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Italy Energyscope

Energy system modeling and scenarios for the Italian energy transition

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Abstract

Sustainability of national energy systems has a strategic role in current and future energy-environmental policies as it involves key points such as security of energy supply, mitigation of environmental impacts (with special focus on climate-changing emissions) and energy affordability. In this context, modeling tools able to represent a simplified yet detailed configuration of national energy systems become more and more important. These energy models can support decision-makers realizing the process towards the so-called energy transition by producing reliable trajectories of development for the energy system in a certain time horizon, coherently with the given hypothesis and constraints. However, widely-used energy models are often neither fully accessible nor usable, making difficult critically examining the results available on literature.

In this context, we present the application of the open-source energy model Energyscope TD [111] to the Italian case-study in order to identify multiple low-carbon scenarios up to 2030 and beyond, during the decarbonization process. First, the structure and formulation of the linear programming (LP) model is briefly presented and described. With respect to previous works adopting this modeling framework, the proposed solution, called *Italy Energyscope*, adds new resources, energy conversion technologies and demands. Furthermore, since the Italian energy system is highly heterogeneous, *Italy Energyscope* is able to take into account energy demands, availability of resources and weather conditions at the macro-regional level. Second, in order to test the accuracy of the model, *Italy Energyscope* is validated on the Italian energy system in the year 2015. This choice is due to the availability of precise data for the aforementioned year, fully documented and reported. Once demonstrated the reliability of the model and the accuracy of the results, different alternative scenarios of decarbonization for the year 2030 are defined. In particular, from the scenarios analysis three major results are obtained: (i) business as usual scenarios do not meet the environmental goals for 2030; (ii) the recent national directive called “NES 2017” [155] defines a feasible and affordable path to meet the 40% emissions reduction target with respect to 1990; (iii) the Italian maximum decarbonization potential is quantifiable in a 97% emissions reduction with respect to 1990, and could be theoretically met through huge technical and economic efforts in electrifying the end-use energy demand by using electric vehicles, heat pumps and by developing both renewables and Carbon Capture and Storage (CCS) technologies.

Sommario

La sostenibilità dei sistemi energetici nazionali ha un ruolo strategico nelle attuali e future politiche energetico-ambientali coinvolgendo punti chiave come la sicurezza dell'approvvigionamento, la mitigazione degli impatti ambientali (con particolare attenzione alle emissioni climalteranti) e l'accessibilità energetica. In questo contesto, diventano sempre più importanti gli strumenti di modellazione in grado di rappresentare una configurazione dei sistemi energetici su scala nazionale semplice ma dettagliata. Questi modelli possono infatti supportare i decisori politici a realizzare il processo verso la cosiddetta transizione energetica riproducendo possibili traettorie di sviluppo del sistema in un certo orizzonte temporale, coerentemente con le ipotesi e i vincoli dati. Tuttavia, i modelli energetici disponibili spesso non sono nè completamente accessibili nè utilizzabili, rendendo difficile esaminare criticamente i risultati reperibili in letteratura.

In questo contesto viene presentata l'applicazione del modello open-source Energyscope TD [111] al caso studio italiano al fine di definire molteplici scenari a basse emissioni di carbonio durante il processo di decarbonizzazione. In primis, la formulazione del modello di programmazione lineare viene brevemente descritta. Rispetto ai lavori precedenti che hanno adottato questo framework di modellizzazione, la soluzione proposta, chiamata *Italy Energyscope*, aggiunge nuove risorse, tecnologie di conversione e domande energetiche. Inoltre, poichè il sistema energetico italiano è estremamente eterogeneo, *Italy Energyscope* è in grado di considerare la domanda di energia, la disponibilità delle risorse e le condizioni metereologiche a livello macro-regionale. In secundis, al fine di testarne l'accuratezza, il modello proposto è convalidato rispetto al sistema energetico italiano del 2015. Questa scelta è dovuta alla disponibilità di dati precisi, documentati e riportati in maniera esaustiva. Una volta dimostrate l'affidabilità e l'accuratezza dei risultati, vengono definiti diversi scenari di transizione energetica per il 2030. In particolare, tre risultati principali sono ricavati dall'analisi degli scenari: (i) un trend di crescita delle rinnovabili costante ed uguale a quello attuale non porta a soddisfare gli obiettivi ambientali fissati per il 2030; (ii) la recente "SEN 2017" definisce un strada percorribile verso una riduzione del 40% delle emissioni rispetto al 1990; (iii) il potenziale italiano di massima decarbonizzazione è quantificabile in una riduzione delle emissioni del 97% rispetto al 1990, e potrebbe essere raggiunto attraverso ingenti sforzi sia tecnici che economici atti ad aumentare l'elettrificazione della domanda di energia per uso finale utilizzando veicoli elettrici, pompe di calore e sviluppando tecnologie sia rinnovabili che di cattura e stoccaggio del carbonio.

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Chapter 1

Introduction

1.1 The energy transition

1.1.1 Context

In the last few decades, the impact of human activities on our planet has become more and more observable and noticeable, causing dramatic and rapid changes in climate as well as bringing serious hazards for human health worldwide. The planet's average surface temperature, in fact, has risen about 0.9 °C during the last century [121], a change driven largely by constantly carbon dioxide and other anthropogenic greenhouse-gases (GHG) emissions into the atmosphere. As a consequence, sea levels are rising, glaciers are melting and precipitation patterns are changing all around the world. Extreme weather events are becoming more intense and frequent [121]. At the same time, global temperature increase influences both quality and availability of primary determinants of human welfare such as clean air, sufficient food and safe drinking water. According to the World Health Organization (WHO), between 2030 and 2050, climate change is set to directly cause approximately 250 000 additional deaths per year [165], due to malnutrition, malaria, diarrhoea and heat stress.

All this evidence indicates that these phenomena are set to continue over this century if the actual emission trend will be maintained. Therefore, reducing the levels of heat-trapping gases in the atmosphere and coping with the already present consequences of climate change are fundamental drivers that will characterise policies in the long and very long term (until 2050 and beyond). A deep transformation of energy systems towards the so called "Energy Transition" is definitely required. This *"pathway toward the transformation of the global energy sector from fossil-based to zero-carbon"* [96] aims at setting to zero energy-related CO_2 emissions via an increased penetration of RES, energy efficiency measures and a better management of energy demand. The energy sector, in fact, is the largest contributor to national total emissions standing for roughly 2/3 of all anthropogenic GHG emitted [93]. In this context, the Kyoto Protocol (1997) has set for the first time targets for reducing emissions. However, despite increasing awareness of climate change, fossil fuels still cover more than 80% of the world primary energy consumption [95]: as a consequence, global GHG emissions continue on a sharp rise.

Figure 1.1 shows the trend of global CO_2 emissions in the period 1990-2016 for the major polluters in giga-tons [62]. During this time lapse, global emissions steadily increased especially due to the contribution of developing countries (i.e.

China and India), passing from 20.52 to 32.31 Gt of CO_2 per year. In the same period, the share of developed countries has slowly decreased according to the data provided by the Organisation for Economic Cooperation and Development (OECD) [62].

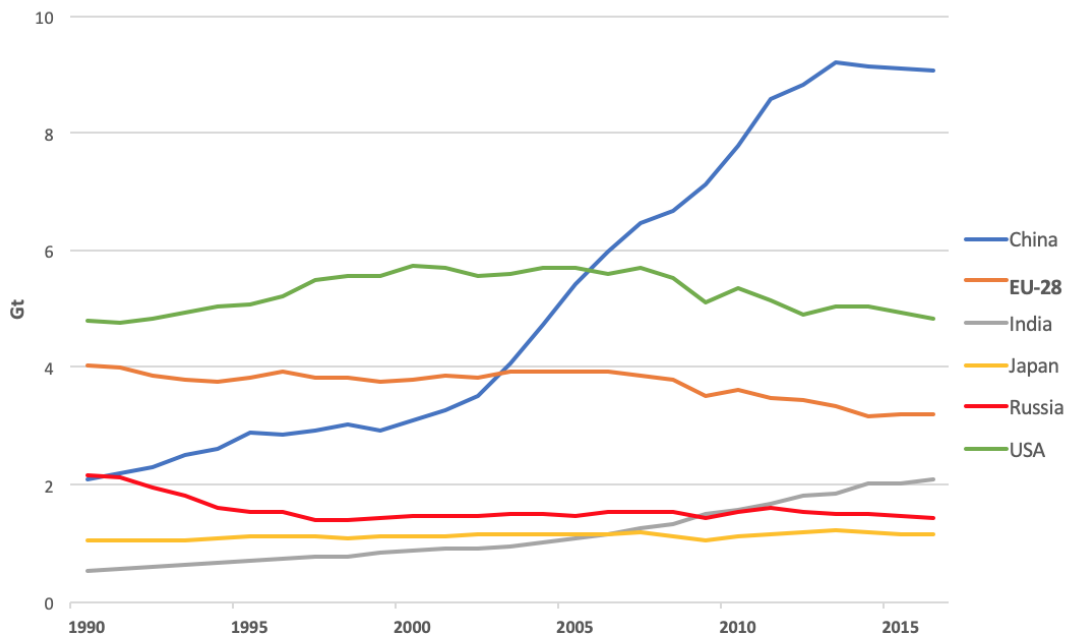


Figure 1.1: Evolution of CO_2 emissions for world major polluters, data extracted from OECD air and GHG emissions 2016 [62].

The actual emission trend shown in Figure 1.1 will clearly not be sufficient to mitigate the consequences of climate change on our planet. The solution proposed by the Paris Agreement on Climate Change (2015) consists in drastically reducing the amount of fossil carbon emitted in form of CO_2 into the atmosphere by 40% to 70% on a global scale by 2050 compared with 1990 according to [93]. With these measures, we will be able to mitigate the threat of climate change by keeping a global average temperature rise this century well below 2 degrees Celsius above pre-industrial levels [44]. In order to pursue this ambitious but necessary energy transition process, a vast decarbonization of energy systems has to be planned and quickly realized on a global and national scale, ensuring the competitiveness of industry and granting secure and stable access to energy.

