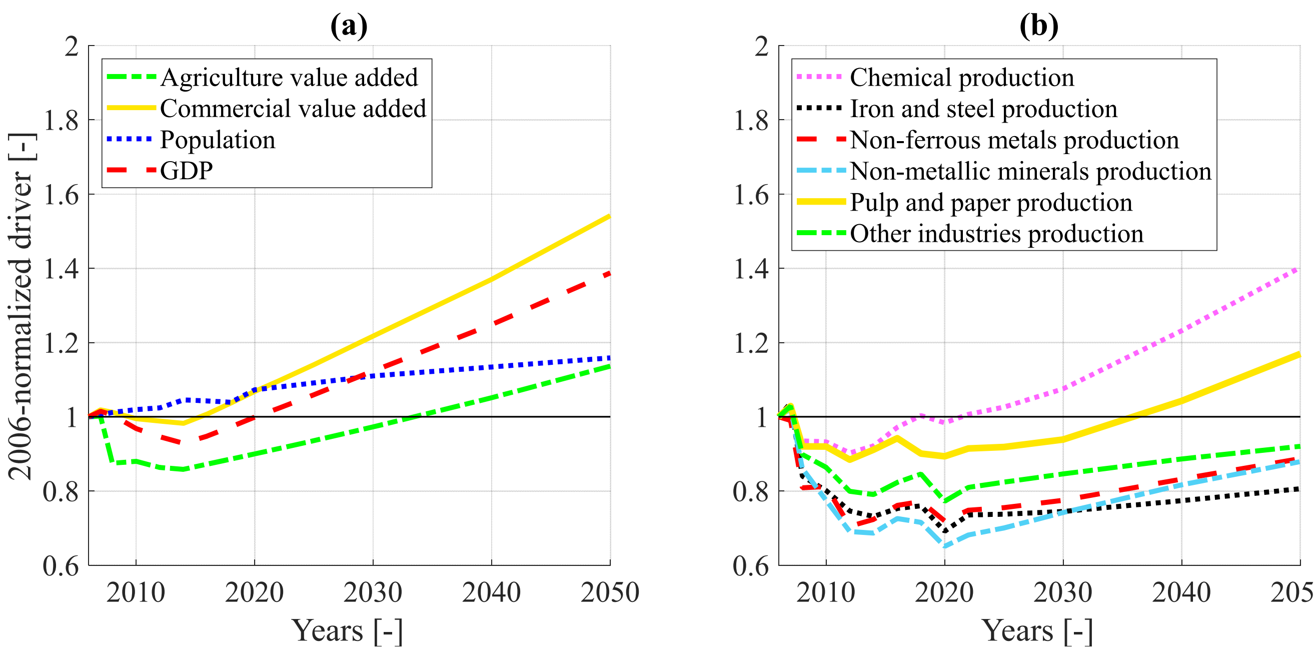

Figure A2. 2006-normalized socio-economic drivers included in TEMOA-Italy: (**a**) agriculture and commercial value added, population and GDP (2006–2018 are historical data, 2020–2050 are future projections from [63]); (**b**) industrial production for each industrial subsector (2006–2020 are historical data, 2022–2050 are future projections from [15]).

Appendix B.2. Techno-Economic Characterization of the Main Demand-Side Subsectors

Appendix B.2. reports a summary overview of the techno-economic characterization of existing and new technologies for the most energy consuming subsector of each demand-side energy sector (chemical industry, cars for transport, and residential space heating for buildings). The detailed data are available in [12] for industry, [13] for transport, and [58] for buildings.

Table A2. Techno-economic characterization for chemical industry technologies [12].