1.1.2 Energy transition in Europe

In the recent years the European Union (EU) has decided to take on a global leadership role in reducing GHG emissions. According to Figure 1.1, the EU is currently the third major polluter worldwide although its emission trend has progressively decreased over the last decade. Despite this reduction, the consequences of temperature increase in Europe are still noticeable: climate change threats European plant diversity [167], agriculture [30] and it is a (contributing) cause of extreme weather events [109, 78]. Southern and central Europe are experiencing more frequent heat waves, the Mediterranean area is becoming drier while northern Europe is getting significantly wetter [47]. Furthermore, climate change is a public health risk strictly related with some diseases [86, 140] and it contributes to nearly 26 000 European premature deaths every year mainly due to the synergy with air pollutants [126, 63]. It also burdens public health spending and could lead to significant economic damages on a regional and sectoral dimensions [42].

Trying to mitigate these potentially disastrous effects, the EU has defined targets for reducing its GHG emissions progressively up to 2050. To do this, ambitious goals to be achieved as early as 2020 have been set, as described in the so-called "Climate and Energy Package" (known as the "20-20-20" package [73]). The EU has adopted a 20% GHG emissions reduction target for 2020 relative to 1990 as part of its climate and energy package [55], has established the world largest emissions trading system (the EU ETS) and has already implemented a series of emission reduction, energy efficiency and RES deployment policies [48]. The initial effectiveness of these policies has already been proved since the EU has reduced its contribution to global emissions, as shown in Figure 1.1, being on track to meet its emissions reduction target for 2020 [55].

The goals for the next steps are defined in the "2030 Climate and Energy Framework" [56]. The Framework includes EU-wide policy objectives from 2021 with the aim to extend to 2030 the current legislative 2020 framework. The objective is to send a strong signal to the market, encouraging private investment in new pipelines, electricity networks, and low-carbon technologies. These are intermediate steps on the way to achieve the transformation towards a low-carbon economy. The cost of meeting the targets does not substantially differ from the price we need to pay anyway to replace the ageing energy system. However, despite the recent achievements, the EU energy mix still relies on fossil fuels (73% in terms of gross inland consumption in 2015 [4]) that ought to be phased out to further reduce emissions and effectively fight climate change. In these terms, the "Energy Roadmap 2050" [57] envisages a significant reduction in GHG emissions compared to 1990 levels by 2050, with a 95% target for the electricity sector, and a RES share amounting to 75% in gross final energy consumption. Furthermore, it suggests diversified supply technologies, low nuclear, increased investment expenditure (CAPEX) accompanied by a reduction in spending for fuel (OPEX) and increased interaction between centralised and distributed systems. Minimum targets for 2030 and 2050 are listed in Table 1.1

Table 1.1: Minimum targets for 2030 and 2050 according to the "2030 Climate and Energy Framework" [56] and the "Energy Roadmap 2050" [57].

Topic	**Target 2030**	**Target 2050**
Reduction in GHG emissions (vs. 1990 levels)	40%	80-95%
Share for renewable energy	32%	75%
Improvement in energy efficiency	33%	Reduction 41% consumption (vs. 2005)

Robust policies at EU and Country level and the uptake of low-carbon technologies have so far contributed to the previously mentioned achievements. The EU is heading in the right direction, but it should go there faster. Innovation, including progress on renewable energy and energy efficiency, has to be encouraged in order to become the main driver of the European energy transition, leading to a continental carbon-free energy system as soon as possible.

1.1.3 Energy transition in Italy

Figure 1.2 shows a breakdown of global CO2 emissions by country in 2016 [62]. In the same year, Italy was responsible of the emission of 325.7 Mt of CO_2, standing for roughly 1.0% of the global whole repartition (32.31 Gt of CO_2).

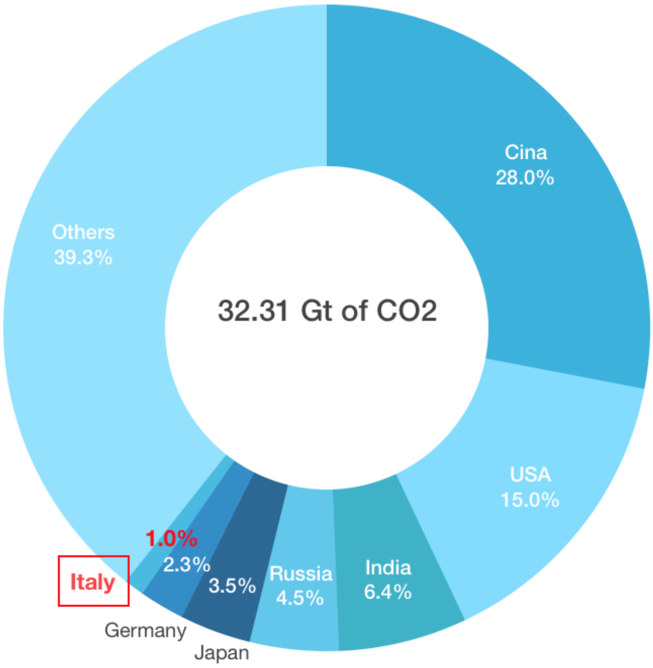


Figure 1.2: Repartition of the world CO_2 emissions, data extracted from OECD air and GHG emissions 2016 [62].

As a co-signer of the Kyoto Protocol and of the Paris Agreement on Climate Change, Italy is committed to develop, publish and regularly update national emission inventories as well as schedule and implement policies to reduce these emissions. Italy's total primary energy supply (TPES) has decreased by 19.1% over the past ten years [94]. As a consequence, domestic GHG emissions have progressively declined between 1990 and 2015 (from 520 to 433 millions of CO_2 equivalent tons [136]). Several factors such as greater use of natural gas replacing coal and oil, renewable energy growth in the power sector (33.5% contribution in 2015 [155]) and improvements in energy efficiency have contributed to this reduction. The economic recession has contributed significantly as well. However, despite these promising achievements, the Italian energy system still strongly relies on fossils, which accounts for 79.1% of the country's TPES in 2015, broken down in natural gas (36.7%), oil (34.2%) and coal (8.2%) [94].

In this context, Italy has recently put in place new ambitious political measures in order to actively implement energy transition policies towards a low-carbon society. In line with the decarbonization targets, the recent document titled "Proposta di Piano Nazionale Integrato per l'Energia e il Clima" [130], together with the National Energy Strategy (NES), sets a list of national objectives for the next future. The NES 2017 [155], that will be integrated in the next "Piano Energia e Clima", listed different targets for 2030, coherent with what is expected in [57]. The two key proposed points are: achieving and sustainably exceeding the 2030 environmental and decarbonization objectives defined at European level (-26% GHG emissions with respect to 2016), and continuing to improve security of supply and flexibility of energy systems and infrastructures. Furthermore, the decarbonization process of the Italian energy system (through specific actions and renovations) can play a fundamental role not only in reducing energy related emissions but also in improving national competitiveness in the energy market. In this context, the critical points to be faced include a reduction of both energy prices for businesses and families (generally higher than in other European Countries) and dependence on imported fossil fuels, lowering it from 81% in 2015 to at least 63% in 2030.

In keeping with these needs, the "Proposta di Piano Nazionale Integrato per l'Energia e il Clima" embraces European directives. So, the expected results for the next few years include an increasing penetration of renewables (mainly wind and photovoltaic, whose production is expected to double by 2030 [155], covering at least 30% of TPES in the same year), the phase-out of coal power plants by 2025 and the need to strengthen efforts in energy efficiency of residential buildings and in electrification [155].

1.2 State of the art: energy system modeling and scenarios

As reviewd by Söderholm at al. [149], national decarbonizing strategies and policies that have medium and long-term goals, are more robust if based on the analysis of possible future scenarios developed with the help of mathematical energy models [89]. These are not forecasts, but give possible trajectories of the investigated energy system in a certain time horizon consistent with the given constraints and hypotheses of development. Even if the future will hardly be exactly the one projected by the scenarios, as the actual trend of variables is likely to deviate from the hypotheses assumed, these models are often used as supporting tool by policy-makers [32, 31, 81]. So, in recent years a large panel of studies based on mathematical models able to quickly develop reliable low-carbon energy pathways has been published [12, 64, 77, 34, 159]. Connolly et al. [51] perform an extensive review of existing energy models proposed in literature and currently used. They are generally classified using a number of alternative criteria, as described by Bhattacharyya et al. [29]. To name a few, we can consider the analytical modeling approach (top-down and bottom-up) or the methodology (partial equilibrium, general equilibrium, hybrid, optimisation, econometric), the spatial dimension (national, regional or global) and the time horizon. The different criteria that can be used to categorize the energy models are briefly summarized in Table 1.2. For a more complete and in-depth analysis of each of these characterization criteria, see the study performed by Nakata et al. [120].

In the context of the global energy-transition described in Sec. 1.1, the attention is focused on models that can help public administrations to define multi-sectoral energy policies, providing forecasting decarbonization scenarios at a national-regional scale. Thus, a literature review is necessary for the following reasons: (i) identifying the already available and established energy models at a national-regional scale; (ii) reviewing the studies in which they are applied according to certain criteria of characterisation (e.g. energy sectors included, optimization strategy, computational time); (iii) choosing which energy model formulation would be the best to be applied to the Italian energy transition case study described in Sec. 1.1.3.

Table 1.2: Summary of energy model's design approach [25].

Category	Explanation
Analytical	Top-down and Bottom-up
Purposes	Forecasting, exploring and backcasting
Methodology	Econometrics, macro-economic, economic equilibrium, hybrid, optimization, simulation and multi-criteria
Mathematical approach	Linear programming, mixed integer programming, dynamic programming etc.
Geographical	Global, regional, national, local
Time horizon	Short, medium and long term
Data requirement	Qualitative, quantitative, aggregated and disaggregated

1.2.1 Models and studies

A literature review is here presented to evaluate the available state-of-the-art energy models applied at a national/regional scale for the development of low-carbon scenarios until the year 2050 and beyond.

Firstly, an energy system models comparison is performed. Based on the reviews by Connolly et al. [51] and Limpens et al. [111], six of the most popular energy models for national scale application are compared according to the following criteria: inclusion of electricity, heat and mobility sectors, availability (open use and/or open source), optimization or simulation strategy, resolution time and computational running cost. The results are reported in Table 1.3.

Table 1.3: Energy system models comparison. Legend: ✓ criterion satisfied; (✓) criterion partially satisfied. Adapted from [51, 111]. Abbreviations: electricity (elec.), mobility (mob.), operation (oper.), investment (inv.), time resolution (res.), running time (run.), second(s) (s), minute(s) (m), hour(s) (h), month(s) (mo), year(s) (y).

Tool	Source	Sectors			Open		Opti.		Time	
		Elec.	Heat	Mob.	Use	Sour.	Oper.	Inv.	Res.	Run.
MARKAL/TIMES	[72, 114]	✓	✓	✓	(✓)			✓	y	min
PRIMES	[22, 38]	✓	✓	✓	(✓)				y	
EnergyPLAN	[124, 161]	✓	✓	✓	✓		✓		h	s
OSeMOSYS	[123, 90]	✓	✓	✓	✓	✓		✓	h	h
Energyscope	[152, 153]	✓	✓	(✓)	✓	✓	✓	✓	mo	s
Energyscope TD	[111]	✓	✓	✓	✓	✓	✓	✓	h	min

Secondly, several studies are compared in order to find which model would be the most effective in order to represent an energy system similar to the Italian one. In this context, the classification is based on the following criteria: (i) Which model is used? (ii) Which is the Country studied? (iii) Is the study multi-sector based (electricity, mobility and heating-cooling)? (iv) Which is the objective function (cost and/or emissions)? (v) Which are the time properties (time-step resolution, base and reference-target year)? The obtained results are reported in Table 1.4.

Globally, the MARKAL/TIMES [72, 114, 76] energy models family is the most widely used in the context of carbon mitigation strategies. The MARKAL (acronym

Table 1.4: Review of national/regional deep decarbonization scenarios.

Tool	Country	Sectors Elec.	Heat	Mob.	Objec. Cost	Emis.	Step	Time Base y	Ref. y
MARKAL/TIMES	China [146]		✓		✓		y	2010	2050
	UK [23]	✓		✓	✓		y	2010	2050
	Italy [40]	✓		✓	✓		5y	2004	2030
	Canada [106]	✓	✓	✓	✓		y	2011	2050
	Italy [12]	✓	✓	✓	✓		y	2006	2060
	China [163]	✓	✓	✓	✓		5y	2000	2050
	Ireland [1]	✓	✓	✓	✓		5y	2005	2050
	UK [64]	✓	✓	✓	✓		5y	2010	2050
	Portugal [77]	✓	✓	✓	✓		5y	2005	2050
	France [21]	✓	✓	✓	✓		5y	2005	2050
	US [117]	✓	✓	✓	✓		5y	2005	2050
PRIMES	EU [46]	✓	✓	✓			5y	2015	2050
	EU [147]			✓			5y	2005	2050
EnergyPLAN	Finland	✓	✓	✓			snapshot[a]	2012	2020-2050
	Italy [34]	✓	✓	✓			-	2014	2050
	Macedonia [27]	✓	✓	✓			-	2008	2030-2050
	Ireland [52]	✓	✓	✓			-	2007	x[b]
	Denmark [116]	✓	✓	✓			-	2004	2030-2050
OSeMOSYS	Global [112]	✓	✓	✓	✓		5y	2015	2050
	Ireland [164]	✓	✓	✓	✓		5y	2005	2050
	Portugal [18]	✓			✓	✓	y	2015	2050
	Egypt [134]	✓			✓		y	2015	2040
	Saudi Arabia[87]	✓			✓		y	2015	2030
	Tunisia [54]	✓			✓		y	2015	2030
Energyscope	Switzerland [152, 84]	✓	✓	✓	✓	✓	snapshot[a]	2011	2030
Energyscope TD	Switzerland [111]	✓	✓	✓	✓	✓	snapshot[a]	2011	2035

[a]Snapshot models evaluate the energy system configuration/operation over a defined time span (e.g. one year), without modeling the evolution pathway.

[b]Paper focused on the possibility of a 100% renewable energy system without time constraints.

for MARKet ALlocation) is a bottom-up model representing both the energy supply and demand sides of the energy system. The TIMES (The Integrated MARKAL-EFOM System) model [115] is an evolution of MARKAL. It is an economic model generator that can be adapted to model different energy systems at the national, state and regional level over a long-term, multi-period time horizon (usually 20–50 or 100 years) [72]. It is usually applied to the analysis of the entire energy sector, but may be also applied to detailed single-sector studies. The MARKAL/TIMES is currently used in more than 70 countries by 250 different institutions [51] and has been used for different decarbonization analysis worldwide at a national level. Specifically, application to building sector in China [146], to power system in UK [23] and Italy [40] and to the overall energy system in China [163], Canada [106], Italy [12], Ireland [1], UK [64], Portugal [77], France [21] and US [117] were performed.

A similar approach and structure is used on an European scale with the Pan-European TIMES model (abbreviation TIMES PanEU), whose features and applications are fully described by Blesl et al. [32, 31]. Furthermore, the European Commission has so far mainly used a modeling tool, called PRIMES [22], to develop low-carbon projections both at European and for individual member states level until 2050 by five-year periods [57, 46, 49, 36]. Antoniou at al. [19] describe its main features in details: it is a partial equilibrium modeling framework that simulates energy consumption and the energy supply system in the EU and in each of its member States. The PRIMES modeling suite includes satellite sector-specific models for transport (PRIMES-TREMOVE [35, 147]), biomass supply, gas supply, refineries and hydrogen supply. Capros et al. [38, 37] performed an extensive study to asses European decarbonization pathways combining both TIMES PanEU and PRIMES results.

An other widely used modeling tool in the European context is EnergyPLAN that can be used to assist in the design of energy systems with high RES penetration. A detailed description of the tool and its applications can be found in [161]. Briefly, EnergyPLAN [51, 161] is a deterministic input/output computer model used for the annual analyses of regional and national complex energy systems in one hour time-steps. The EnergyPLAN model has been used so far in order to simulate deep decarbonization scenarios for Finland [41], Italy [34, 129], Macedonia [27], Ireland [52] and Denmark [116].

Besides, the three aforementioned energy models have been already used to describe possible decarbonization paths of the future Italian energy system. They all represents the main energy sectors with high accuracy and one year time-step. The computational time is estimated in the range of minutes, then suitable for quick scenarios assessment. However, the modeling objective is exclusively the total system cost and, more important, they are neither freely available nor open-source. As a consequence, the results shown in the reported studies are usually difficult to interpret and compare since it is nearly impossible to know the modeling methodology behind each scenario and the input data used to evaluate them. Thus, TIMES, PRIMES and EnergyPLAN are not completely suitable for academic purposes and can not be used in this work for further evaluations about the Italian energy transition.

Focusing instead on available long-term open-source energy planning softwares, the Open Source Energy Modeling System (OSeMOSYS)[123] and the Energyscope [159] are reviewed. The first one is basically a bottom-up, least-cost energy system optimization framework [90]. Previous studies have used OSeMOSYS to evaluate high decarbonization scenarios of the energy system globally [112], in Ireland [164] and in Saudi Arabia [87], of the power sector in Portugal [18], in Egypt [134] and in Tunisia [54] and of the urban residential buildings energy services [110]. OseMOSYS is freely available, generally not limited to only one sector but it usually has a computational time that is not suitable for fast predictions (about one hour). On the other hand, the Energyscope is fast, freely available and highly versatile since the overall energy system can be optimized both in terms of cost and emissions. It is an open-source Mixed integer linear programming (MILP) model with monthly time resolution, whose structure and mathematical formulation is based and linked with works by Moret [152] and Codina Gironès [84]. It is used as an energy transition supporting tool to asses low-carbon scenarios both in Switzerland (at national, regional and urban level) [153, 85] and internationally (Belgium, Chile, Cuba, EU). Furthermore, it is the heart of energyscope.ch [159], an online platform helping citizens and politicians understand and decide about the Swiss energy transition. Afterwords, the model has been further developed by Limpens et al. [111] in order to have a linear programming (LP) modeling framework with Typical days (TDs) clustering, seasonality and additional technologies to better characterising storage applications and RES intermittency with an hourly time resolution.

Finally, Table 1.5 summarizes the critical features of the different modeling frameworks introduced in this section in order to find out which is the most suitable for an application at an Italian scale in this work of thesis. The performed literature review indicates that EnergyScope TD is the tool that fits the most the aforementioned criteria of spatial dimension, availability, coverage, flexibility, and computational speed making its linear programming model formulation an interesting option for the development of low-carbon scenarios for the Italian energy transition.

Table 1.5: Investigated energy system models final comparison. Legend: ✓ criterion satisfied; ✗ criterion not satisfied; ✗ data missing. Adapted from [111, 152].

Tool	Multi-sector	Open Source&Use	Optimisation	Comp. Time
MARKAL/TIMES	✓	✗	Investment only	5-35 min
PRIMES	✓	✗	✗	✗
EnergyPLAN	✓	✗	Operation only	s
OSeMOSYS	✓	✓	Investment only	mins
Energyscope TD	✓	✓	✓	$\sim$ 1 min

1.3 Objective

This work of thesis aims at applying *an already available open-source modeling framework for national and regional energy systems to the Italian case-study in order to identify multiple low-carbon scenarios up to 2030 and beyond, during the so-called energy transition.* The model of reference, called Energyscope TD, is a linear programming (LP) model of optimization developed by Limpens et al. [111] which derives from previous works by Moret [152] and Codina Gironès [84]. Thus, the main focus of this work is firstly collecting new data fully describing the Italian energy system in order to implement the already available model formulation and make it suitable to national applications. The result is the development of a new version of Energyscope TD, called *Italy Energyscope*. Since nowadays it is really difficult to reproduce published results of the current scientific literature [139], a fully documented model is provided, both in terms of equations and data input for the complex Italian energy system. With respect to previous formulations, *Italy Energyscope* provides a detailed characterisation of the Italian fluxes of energy by adding: (i) new sectors (e.g. agriculture), end-use demands (cold for space cooling and processes, farming mobility) and the related hourly time series; (ii) new energy conversion technologies, both renewable (e.g. CSP, wave) and traditional (e.g. motorcycles); (iii) new resources (e.g. bioliquid and biogas). Furthermore, the model formulation is implemented in order to enable a regional definition of energy demand, availability of resources, capacity of renewables. In this way, not only national but also (macro-) regional considerations about the Italian energy system are possible. In addition, new specific linear constraints regarding the energy transition of the Country (e.g. relationship between the investments on the electric grid and coal phase-out) are added. This simplified, yet complete representation of the Italian energy system will be then used to asses several scenarios of shallow and deep decarbonization following either recent climate-energy directives or current trend of development of renewable and efficient technologies. In this way we are able to understand which pathways can meet European targets on emissions in 2030 and which are the alternative paths towards a nearly-zero carbon emissions layout.