Technology			Efficiency [PJ/Mt]	Availability Factor	Lifetime	Investment Cost [M€/cap.]	Fixed O&M Cost [M€/cap.]
Existing		Ammonia	65.57	1.00	30	-	-
		Chlorine	12.85	1.00	30	-	-
		Aromatics	73.21	1.00	30	-	-
		Olefins	75.18	1.00	30	-	-
		Methanol	48.86	1.00	30	-	-
		Other chemicals	10.00	1.00	30	-	-
New	Ammonia	Natural gas steam reforming	46.08	0.90	25	860.00	21.50
		Naphtha POX	48.31	0.90	25	1203.00	30.08
		Coal gasification	45.76	0.90	25	2063.00	51.58
		Biomass gasification	58.30	0.90	25	6000.00	300.00
		Electrolysis	40.34	0.90	25	104.00	2.60
		Natural gas steam reforming with CCS	45.52	0.90	25	930.00	51.00
	Chlorine	Mercury	16.11	0.95	30	675.80	6.70
		Diaphragm	13.05	0.95	30	675.80	6.70
		Membrane	12.33	0.95	30	675.80	6.70
	Methanol	Natural gas steam reforming	37.90	0.85	25	295.00	21.50
		COG steam reforming	52.50	0.85	30	295.00	21.50
		LPG steam reforming	37.80	0.85	30	295.00	21.50
		Coal gasification	50.10	0.85	30	710.00	17.75
		Biomass gasification	61.40	0.85	30	4900.00	245.00
		Electrolysis	23.90	0.95	30	44.00	1.10
	HVC	Naphtha steam cracking	94.20	0.90	30	2057.00	51.40
		Ethane steam cracking	70.60	0.85	30	1487.00	37.20
		Gas oil steam cracking	102.20	0.85	30	2328.00	58.20
		LPG steam cracking	93.00	0.85	30	1900.00	47.50
		Naphtha catalytic cracking	74.10	0.85	30	3000.00	75.00
		Bioethanol dehydration	94.90	0.85	30	1328.00	33.20
	Olefins	Prophane dehydrogenation	69.40	0.85	30	1691.00	42.30
		Methanol-to-olefins	65.77	0.85	30	1000.00	25.00

Table A3. Techno-economic characterization for road transport cars [13].

	Technology	Efficiency [Bvkm/PJ]	Availability Factor	Lifetime	Investment Cost [M€/cap.]	Fixed O&M Cost [M€/cap.]
Existing	Gasoline car	0.30	1.00	12	-	-
	Diesel car	0.36	1.00	12	-	-
	LPG car	0.25	1.00	12	-	-
	Natural gas car	0.27	1.00	12	-	-
	Biofuels car	0.44	1.00	12	-	-
New	Gasoline car	0.31 ÷ 0.41	1.00	12	1000.00	62.63
	Diesel car	0.38 ÷ 0.50	1.00	12	1081.78	62.63
	LPG car	0.34	1.00	12	1081.78	64.37
	Natural gas car	0.36	1.00	12	1081.78	64.37
	Electric car	1.18 ÷ 1.37	1.00	12	2202.34 ÷ 1262.66	51.33
	Hybrid electric car	0.45 ÷ 0.69	1.00	12	1284.14 ÷ 1140.63	61.76
	Fuel cell car	0.64 ÷ 0.94	1.00	12	4328.62 ÷ 1814.60	70.03 ÷ 60.89

Table A4. Techno-economic characterization for residential space heating technologies [58].

	Technology	Efficiency [PJ_u/PJ_f]	Availability Factor	Lifetime	Investment Cost [M€/cap.]	Fixed O&M Cost [M€/cap.]
Existing	Natural gas boiler	0.73	0.18	20	-	-
	Diesel fuel boiler	0.73	0.18	20	-	-
	LPG boiler	0.68	0.18	20	-	-
	Wood stove	0.25	0.18	20	-	-
	Heat exchanger	0.90	0.18	20	-	-
New	Diesel fuel boiler	0.81	1.00	20	5.87	0.06
	Condensing diesel fuel boiler	0.90 ÷ 0.98	1.00	20	8.72	0.09
	Solar and diesel fuel boiler	0.82 ÷ 0.90	1.00	20	23.50 ÷ 21.48	0.07
	Natural gas boiler	0.78 ÷ 0.90	1.00	20	4.99	0.05
	Condensing natural gas boiler	0.85 ÷ 0.98	1.00	20	6.84	0.07
	Solar and natural gas boiler	0.82 ÷ 0.90	1.00	20	22.40 ÷ 20.56	0.06
	LPG boiler	0.81	1.00	20	5.47	0.05
	Condensing LPG boiler	0.90 ÷ 0.98	1.00	20	7.00	0.07
	Solar and LPG boiler	0.82 ÷ 0.90	1.00	20	23.00 ÷ 21.02	0.06
	Wood stove	0.50	1.00	20	2.00	0.02
	Wood pellet stove	0.76 ÷ 0.83	1.00	20	15.85	0.16
	Electric heat pumps	3.30 ÷ 5.75	1.00	20 ÷ 50	47.56 ÷ 66.59	0.48 ÷ 0.67
	Multipurpose heat pump	3.30 ÷ 4.71	0.40	20	47.56	0.48
	Heat exchanger	0.90	1.00	20	2.88	0.03
	Insulation	-	-	20 ÷ 50	481.32 ÷ 2767.65	-