Finally, the overall objective of this thesis is the development of an efficient, reliable and usable tool that could help Italian people interested in the energy transition to evaluate the potential environmental, technical and economic impacts of alternative strategies towards a decarbonized future configuration of the national energy system.

Chapter 2

The Italy Energyscope model

As described in Ch. 1, the available state-of-the-art energy models for strategic energy planning at regional or national scale are multiple and highly heterogeneous. Consequently, for the purpose of applying an open-source model to the Italian case study, the best option is try to implement the already freely available Energyscope TD model proposed by Limpens et al. [111]. The resulting modeling formulation, called *Italy Energyscope*, is suitable for applications to the Italian case study since it presents the combination of the six following items: (i) an energy system considering all the energy flows among different sectors within its boundaries; (ii) a model which balances the system end-use demands taking into account electricity, heat (at high and low temperature), cold (either for processes or for space cooling) and mobility (private, public, freight and farming); (iii) a model able to take into account regionality by considering weather conditions, energy demands, availability of resources and capacity of energy renewables at a (macro-) regional scale; (iv) a model which designs the energy system by importing fossil fuels and electricity, and installing technologies checking its operations and minimising its overall costs or emissions; (v) its hourly resolution, which makes it suitable to implement both the integration of variable renewables with thermal and electricity storage and the variability of demand; (vi) its mathematical linear programming (LP) formulation, which guarantees a low computational time thanks to the use of typical days (TDs), obtained by clustering days with similar energy demand and weather characteristics.

Thus, a detailed description of the *Italy Energyscope* model is provided in this chapter: the methodology adopted is fully documented, as well as the different sets of equations defining its linear programming (LP) model formulation. In addition, new modeling parameters and constraints introduced to better characterise the Italian energy system are reported and described.

2.1 Methodology

Figure 2.1 shows the two-steps methodology adopted in the *Italy Energyscope* model, replicating the methodology proposed in [111]. Basically, starting from the given inputs (time series, scenario parameters, technical characteristics of conversion technologies and resources etc...) representing the Italian energy system in a selected past, present or future year, the modeling framework consists in two main steps:

- generation of a proper set of typical days, according to the clustering algorithm proposed by Limpens et al. [111];

- identification of the optimal design and operation of the Italian energy system with the main model over the TDs previously generated.

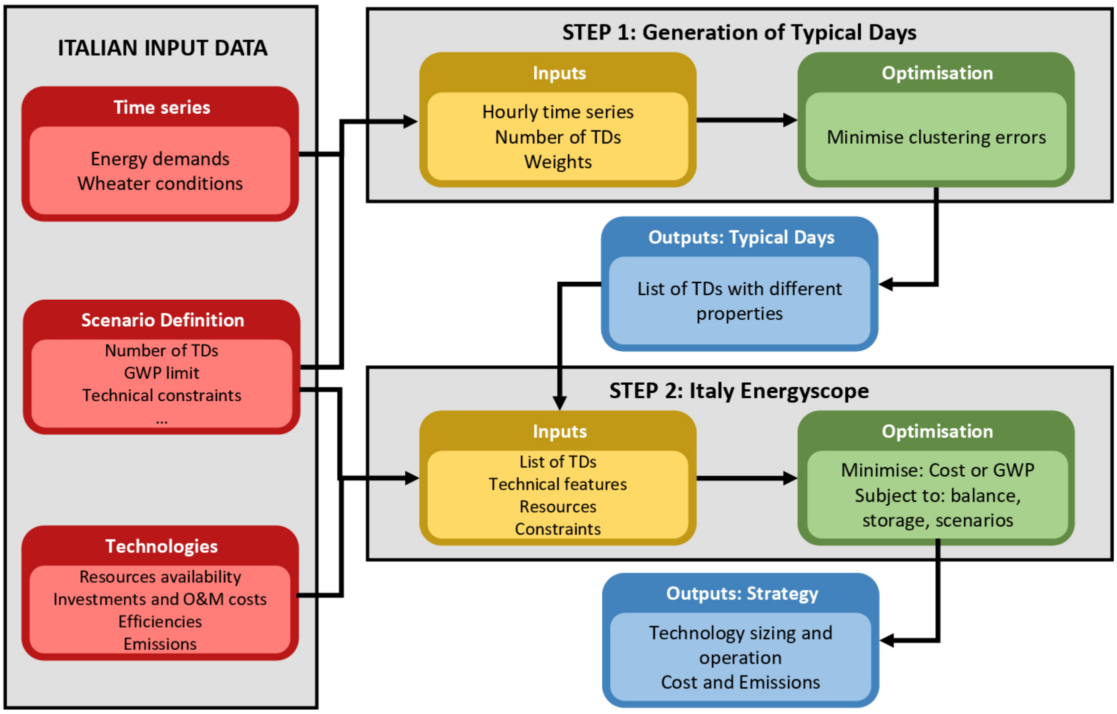


Figure 2.1: Two-steps *Italy Energyscope* methodology, adapted from Energyscope TD [111]. Abbreviations used: typical days (TDs), Global Warming Potential (GWP).

2.1.1 Typical days

The Energyscope model formulation developed by Moret [152] and Codina Gironès [85] has a monthly time resolution. However, due to the higher and higher penetration of renewable energy conversion technologies in national energy systems, hourly defined data have become fundamental since they can better model the integration of intermittent RES and the high variability of energy demand. In this context, Limpens et al. [111] improved the already present monthly formulation of Energyscope by implementing a model with hourly resolution and typical days, the Energyscope TD. In fact, in order to avoid an excessively high computational time, energy models hardly ever perform optimisation over the different 8760 hours of the year. Ortiga et al. [122] suggest to overcome this problem by working only with a selected number of representative days called typical days (TDs). Basically, typical days are particular 24-hours aggregations representing specific time periods. For instance, three TDs can be used to represent three different periods of the year: one for winter, one for mid-season and another one for summer, as implemented in [168]. This solution is considered an effective trade-off between accuracy and computational time, generally reduced by several orders of magnitude, as demonstrated in [122]. Choosing the proper number of TDs is another key point in energy planning in order to limit the computational expense without too much simplifying the temporal characterisation. For this reason, scientific papers usually consider a number of TDs varying from 5 to 20 [122, 111, 80]. Furthermore, since energy models usually cope with some limitations due to the discontinuity between one TD and another, Energyscope TD adopts the solution suggested by Gabrielli et al. [80] in order to take into account inter-days phenomena and seasonality, particularly interesting for thermal storage integration. Basically, each day of the year is associated to the TD that fits the most its features and all the days are linked together through a sequence (i.e. they are indexed over TDs): in this way, the energy information related with the 24th hour of day X is kept and directly connected to the 1st hour of day X+1. This solution enables, for instance, short-term solar thermal storage applications to transfer part of their stored energy from one day to another.

The typical days used in the *Italy Energyscope* model are obtained by using the same clustering algorithm proposed by Limpens et al. [111]. Furthermore, the Italian modeling framework considers seven instead of six time series for the year 2015: electricity demand, heat demand, solar irradiation, wind, hydro dams and hydro river electricity production plus cooling demand. The latter is related to the novel end-use energy demand, specially implemented to not omit the growing cooling need due to the warmer and warmer Mediterranean climate. These series give a simplified yet complete representation of the Italian intermittent energy demand and RES production, and then of weather conditions on a regional/national scale. More details about the Italian time series used for scenarios evaluation are reported further in this work in Sec. 3.1.1, while for a detailed analysis about the clustering method adopted to generate TDs refers to Limpens et al. [111].

2.1.2 Modeling framework

Taking up the definition proposed by Keirstead et al. [108], an energy model can be defined as *"a formal system that represents combined processes of acquiring and using energy to satisfy the energy demand of a given [...] area"*. Thus, the modeling framework adopted in Energyscope TD and implemented in *Italy Energyscope* is a simplified representation of a regional/national energy system, taking into account all the energy flows within its boundaries. It belongs to the *snapshot* category, according to the classification proposed by Codina Gironès et al. [85], since it models all the years in which the system is operated.

Figure 2.2 shows the conceptual energy system structure proposed in the *Italy Energyscope* model, regionally divided in three main components: *resources*, *energy conversion technologies* and *demand*. With respect to previous works using the Energyscope formulation, the main novelty of *Italy Energyscope* consists in taking into account the spatial characterisation of the problem by dividing the investigated geographical area into a number of individual networks (*REGIONS*) that can interact with each other. The geographical configuration of Italy, in fact, strongly influences both the demand and production of energy on a regional scale. So, the parameters used to model the Italian energy system cannot be homogeneously considered all around the Country as well as the time series used to define TDs (i.e. parameters and variables are regionally defined). As an example, adopting the same PV production hourly time series for both the North and the South of the Country could lead to a wrong estimation of the actual renewable electricity generation. The same applies for regional availability of local resources such as woody biomass, differently located from one area to another. For this reason, the assumption of "energy homogeneity" made for the Swiss case study in [152] and [111] could generate huge approxima-

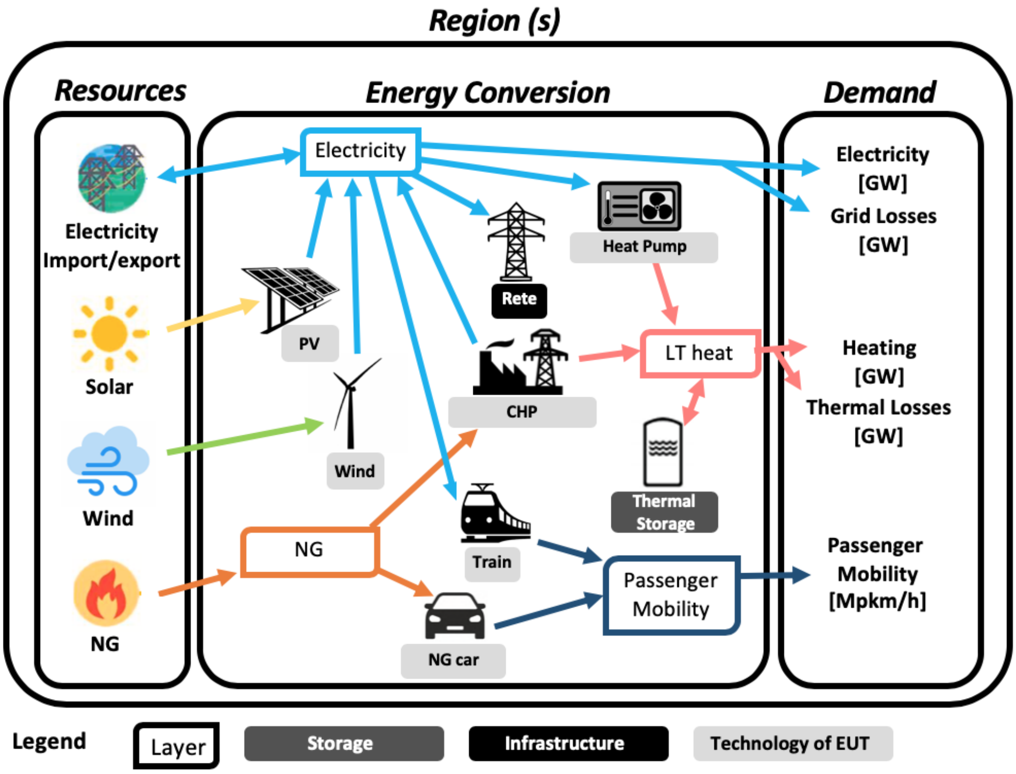


Figure 2.2: Conceptual representation of a national energy system regionally defined. Abbreviations: natural gas (NG), combined heat and power (CHP), photovoltaic (PV), low temperature (LT), end-use type (EUT).

tions and errors if kept for Italian applications. So, *Italy Energyscope* adopts a regionalised modeling framework in order to obtain more accurate and reliable results. The number of regions considered can vary and is determined according to the level of details of available data, the allowable degree of approximation and the computational time.