Appendix C. Detailed Results Comparison of Final Technologies Belonging to the Demand-Side Sectors

Appendix C reports the detailed comparison of models results for each final demand production technology of industry (Table A5), transport (Table A6), and buildings (Table A7) in all future milestone years (2007–2050). The cumulative activity of each technology along the entire time horizon (evaluated according to Equation (6)) is also reported together with the sub-sectorial average relative difference (evaluated according to Equation (7)).

Table A5. Activity of final technologies producing industrial service demands and cumulative activity along the entire time horizon, compared for TIMES-Italy and TEMOA-Italy results. Evaluated average relative difference on cumulative activity associated to the technology mix of each industrial subsector.

Subsector	Technology	Model	Process Activity [Mt]													Cumulative Activity [Mt]	$diff_{cum}$ [%]
			Year														
			2007	2008	2010	2012	2014	2016	2018	2020	2022	2025	2030	2040	2050		
Chemical	Ammonia existing	TIMES-Italy	0.62	0.58	0.50	0.44	0.37	0.30	0.24	0.17	0.10					6.11	0.31
		TEMOA-Italy	0.62	0.57	0.50	0.44	0.37	0.30	0.24	0.17	0.10					6.10	
	Ammonia naphtha POX	TIMES-Italy			0.09	0.14	0.14	0.14	0.14	0.14	0.14	0.14				2.69	
		TEMOA-Italy	0.02	0.02	0.09	0.14	0.21	0.21	0.20	0.00	0.20	0.19				3.30	
	Ammonia natural gas steam reforming	TIMES-Italy	0.02	0.02			0.08	0.18	0.27	0.32	0.40	0.52	0.69	0.79	0.90	22.94	
		TEMOA-Italy	0.00	0.00			0.01	0.11	0.20	0.46	0.35	0.46	0.69	0.79	0.89	22.30	
	Chlorine existing	TIMES-Italy	0.20	0.19	0.18	0.16	0.14	0.13	0.09	0.09	0.07	0.04				2.61	
		TEMOA-Italy	0.20	0.19	0.17	0.15	0.12	0.10	0.08	0.06	0.03	0.00				2.03	
	Chlorine membrane	TIMES-Italy	0.01	0.01	0.02	0.03	0.05	0.08	0.12	0.12	0.14	0.17	0.23	0.26	0.30	7.97	
		TEMOA-Italy	0.01	0.01	0.03	0.05	0.07	0.11	0.14	0.15	0.18	0.22	0.23	0.26	0.30	8.57	
	Aromatics existing	TIMES-Italy	0.77	0.74	0.63	0.60	0.54	0.47	0.40	0.34	0.27	0.17				9.86	