Figure 2.3 graphically illustrates the *Italy Energyscope* application to the Italian case study with a detailed representation of all the energy flows involved starting from resources, passing through the available energy conversion technologies and finally ending with the different energy demands. With respect to previous Energyscope formulations the following novelties have been added:

- cold (for both space cooling and industrial/services processes) and farming mobility end-use demand (EUD) of energy;
- new non-woody biomass such as biogas and biomass for electricity (i.e. bioliquid);
- new traditional technologies for mobility (e.g. motorcycles and farming machines), electricity generation (e.g. steam cycles fueled with biomass, biogas and bioliquid internal combustion engines (ICE), low-medium enthalpy geothermal power plants, waste incinerator), cooling (e.g. refrigeration cycles and heat pumps) and heat production (e.g. coal boiler for DHN);
- promising renewables for electricity production, e.g. offshore wind and concentrated solar power (CSP), and technologies for the upgrading of biogas into

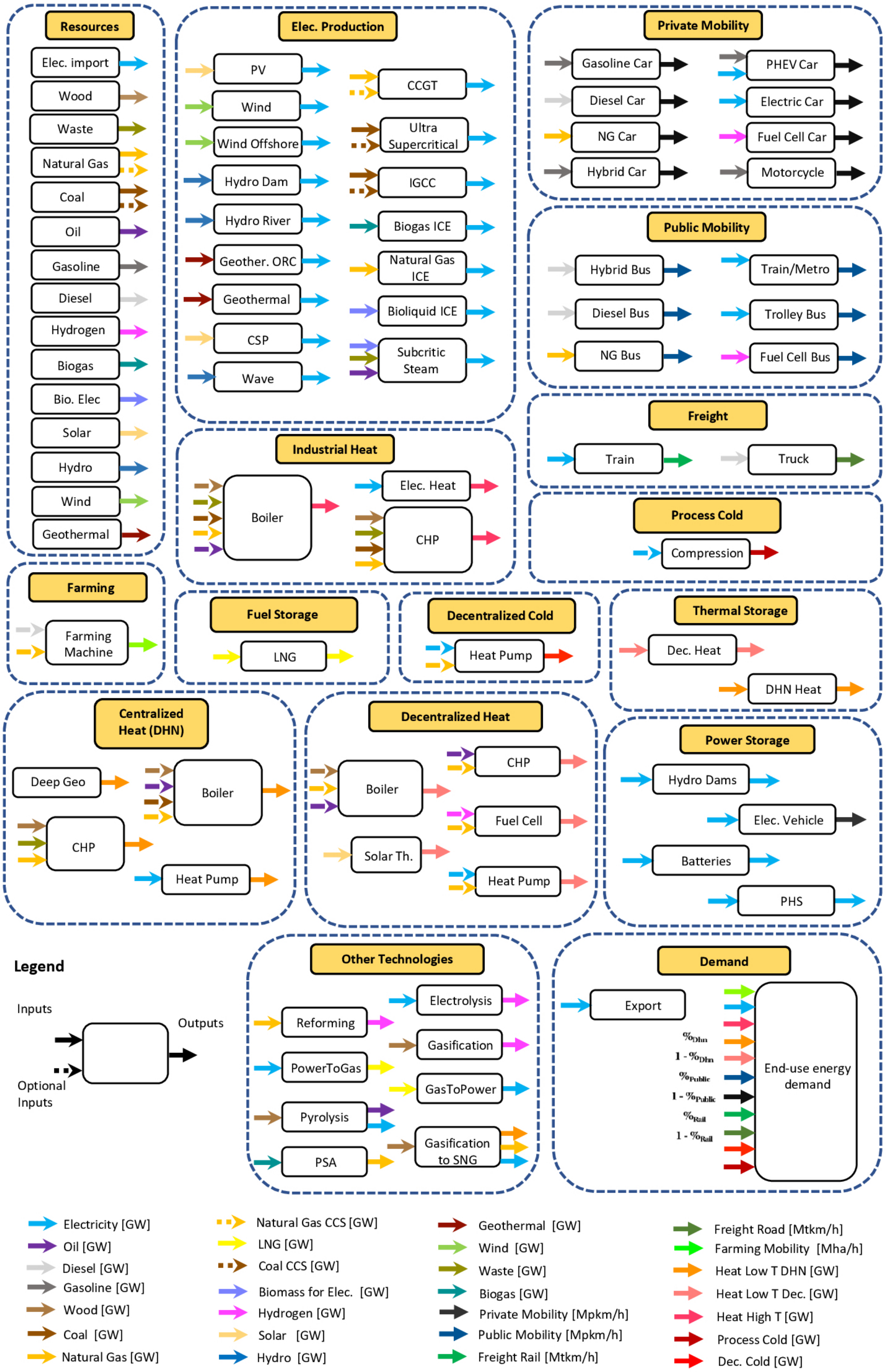


Figure 2.3: Application of the LP modeling framework to the energy system of Italy. Abbreviations: natural gas (NG), carbon capture and storage (CCS), synthetic natural gas (SNG), geothermal (geoth.) combined cycle gas turbine (CCGT), integrated gasification combined cycle (IGCC), photovoltaic (PV), temperature (T), plug-in hybrid electric vehicle (PHEV), cogeneration of heat and power (CHP), biomass for electricity generation (Bio. Elec), pressure swing adsorption (PSA). Adapted from Moret [152].

biomethane, e.g. pressure swing absorption (PSA);

Finally, nuclear power plants and uranium are not considered in this specific case study due to the Italian energy policy in this regard [103].

Basically, given in input the end-use energy demands, the main technical and economic features of the energy conversion technologies, the availability and the import cost of energy resources, the model is able to identify the optimal operation strategy in order to supply the demand and minimize a selected objective function (e.g. the total annual cost or GHG emissions of the energy system) under specific energy balance constraints. In this context, resources include both renewables and fossils while electricity is the only resource that can be exported abroad. Imported and local resources can be then converted with different energy conversion technologies in order to satisfy the different energy demands. In this novel formulation, the specific EUDs supplied are heat, electricity, mobility and cold. Each EUD is divided into different end-use demand categories (EUC), which are further classified in types (EUT). Heating demand is then divided in two EUC (high and low temperature heat, the latter further classified in centralised and decentralised) while cold demand is split in cold for industrial processes and for space cooling. Mobility is divided in three EUC: passenger (public and private), freight (rail and road) and farming mobility. Finally, we define three types of energy conversion technologies: *technologies of end-use type*, *storage technologies* and *infrastructure*. They link together different *layers*, defined as *"the elements in the system that need to be balanced in each period"* [152] including resources and EUD. However, while technology of end-use type can convert the energy from one layer to an EUT layer in order to supply the EUD, storage technologies can only convert energy from one layer to the same one. For instance, coal power plants convert coal into electricity while thermal storage technologies can only store low temperature heat for a future use of the same type of energy. Infrastructure groups the electricity grid, the district heating network (DHN), and the intermediate energy conversion technologies (i.e. not directly supply EUD), e.g. electrolysis and reforming produce hydrogen using electricity and natural gas, respectively, or PSA upgrades biogas to biomethane.

2.2 Linear programming model formulation

The conceptual energy system structure described in Figure 2.2 is mathematically formulated as a linear programming problem. LP models always include the following elements:

- *parameters*, fixed known values given as input of the model formulation;
- *sets*, groups of the different elements of the system;
- *decision variables*, unknown quantities defined within an upper and a lower bound which are going to be calculated by the solver. They can be further split in two categories: *independent* decision variables are completely free to change while *dependent* decision variables are linked via equality constraints to the previous ones;

- *constraints*, inequality or equality bonds on decisions set to discriminate the options of values of the decision variables that represent acceptable solutions of the problem, from those that are not;

- *objective function*, the quantity to maximize or minimize, expressed as a function of the decision variables;

In these problems, all the bonds between the quantities involved, plus the value of the objective function, are linear: variables, of whatever nature they may be, can only be multiplied by a constant and added together. Moreover, the variables are not bound to assume discrete sets of values, i.e. they can assume real values. The solution of an optimization problem formulated with a mathematical LP model consists in the determination of the values of the variables that satisfy all the constraints and maximize or minimize the selected objective function. Thus, once the model formulation has been developed through a specific set of linear equalities and/or inequalities, the search for the optimal solution is carried out by specific optimization engines. In this work, the commercial software IBM CPLEX 12.9 is used [92].

Finally, since nowadays it is really difficult to reproduce published results of the current scientific literature [139], a fully documented model is provided in this section, describing all the sets, parameters, variables, objective functions and constraints adopted. All the values of the parameters used to characterise the Italian energy system case study are provided in Appendix A.

2.2.1 Sets, parameters and variables

Figure 2.4 is a visual representation of the sets used in the regionalised *Italy Energyscope* modeling framework with their relative indexes used throughout this thesis. Tables 2.1, 2.2 and 2.3 list the model parameters and Tables 2.4 and 2.5 list the model variables.