		TEMOA-Italy	0.77	0.74	0.63	0.60	0.54	0.47	0.40	0.34	0.27	0.17				9.86	
	Olefins existing	TIMES-Italy	2.84	2.64	2.43	2.22	1.98	1.73	1.48	1.24	0.99	0.62				36.33	
		TEMOA-Italy	2.84	2.64	2.38	2.22	1.98	1.73	1.48	1.23	0.99	0.62				36.21	
	HVC gas oil steam cracking	TIMES-Italy	0.11	0.11	0.42	0.54	0.93	1.43	1.86	2.10	2.50	3.05	4.01	4.60	5.23	139.46	
		TEMOA-Italy	0.12	0.12	0.47	0.55	0.92	1.43	1.86	2.11	2.51	3.05	4.02	4.60	5.24	139.71	
	Methanol existing	TIMES-Italy	0.05	0.05	0.04	0.04	0.03	0.02	0.02	0.01	0.01					0.49	
		TEMOA-Italy	0.05	0.04	0.04	0.04	0.03	0.02	0.02	0.01	0.01					0.49	
	Methanol natural gas steam reforming	TIMES-Italy	0.00	0.00	0.00	0.01	0.02	0.02	0.03	0.04	0.04	0.05	0.05	0.06	0.07	1.96	
		TEMOA-Italy	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.04	0.04	0.05	0.05	0.06	0.07	1.98	
	Other chemicals	TIMES-Italy	16.02	15.01	14.97	14.49	14.79	15.60	16.11	15.79	16.16	16.47	17.26	19.78	22.51	798.30	
		TEMOA-Italy	16.02	15.02	14.97	14.50	14.79	15.61	16.11	15.81	16.18	16.48	17.27	19.79	22.52	798.69	
Iron and steel	Basic oxygen furnace existing	TIMES-Italy	11.33	9.48	8.39	6.83	6.08	5.63	4.74	3.70	3.54	2.46				123.95	2.57
		TEMOA-Italy	11.30	9.63	8.62	7.27	6.39	5.81	5.10	3.92	3.94	2.46				128.90	
	Basic oxygen furnace new	TIMES-Italy	0.65		0.23	0.44	0.31	0.18	0.36	0.24	0.65	0.65	0.65	0.17		17.57	
		TEMOA-Italy	0.96		0.00	0.00	0.00	0.00	0.00	0.02	0.25	0.41	0.00	0.00		3.79	
	HIsarna process	TIMES-Italy										1.09	3.59	4.23	4.59	97.44	
		TEMOA-Italy										1.33	4.24	4.41	4.59	106.90	
	Electric arc furnace existing	TIMES-Italy	18.98	17.08	16.50	14.85	13.20	11.55	9.90	8.25	6.60	4.13				242.09	
		TEMOA-Italy	19.00	16.94	16.50	14.90	13.20	11.60	9.90	8.25	6.60	4.13				242.03	
	Electric arc furnace new	TIMES-Italy	1.83		0.22	1.48	3.55	6.45	9.04	9.69	12.47	15.00	19.32	20.07	20.91	631.74	
		TEMOA-Italy	1.54		0.22	1.43	3.57	6.41	9.04	9.70	12.49	15.01	19.32	20.07	20.90	631.43	