More in details, Table 2.1 reports the time-series parameters, which are related to the end-use energy demands and weather conditions regionally defined according to the *Italy Energyscope* formulation. The hourly end-use types of demand can be either constant (e.g process heating, process cooling and farming mobility) or hourly defined according to specific time series as happens for electricity ($\%_{elec}$), space heating ($\%_{sh}$), space cooling ($\%_{sc}$), passenger mobility ($\%_{pass}$) and freight mobility ($\%_{freight}$). The period capacity factor ($c_{p,t}$) takes into account intermittency of technologies by limiting their production at certain time steps. Thus, $c_{p,t}$ is usually used to integrate weather conditions for RES such as thermal solar, photovoltaic, wind, hydro dams and hydro run-of-river. As an example, PV panels have a $c_{p,t}$ equal to zero during night hours when no solar irradiance is present and greater than or equal to zero during daytime. On the contrary, non-intermittent technologies do not have to be binded according to weather conditions or energy demands, so the default value of $c_{p,t}$ is set to 1.

Table 2.2 shows the model inputs defined by the user in order to describe future scenarios of development of the investigated energy system through economic, socio-environmental and technical data. Firstly, the different annual end-use demands ($endUses_{year}$) per each sector, type and region are defined. Then, total annual end-uses in energy services ($endUsesInput$) are deduced. Focusing on economic data, two parameters are introduced to take into account the annualisation of investments

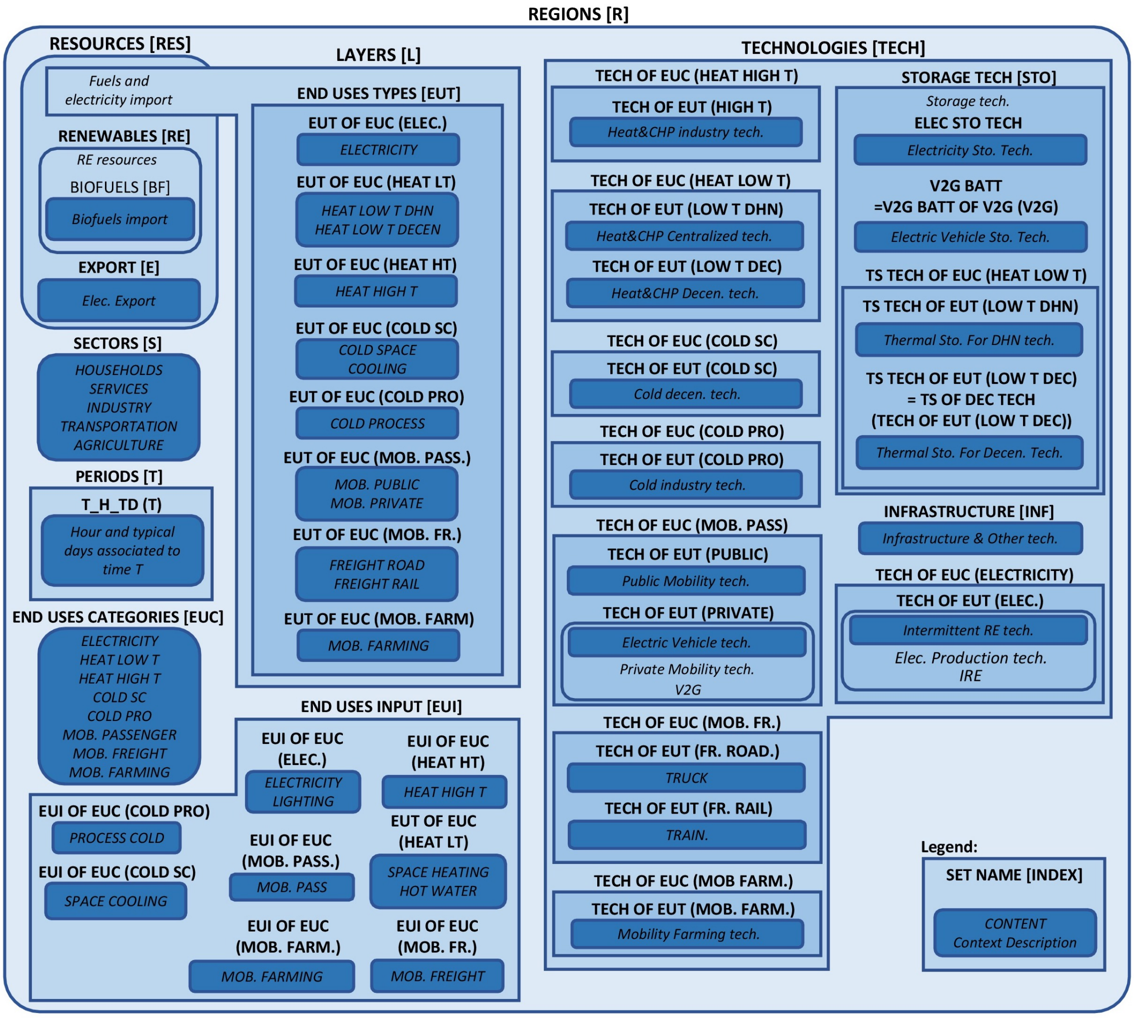


Figure 2.4: Graphical schematic representation of the sets and indexes of the LP framework adopted in the Italy Energyscope. Abbreviations used: space heating (SH), space cooling (SC), hot water (HW), temperature (T), process (PRO), mobility (MOB), vehicle-to-grid (V2G), thermal storage (TS). Adapted from Limpens et al. [111].

Table 2.1: Time series parameters list with description. Set indices as in Figure 2.4: hours (h), typical day (td), region (r). Adapted from [111].

Parameter	Units	Description
$\%_{elec}(h, td, r)$	[-]	Yearly share (adding up to 1) of electricity end-uses
$\%_{sh}(h, td, r)$	[-]	Yearly share (adding up to 1) of SH end-uses
$\%_{sc}(h, td, r)$	[-]	Yearly share (adding up to 1) of SC end-uses
$\%_{pass}(h, td, r)$	[-]	Yearly share (adding up to 1) of passenger mobility end-uses
$\%_{fr}(h, td, r)$	[-]	Yearly share (adding up to 1) of freight mobility end-uses
$c_{p,t}(tech, h, td, r)$	[-]	Period capacity factor (default 1)

(τ) and the inflation with an interest rate (i_{rate}). From the socio-environmental point of view, the annual end-use demand has to be meet following international climate-energy policies imposing several targets on specific GHG emissions reduction (gwp_{limit}) or RES penetration for a future target year, as described in Sec. 1.1.2 and 1.1.3. Furthermore, the system allows several macro-parameters to force the technology mix and imports towards a specific direction by limiting the availability of resources at a regional/national scale ($avail$) or by forcing the public transportation share over the total passenger demand between a lower and an upper bound ($\%_{public,min}$, $\%_{public,max}$). The same applies to trains for freight ($\%_{rail,min}$, $\%_{rail,max}$) and to DHN ($\%_{dhn,min}$, $\%_{dhn,max}$), whose penetration depends on different aspects such as the geographical conformation of the Country or decarbonization directives. Each technology can also be limited by the minimum/maximum regionally installable capacity (f_{min}, f_{max}) or relatively to its layer mix ($f_{min,\%}$, $f_{max,\%}$). As an example, the model allows to impose a minimum share of flexible thermal power plants in the electricity generation mix in order to compensate the variability of RES. Furthermore, a technical parameter defined as the ratio between the highest yearly energy demand and the highest typical days demand ($\%_{Peak_{sh}}$) is introduced to not underestimating the cost of centralised heat production. Finally, the time period ($t_{op}(t)$) duration is specified.

Table 2.2: Scenario parameter list with description. Set indices as in Figure 2.4. Adapted from [111].

Parameter	Units	Description
$endUses_{year}(eui, s, r)$	[GWh/y][a]	Annual end-uses in energy services per sector
$endUsesInput(eui, r)$	[GWh/y]	Total annual end-uses in energy services
$\tau(tech)$	[-]	Investment cost annualization factor
i_{rate}	[-]	Real discount rate
gwp_{limit}	[ktCO$_2$-eq.]	Higher CO$_2$-eq. emissions limit
$\%_{public,min}$, $\%_{public,max}$ [b]	[-]	Upper and lower limit to $\%_{\mathbf{Public}}$
$\%_{rail,min}$, $\%_{rail,max}$ [c]	[-]	Upper and lower limit to $\%_{\mathbf{Rail}}$
$\%_{dhn,min}$, $\%_{dhn,max}(r)$ [d]	[-]	Upper and lower limit to $\%_{\mathbf{Dhn}}$
f_{min}, $f_{max}(tech,r)$	[GW][ef]	Min./max. installed size of the technology
$f_{min,\%}$, $f_{max,\%}(tech,r)$	[-]	Min./max. relative share of a technology in a layer
$avail(res,r)$	[GWh/y]	Resource yearly total availability
$\%_{Peak_{sh}}$	[-]	Ratio peak/max. space heating demand in typical days
$t_{op}(t)$	[h]	Time periods duration

[a] [Mpkm] (millions of passenger-km) for passenger, [Mtkm] (millions of ton-km) for freight mobility end-uses, [Mha] (millions of hectares) for farming mobility.

[b] The penetration of public over total passenger mobility is assumed to be regionally constant.

[c] The penetration of rail over total freight mobility is assumed to be regionally constant.

[d] The penetration of centralised heat over total low temperature heat is regionally defined due to different climatic conditions.

[e] [Mpkm/h] for passenger, [Mtkm/h] for freight mobility, [Mha/h] for farming mobility end-uses.

[f] [GWh] if $tech \in STO$.

Table 2.3 defines the technical, economic and environmental parameters introduced in order to characterise each energy conversion and storage technology and all the resources implemented in *Italy Energyscope*. Regarding resources, both their cost (c_{op}) and emission factor (gwp_{op}) are assumed to be constant all around the Country, i.e. not regionally defined. Regarding technologies, both the investment

Table 2.3: Technology related parameter list. Set indices as in Figure 2.4. Adapted from [111].