Table A5. *Cont.*

Subsector	Technology	Model	Process Activity [Mt]													Cumulative Activity [Mt]	$diff_{cum}$ [%]
			Year														
			2007	2008	2010	2012	2014	2016	2018	2020	2022	2025	2030	2040	2050		
Non-ferrous metals	Aluminum existing	TIMES-Italy	2.03	1.68	1.66	1.43	1.41	1.24	1.06	0.88	0.71	0.44				25.09	0.07
		TEMOA-Italy	2.03	1.68	1.66	1.43	1.41	1.24	1.06	0.88	0.71	0.44				25.08	
	Aluminum new	TIMES-Italy	0.05	0.01	0.05	0.05	0.11	0.36	0.56	0.63	0.86	1.14	1.63	1.75	1.86	51.18	
		TEMOA-Italy	0.05	0.02	0.05	0.05	0.11	0.36	0.56	0.63	0.86	1.14	1.63	1.75	1.86	51.18	
	Copper existing	TIMES-Italy	0.38	0.32	0.31	0.27	0.27	0.23	0.20	0.17	0.13	0.08				4.72	
		TEMOA-Italy	0.38	0.32	0.31	0.27	0.27	0.23	0.20	0.17	0.13	0.08				4.72	
	Copper new	TIMES-Italy	0.01	0.00	0.01	0.01	0.02	0.07	0.11	0.12	0.16	0.22	0.31	0.33	0.35	9.64	
		TEMOA-Italy	0.01	0.00	0.01	0.01	0.02	0.07	0.11	0.12	0.16	0.22	0.31	0.33	0.35	9.63	
	Other non-ferrous metals	TIMES-Italy	1.40	1.14	1.14	0.99	1.02	1.07	1.09	1.01	1.05	1.06	1.09	1.17	1.25	51.23	
		TEMOA-Italy	1.40	1.14	1.14	0.99	1.02	1.07	1.09	1.01	1.06	1.06	1.09	1.17	1.25	51.21	
	Zinc existing	TIMES-Italy	0.36	0.30	0.30	0.26	0.25	0.22	0.19	0.16	0.13	0.08				4.51	
		TEMOA-Italy	0.37	0.31	0.31	0.27	0.25	0.22	0.19	0.16	0.13	0.08				4.55	
	Zinc new	TIMES-Italy	0.01		0.01	0.01	0.02	0.06	0.10	0.11	0.16	0.21	0.29	0.31	0.33	9.19	
		TEMOA-Italy	0.01		0.00	0.00	0.02	0.06	0.10	0.11	0.16	0.21	0.29	0.31	0.33	9.15	
Non-metallic minerals	Dry cement kilns existing	TIMES-Italy	33.14	29.10	26.88	22.25	22.81	20.17	17.29	14.41	11.53	7.20				409.53	0.35
		TEMOA-Italy	33.10	29.58	25.70	24.20	23.00	20.10	17.30	14.40	11.50	7.20				412.16	
	Wet cement kilns existing	TIMES-Italy	13.21	11.60	10.23	8.87	7.51	8.04	6.89	5.74	4.59	2.87				159.11	
		TEMOA-Italy	13.20	11.60	11.40	8.88	7.52	8.03	6.89	5.74	4.59	2.87				161.45	
	Blended cement new	TIMES-Italy	2.57	0.49		1.95	2.57	6.55	10.08	11.02	16.51	23.47	35.54	39.10	42.09	1107.47	
		TEMOA-Italy	2.63	0.00		0.00	2.37	6.63	10.09	11.03	16.57	23.50	35.52	39.12	42.08	1102.73	
	Dry clinker new	TIMES-Italy	1.70	0.32		1.28	1.70	4.32	6.65	7.27	10.90	15.49	23.46	25.81	27.78	730.93	
		TEMOA-Italy	1.74	0.00		0.00	1.57	4.38	6.66	7.28	10.93	15.51	23.45	25.82	27.77	727.80	
	Bricks existing	TIMES-Italy	5.88	5.17	4.56	3.95	3.34	2.74	2.13	1.52	0.91					55.44	
		TEMOA-Italy	5.47	5.17	4.56	3.95	3.34	2.73	2.13	1.52	0.91					55.01	
	Bricks new	TIMES-Italy	0.33	0.06	0.15	0.25	0.83	1.68	2.22	2.44	3.23	4.26	4.51	4.97	5.35	157.40	
		TEMOA-Italy	0.74	0.06	0.15	0.25	0.84	1.68	2.22	2.44	3.23	4.26	4.51	4.97	5.34	157.81	
	Glass existing	TIMES-Italy	3.52	3.13	2.73	2.51	2.45	1.99	1.70	1.45	1.22	0.77				42.93	
		TEMOA-Italy	3.52	3.13	2.75	2.52	2.30	2.14	1.84	1.53	1.21	0.77				43.39	
	Glass new	TIMES-Italy	0.20		0.09		0.05	0.66	0.90	0.92	1.26	1.78	2.70	2.97	3.20	84.49	
		TEMOA-Italy	0.12		0.00		0.12	0.43	0.69	0.77	1.19	1.71	2.69	2.98	3.20	82.50	
	Lime existing	TIMES-Italy	5.02	4.41	4.02	3.37	3.29	3.06	2.62	2.18	1.75	1.09				61.64	
		TEMOA-Italy	5.02	4.41	4.02	3.40	3.28	2.84	2.42	2.08	1.75	1.09				60.63	
	Lime new	TIMES-Italy	0.28	0.05		0.21	0.28	0.71	1.09	1.19	1.79	2.54	3.85	4.24	4.56	120.05	
		TEMOA-Italy	0.29	0.06		0.19	0.29	0.93	1.30	1.30	1.79	2.55	3.85	4.24	4.56	121.18	

Table A5. *Cont.*

Subsector	Technology	Model	Process Activity [Mt]													Cumulative Activity [Mt]	$diff_{cum}$ [%]
			Year														
			2007	**2008**	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**	**2022**	**2025**	**2030**	**2040**	**2050**		
Pulp and paper	Paper mill existing	TIMES-Italy	9.59	8.90	8.34	7.51	6.67	5.84	5.00	4.17	3.34	2.09				122.89	**0.65**
		TEMOA-Italy	9.59	8.95	8.34	7.51	6.67	5.84	5.00	4.17	3.34	2.08				122.97	
	Paper mill new	TIMES-Italy	0.71	0.31	0.87	1.35	2.45	3.59	4.01	4.77	5.82	7.11	9.40	10.44	11.71	321.81	
		TEMOA-Italy	0.71	0.26	0.87	1.34	2.45	3.59	4.02	4.78	5.82	7.11	9.40	10.44	11.71	321.84	
	Chemical pulp existing	TIMES-Italy	0.15	0.14	0.13	0.12	0.10	0.09	0.08	0.06	0.05	0.03				1.90	
		TEMOA-Italy	0.15	0.14	0.13	0.12	0.09	0.07	0.06	0.04	0.02	0.00				1.90	
	Chemical pulp new	TIMES-Italy	0.01		0.01	0.01	0.03	0.04	0.05	0.06	0.07	0.08	0.11	0.11	0.12	3.61	
		TEMOA-Italy	0.01	0.00	0.01	0.01	0.03	0.04	0.05	0.06	0.07	0.09	0.11	0.11	0.12	3.62	
	Mechanical pulp existing	TIMES-Italy	0.33	0.32	0.29	0.26	0.23	0.20	0.17	0.14	0.12	0.07				4.29	
		TEMOA-Italy	0.37	0.35	0.30	0.26	0.22	0.18	0.14	0.10	0.06	0.00				3.67	
	Mechanical pulp new	TIMES-Italy	0.04		0.04	0.04	0.07	0.10	0.11	0.13	0.16	0.19	0.25	0.26	0.27	8.28	
		TEMOA-Italy	0.00	0.00	0.01	0.01	0.04	0.08	0.09	0.12	0.15	0.19	0.25	0.26	0.27	8.01	
	Recycled pulp existing	TIMES-Italy	5.35	5.10	4.65	4.18	3.72	3.25	2.79	2.32	1.86	1.16				68.77	
		TEMOA-Italy	5.28	5.11	4.59	4.12	3.67	3.20	2.75	2.31	1.84	1.16				68.10	
	Recycled pulp new	TIMES-Italy	0.35		0.43	0.69	1.25	1.82	2.02	2.38	2.88	3.48	4.52	5.04	5.67	156.13	
		TEMOA-Italy	0.44	0.00	0.54	0.79	1.34	1.92	2.12	2.49	3.01	3.59	4.60	5.03	5.65	159.09	
Other industries	Other industries existing	TIMES-Italy	487.4	425.8	409.3	384.8	381.5	405.1	416.3	380.1	394.0	399.1	407.2	416.9	424.9	18,785.8	**0.02**
		TEMOA-Italy	487.7	426.1	409.5	384.9	381.8	405.0	416.3	379.9	393.9	399.0	407.0	416.6	424.8	18,781.8	

Table A6. Activity of transport road cars and cumulative activity along the entire time horizon, compared for TIMES-Italy and TEMOA-Italy results. Evaluated average relative difference on cumulative activity.

Technology	Model	Process Activity [Bvkm]													Cumulative Activity [Bvkm]	$diff_{cum}$ [%]
		Year														
		2007	**2008**	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**	**2022**	**2025**	**2030**	**2040**	**2050**		
Biofuels existing	TIMES-Italy	0.78	0.75	0.62	0.50	0.37	0.25	0.12							6.00	**0.57**
	TEMOA-Italy	0.81	0.75	0.62	0.50	0.37	0.25	0.12							6.02	
Diesel existing	TIMES-Italy	97.12	92.50	77.08	61.67	46.25	30.83	15.42							744.61	
	TEMOA-Italy	100.00	92.30	76.90	61.50	46.20	30.80	15.40							746.20	
Gasoline existing	TIMES-Italy	127.34	121.27	101.06	80.85	60.64	40.42	20.21							976.26	
	TEMOA-Italy	131.00	121.00	101.00	80.60	60.50	40.30	20.20							978.20	
LPG existing	TIMES-Italy	10.08	9.60	8.00	6.40	4.80	3.20	1.60							77.31	
	TEMOA-Italy	10.40	9.60	8.00	6.40	4.80	3.20	1.60							77.60	