Parameter	Units	Description
$f(res \cup tech \setminus sto, l, r)$	[GW][a]	Input from (< 0) or output to (> 0) layers. $f(i, j) = 1$ if j is main output layer for technology/resource i
$c_p(tech,r)$	[-]	Yearly capacity factor
$c_{inv}(tech)$	[M€/GW][ab]	Technology specific investment cost
$c_{maint}(tech)$	[M€/GW/y][ab]	Technology specific yearly OM cost
$n(tech)$	[y]	Technology lifetime
$gwp_{constr}(tech)$	[ktCO$_2$-eq./GW][ab]	Technology construction specific GHG emissions
$gwp_{op}(res)$	[ktCO$_2$/GWh]	Specific CO$_2$ emissions of resources
$c_{op}(res)$	[M€/GWh]	Specific cost of resources
$\eta_{sto,in}, \eta_{sto,out}(sto, l)$	[-]	Efficiency [0; 1] of storage input from/output to layer. Set to 0 if storage not related to layer.
$\%sto_{loss}(sto, l)$	[1/h]	Power and Thermal losses in storage
$t_{sto_{in}}(sto)$	[h]	Charging time of storage
$t_{sto_{out}}(sto)$	[h]	Discharging time of storage
$\%_{Sto_{avail}}(sto)$	[-]	Storage technology availability to change/discharge
$\%net_{loss}(eut)$	[-]	Losses coefficient [0;1] in the networks (Grid and DHN)
$n_{car,max}(r)$	[-]	Maximum number of cars
$ev_{Batt,size}(ev)$	[GWh]	Battery size for EV car technology
$c_{grid,extra}$	[M€]	Cost of reinforce the grid due to iRE penetration

[a] [Mpkm/h] for passenger, [Mtkm/h] for freight mobility end-uses, [Mha/h] for farming mobility.) for farming mobility.

[b] [GWh] if $tech \in STO$.

(c_{inv}) and operating and maintenance (O&P) costs (c_{maint}) are considered. A specific emission factor related with their construction (gwp_{constr}) is accounted for as well. Also for the energy conversion technologies the economic and environmental parameters introduced are not regionally implemented. From an engineering point of view, each technology is then characterised by input and/or output fluxes (f) of energy to/from specific layers, a certain technical lifetime (n) and the time of effective utilization over the 8760 hours of year (c_p). Due to their particular energy behaviour, storage technologies need some additional information. In fact, since they are generally defined as an energy capacity, they are subject to power or thermal losses ($\%sto_{loss}$) and characterised by cyclical charging and discharging processes whose duration ($t_{sto_{in}}$, $t_{sto_{out}}$) and efficiencies ($\eta_{sto,in}, \eta_{sto,out}$) cannot be leaved out. Furthermore, since the asset provided by the storage might not be fully available at certain time, a proper parameter of availability ($\%_{Sto_{avail}}$) is added. Four additional parameters are also required to define the maximum number of cars regionally ($n_{car,max}$), the size of electric vehicles batteries ($ev_{Batt,size}$), the power grid losses ($\%net_{loss}$) and the integration of variable renewables in the power grid itself ($c_{grid,extra}$).

Finally, Tables 2.4 and 2.5 list the independent and dependent decision variables, respectively. The most important independent variable is the vector that includes the size of each technology ($\mathbf{F}(tech,r)$) in each modeled region. Each technology is also characterized by a specific energy flow ($\mathbf{F_t}$), hourly computed for each typical day. The same applies for input ($\mathbf{Sto_{in}}$) and output ($\mathbf{Sto_{out}}$) fluxes to/from storage technologies, whose energy level ($\mathbf{Sto_{level}}$) is directly dependent. Moreover, the energy system is designed by the software through other variables related with socio-political features such as the share of public transportation ($\mathbf{\%_{Public}}$), the share of freight mobility by trains ($\mathbf{\%_{Rail}}$) and the share of DHN ($\mathbf{\%_{DHN}}$). All these variables float between the previously introduced parameters of bonding (Table 2.2). Furthermore, other variables are added for specific technologies (e.g. solar thermal) in order to consider the energy used to backup decentralised heaters during periods of low solar irradiance ($\mathbf{F_{sol}}$ and $\mathbf{F_{t_{sol}}}$).

Table 2.4: Independent variable list with description. All variables are continuous and non-negative, unless otherwise indicated [111].

Variable	Units	Description
$\mathbf{F}(tech,r)$	[GW][ab]	Installed capacity with respect to main output
$\mathbf{F_t}(res \cup tech,h,td,r)$	[GW][ab]	Operation in each period
$\mathbf{Sto_{in}}$, $\mathbf{Sto_{out}}(sto,l,h,td,r)$	[GW]	Input to/output from storage units
$\%_{\mathbf{Public}}$	[-]	Ratio [0;1] public mobility over total passenger mobility
$\%_{\mathbf{Rail}}$	[-]	Ratio [0;1] rail transport mobility over total freight mobility
$\%_{\mathbf{DHN}}(r)$	[-]	Ratio [0;1] centralised over low temperature heat
$\%_{\mathbf{MobPass}}$ [c]	[-]	Constant share of mobility passenger
$\%_{\mathbf{HeatDec}}$ [d]	[-]	Constant share of Heat Low T decentralised
$\mathbf{F_{sol}}$ [d]	[-]	Solar thermal installed capacity per heat decen. technologies
$\mathbf{F_{t_{sol}}}$ [d]	[-]	Solar thermal operating per heat decen. technologies
ship_in(*elec,h,td,r',r"*)	[GW]	Electricity exchanged that comes into the region
ship_in(*elec,h,td,r',r"*)	[GW]	Electricity exchanged that goes out of the region

[a] [Mpkm/h] for passenger, [Mtkm/h] for freight mobility end-uses, [Mha/h] for farming mobility.
[b] [GWh] if *tech* ϵ *STO*.
[c] $\%_{\mathbf{Public}}$*(TECH of EUC(MOB.PASS.))*
[d] $\%_{\mathbf{HeatDec}}$*(TECH of EUC(LOW T DEC)/Dec. Solar)*

Dependent variables are based on the previously defined independent variables. In fact, the hourly end-use energy demand (**EndUses**) depends on the hourly time series, the annual end-uses and the sector strategy. In the same way, once known the installed size (**F**) of the different energy conversion technologies and their operation ($\mathbf{F_t}$), the solver is able to directly compute all the related economic investments ($\mathbf{C_{tot}}$, $\mathbf{C_{inv}}$, $\mathbf{C_{op}}$ etc...), losses ($\mathbf{Net_{losses}}$) and emissions ($\mathbf{GWP_{tot}}$, $\mathbf{GWP_{op}}$ etc...).

Table 2.5: Dependent variable list with description. All variables are continuous and non-negative, unless otherwise indicated [111].

Variable	Units	Description
EndUses(*l,h,td,r*)	[GW][a]	End-Uses demand. Set ot 0 if *l EUT*
$\mathbf{Sto_{level}}(sto,t,r)$	[GWh]	Energy stored over the year
$\mathbf{C_{tot}}$	[M€/y]	Total annual cost of the energy system
$\mathbf{C_{tot}\_r}(r)$	[M€/y]	Regional annual cost of the energy system
$\mathbf{C_{inv}}(tech,r)$	[M€]	Technology total investment cost
$\mathbf{C_{maint}}(tech,r)$	[M€/y]	Technology yearly maintenance cost
$\mathbf{C_{op}}(res,r)$	[M€/y]	Total cost of resources
$\mathbf{GWP_{tot}}$	[ktCO$_2$-eq./y]	Total yearly GHG emissions of the energy system
$\mathbf{GWP_{tot}\_r}(r)$	[ktCO$_2$-eq./y]	Regional yearly GHG emissions of the energy system
$\mathbf{GWP_{constr}}(tech,r)$	[ktCO$_2$-eq./y]	Technology construction GHG emissions
$\mathbf{GWP_{op}}(res,r)$	[ktCO$_2$./y]	Total CO$_2$ emissions of resources
$\mathbf{Net_{losses}}(eut,h,td,r)$	[GW]	Losses in the networks (grid and DHN)

[a][Mpkm/h] for passenger, [Mtkm/h] for freight mobility end-uses, [Mha/h] for farming mobility.

2.2.2 Constraints and objective function

The LP modeling framework adopted in *Italy Energyscope* includes the sets of equations listed in Figure 2.5 and Eq. 2.1-2.42. These equalities and inequalities constraints are adapted from previous works by Moret [152] and Limpens et al. [111] in order to take into account the already introduced regionalisation of modeling elements. Furthermore, additional constraints have been implemented in order to specifically characterise the evolution of the Italian energy system towards low-carbon layouts.

End-uses demand

The adoption of energy EUD as model input parameters instead of Final Energy Consumption (FEC) is in contrast with what usually happens in energy modeling practise. While FEC indicates *"the energy which reaches the final consumer's door"* [75], EUD is *"the last measurable energy flow before the delivery of energy services"* [83]. For instance, looking at passenger mobility supplied with road vehicles, the FEC is the fuel consumed by the vehicles themselves while the EUD is the distance travelled using them. With this solution the same EUD can be supplied with a different FEC according to the technology used, whose choice depends on several factors such as the energy conversion efficiency or the cost/environmental impact of the technology itself. As an example, electric cars are cleaner and more efficient than diesel, then they would be preferred, but at the same time their investment cost is higher. So, depending on the chosen scenario strategy (i.e. objective function and constraints) the model gives the best solution pathway. This modeling choice replaces the conventional sector-based representation of energy demand and, at the same time, introduces a clear differentiation between demand and supply.

Figure 2.5 shows the constraints relative to the calculation of the hourly end-uses demand (**EndUses**), which are computed starting from the normalised time series and yearly EUD values given as input (*endUsesInput*). Electricity end-use is the combination of two different energy demands of which one (lighting) is variable according to $\%_{elec}$ while the other (electrical appliances) is assumed to be constant over the year. Low temperature heat for hot water, heat and cold for processes and mobility farming are also evenly distributed over the year. On the contrary, regional space heating and cooling demand, passenger and freight mobility are distributed over the year according to $\%_{sh}$, $\%_{sc}$, $\%_{pass}$ and $\%_{fr}$, respectively. The regional repartition between centralised (DHN) and decentralised heat is modeled according to the independent variable $\boldsymbol{\%_{DHN}}$. The same applies for the percentage of public transportation over passenger mobility, defined by $\boldsymbol{\%_{Public}}$, and for the percentage of trains over freight mobility, defined by $\boldsymbol{\%_{Rail}}$. Finally, for both electricity and centralised low temperature heat demands, grid/network losses are taken into account with the dependent variable $\mathbf{Net_{losses}}$.