Table A6. *Cont.*

Technology	Model	Process Activity [Bvkm]													Cumulative Activity [Bvkm]	$diff_{cum}$ [%]
		Year														
		2007	2008	2010	2012	2014	2016	2018	2020	2022	2025	2030	2040	2050		
Natural gas existing	TIMES-Italy	3.84	3.66	3.05	2.44	1.83	1.22	0.61							29.44	
	TEMOA-Italy	3.96	3.66	3.05	2.44	1.83	1.22	0.61							29.58	
Diesel new	TIMES-Italy	22.49	26.78	32.42	46.91	61.90	80.85	100.39	119.69	124.39	126.64	129.70	135.94	126.55	5002.77	
	TEMOA-Italy	18.14	26.10	33.86	48.73	63.97	83.22	103.54	123.54	124.98	126.88	130.06	135.91	121.01	5016.08	
Electric new	TIMES-Italy														0.00	
	TEMOA-Italy													25.56	76.69	
Gasoline new	TIMES-Italy	6.98	12.01	28.32	46.16	64.50	86.79	109.68	132.33	134.22	136.62	139.92	146.29	145.53	5371.07	
	TEMOA-Italy	4.00	12.80	28.87	46.73	64.82	86.91	109.12	131.24	133.67	136.32	139.54	146.29	145.53	5342.54	
LPG new	TIMES-Italy			2.91	2.91	2.91	2.91	2.91	2.91						82.61	
	TEMOA-Italy			0.17	0.17	0.17	0.17	0.17	0.17						47.31	
Natural gas new	TIMES-Italy			5.30	6.18	7.07	7.96	8.85	9.73	9.83	9.98	10.22	10.22	10.22	404.59	
	TEMOA-Italy	0.39	0.39	6.23	6.93	7.64	8.34	9.04	9.75	9.85	10.00	10.20	10.20	10.20	411.18	

Table A7. Activity of residential space heating technologies and cumulative activity along the entire time horizon, compared for TIMES-Italy and TEMOA-Italy results. Evaluated average relative difference on cumulative activity.

Technology	Model	Process Activity [Mm^2]													Cumulative Activity [Mm^2]	$diff_{cum}$ [%]
		Year														
		2007	2008	2010	2012	2014	2016	2018	2020	2022	2025	2030	2040	2050		
Wood stove	TIMES-Italy	30.80	33.03	32.20	29.34	28.28	26.72	23.84	20.31	18.23	16.22	19.11	28.49	43.02	1159.02	
	TEMOA-Italy	30.24	35.61	32.29	29.13	26.83	24.90	21.89	20.22	18.04	15.50	19.10	28.47	42.99	1148.24	
Electric heat pumps	TIMES-Italy	4.82	4.61	4.11	4.37	3.10	2.59	2.09	1.58	1.08	0.32	0.00	0.00	0.00	54.52	
	TEMOA-Italy	5.05	4.99	4.81	5.88	5.16	5.40	5.52	5.80	7.76	8.63	10.99	11.21	11.41	402.81	
Geothermal heat pumps	TIMES-Italy	13.41	13.41	13.41	13.41	13.41	13.41	13.41	13.41	13.41	13.41	13.41	13.41	13.41	616.84	
	TEMOA-Italy	13.44	13.44	13.44	13.44	13.44	13.44	13.44	13.44	13.44	13.44	13.41	13.41	13.41	617.55	
Heat exchanger	TIMES-Italy	32.02	30.24	32.36	30.88	27.78	25.49	23.20	22.78	20.76	17.72	12.66	16.75	20.83	925.00	**1.92**
	TEMOA-Italy	32.22	34.60	32.89	30.79	28.79	26.69	24.69	22.60	20.58	17.04	12.50	16.66	20.81	935.30	
LPG boilers	TIMES-Italy	79.66	72.52	67.96	73.08	67.00	67.95	65.84	61.03	60.76	62.72	63.85	38.27	24.42	2620.76	
	TEMOA-Italy	79.65	72.46	58.16	59.90	55.67	56.57	52.69	50.81	49.00	47.37	49.83	54.57	59.47	2498.39	
Natural gas boilers	TIMES-Italy	951.16	966.27	1026.65	1035.61	980.23	1014.44	1038.54	1054.13	1063.66	1065.99	1072.25	1088.90	1106.21	48,633.94	
	TEMOA-Italy	967.92	947.45	1030.68	1057.38	947.24	977.92	1012.92	1024.60	1059.92	1107.25	1110.46	1082.72	1089.09	48,879.30	
Diesel fuel boilers	TIMES-Italy	174.43	169.67	120.04	119.10	195.48	176.55	165.80	165.56	165.38	174.12	182.77	201.22	209.24	8233.18	
	TEMOA-Italy	158.08	181.54	124.80	109.58	238.44	222.58	201.87	201.65	174.88	141.60	148.13	180.37	180.33	7777.64	

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