Cost, emissions and objective function

In the Energyscope TD formulation, two different objective functions can be used to optimize the layout of energy system studied. However, since the *Italy Energyscope* model has a regionalised modeling framework, the overall objective function includes new specific regional terms (i.e. $\mathbf{C_{tot\_}r}$ and $\mathbf{GWP_{tot\_}r}$).

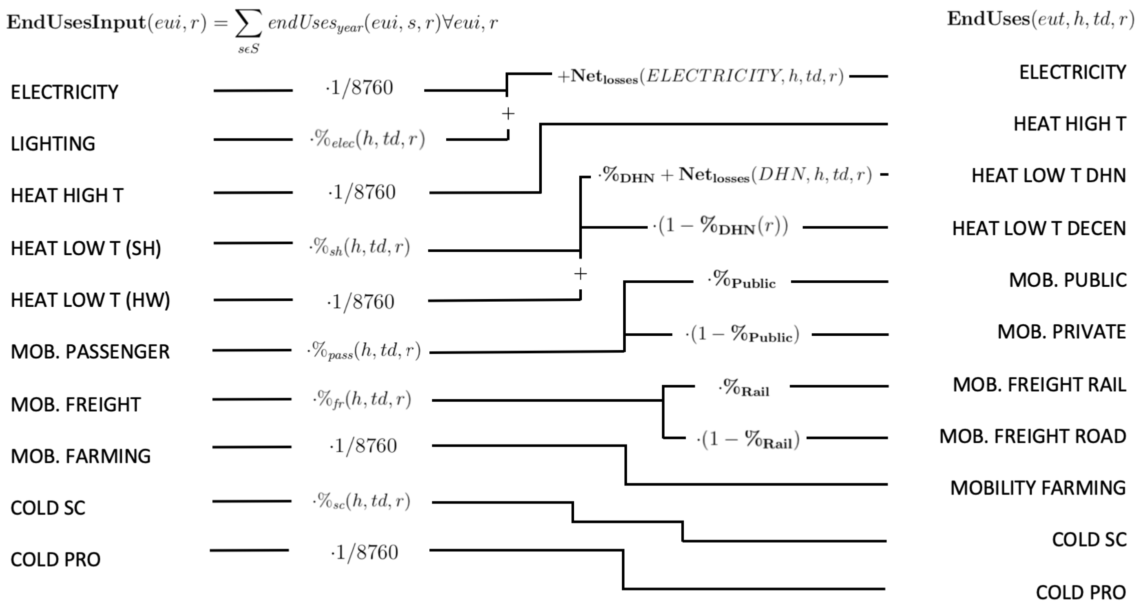


Figure 2.5: EndUses calculation starting from *endUsesInput*. Abbreviations: space heating (sh), space cooling (sc), process (pro), district heating network (DHN), hot water (HW), passenger (pass) and freight (fr). Adapted from [111].

On one hand, the objective function can be the minimization of the total annual cost of the energy system ($\mathbf{C_{tot}}$) as expressed in Eq. 2.1.

$$min. \quad \mathbf{C_{tot}} = \sum_{r \in REG} (\mathbf{C_{tot\_}r})(r) \tag{2.1}$$

The total annual cost of the Italian energy system is defined as the sum of the each energy-related cost at a regional scale. For each region, $\mathbf{C_{tot\_}r}$ is computed as the sum of the annualized investment cost of technologies ($\mathbf{C_{inv}}$), their O&M cost ($\mathbf{C_{maint}}$) and the related operating cost of resources ($\mathbf{C_{op}}$), as expressed in Eq. 2.2. The annualisation factor is calculated using the specific interest rate (i_{rate}) and the technology lifetime (n) through Eq. 2.3. The regional investment cost of each technology is given by its specific investment cost (c_{inv}) multiplied by the installed size ($\mathbf{F}$), as in Eq. 2.4. Similarly, the regional maintenance cost is defined in Eq. 2.5 adopting the specific maintenance cost (c_{maint}). Finally, the regional operating cost of resources is calculated in Eq. 2.6 considering their specific cost (c_{op}), the period duration (t_{op}) and the related operation ($\mathbf{F_t}$).

$$\mathbf{C_{tot\_}r}(r) = \sum_{i \in TECH} (\tau(i)\mathbf{C_{inv}}(i,r) + \mathbf{C_{maint}}(i,r)) + \sum_{j \in RES} \mathbf{C_{op}}(j,r) \quad \forall r \in REG \tag{2.2}$$

$$\tau(j) = \frac{i_{rate}(i_{rate}+1)^{n(j)}}{(i_{rate}+1)^{n(j)}-1} \quad \forall i \in TECH \tag{2.3}$$

$$\mathbf{C_{inv}}(i,r) = c_{inv}(i)\mathbf{F}(i,r) \quad \forall i \in TECH, r \in REG \tag{2.4}$$

$$\mathbf{C_{maint}}(i,r) = c_{maint}(i)\mathbf{F}(i,r) \quad \forall i \in TECH, r \in REG \tag{2.5}$$

$$\mathbf{C_{op}}(j,r) = \sum_{t \in T|(h,td) \in T\_H\_TD(t)} c_{op}(j)\mathbf{F_t}(j,h,td,r)t_{op}(h,td) \quad \forall j \in RES, r \in REG \tag{2.6}$$

On the other hand, the objective function can be the minimization of total annual GHG emission of the system ($\mathbf{GWP_{tot}}$), Eq. 2.7. For the assessment of future low-carbon scenarios, $\mathbf{GWP_{tot}}$ will be predominantly used as objective: in this way, the less efficient conversion pathways will be directly eliminated by the model optimization and the penetration of the most convenient renewable technologies will be maximized. For climate change, the chosen indicator is the GWP, expressed in $ktCO_2$-eq./year. In this context, *Italy Energyscope* introduces an approximation: since Moret [152] provides operating GWP data for the Swiss energy system which are not comparable with the indicators used by Italian research bodies (e.g. ISPRA), we decided to change the values of gwp_{op} according to ISPRA indications by considering only CO_2 emissions [99]. The values of gwp_{constr} adopted are instead the same used for the Swiss technologies. In this way, the overall value of $\mathbf{GWP_{tot}}$ is under-estimated since operating emissions of GHG different from CO_2 are not considered. However, this solution allows us to compare the emissions from fuel combustion of the modeled Italian energy system with the available data reported in [99].

$$\mathbf{GWP_{tot}} = \sum_{r \in REG} \mathbf{GWP_{tot}\_r}(r) \tag{2.7}$$

Similarly to cost evaluation, the total annual GHG emissions of the energy system are defined as the sum of all the energy-related emissions regionally. For each region, $\mathbf{GWP_{tot}\_r}$ is defined as the sum of the emissions related to the construction and the and-of-life disposal of energy conversion technologies ($\mathbf{GWP_{constr}}$), weighted on their effective lifetime (n), and the operating emissions from combustion of resources ($\mathbf{GWP_{op}}$), as expressed in Eq. 2.8. Regional emissions related to construction of technologies (Eq. 2.9) and to operation (Eq. 2.10) are computed similarly to Eq. 2.4-2.5, taking into account the specific emission factor of construction (gwp_{constr}) and resources (gwp_{op}), respectively.

$$\mathbf{GWP_{tot}\_r}(r) = \sum_{i \in TECH} \frac{\mathbf{GWP_{constr}}(i,r)}{n(i)} + \sum_{j \in RES} \mathbf{GWP_{op}}(j,r) \quad \forall r \in REG \tag{2.8}$$

$$\mathbf{GWP_{constr}}(i,r) = gwp_{constr}(i)\mathbf{F}(i,r) \quad \forall i \in TECH, r \in REG \tag{2.9}$$

$$\mathbf{GWP_{op}}(j,r) = \sum_{t \in T|(h,td) \in T\_H\_TD(t)} gwp_{op}(j)\mathbf{F_t}(j,h,td,r)t_{op}(h,td) \quad \forall j \in RES, r \in REG \tag{2.10}$$

System design and operation

In the *Italy Energyscope* model, the installed capacity of each technology ($\mathbf{F}$) with respect to the main output is regionally constrained between an upper and a lower bounds defined by f_{min} and f_{max}, respectively, as shown in Eq. 2.11. This formulation is useful for two main reasons. Firstly, it allows to take into account already existing technologies that will likely be part of the energy system in a future target year (e.g. hydro dams) by f_{min}. Secondly, it limits the penetration of those technologies with a regional limited potential (e.g wind turbines or PV) by f_{max}.

The operation of technologies and resources in each period is determined by the decision variable ($\mathbf{F_t}$), as shown in Eq. 2.12-2.13. The Energyscope modeling framework considers two different terms to take into account the effective productivity of technologies: a regionally and hourly defined capacity factor ($c_{p,t}$), depending on resource availability (e.g. renewables), and a yearly capacity factor (c_p) accounting for technologies periods of downtime and eventual maintenance. Once one of these two terms is defined, the other is automatically set to the default value of 1.

$$f_{min}(i,r) \leq \mathbf{F}(j,r) \leq f_{max}(j,r) \quad \forall j \in TECH, r \in REG \tag{2.11}$$

$$\begin{gathered}\mathbf{F_t}(j,h,td,r) t_{op}(h,td) \leq \mathbf{F}(j,r) c_{p,t}(j,h,td,r) \\ \forall j \in TECH, h \in H, td \in TD, r \in REG\end{gathered} \tag{2.12}$$

$$\begin{gathered}\sum_{t \in T|(h,td) \in T\_H\_TD(t)} \mathbf{F_t}(j,h,td,r) t_{op}(h,td) \leq \mathbf{F}(j,r) c_{p,t}(j,h,td,r) \sum_{t \in T|(h,td) \in T\_H\_TD(t)} t_{op}(h,td) \\ \forall j \in TECH, r \in REG\end{gathered} \tag{2.13}$$

The actual use of each resource in *Italy Energyscope* is limited by its regional availability. Furthermore, this new formulation allows the exchange of resources from one region (*r'*) to another (*r"*). As shown in Eq. 2.14 and 2.15, two additional variables are then introduced, accounting for exchanges from one region layer ($\mathbf{ship_{in}}$) to another ($\mathbf{ship_{out}}$), and vice versa. Eq. 2.16 accounts for the impact of inter-regional exchanges of resources on their local availability.

$$\begin{gathered}\mathbf{ship_{in}}(l,h,td,r',r'') = \mathbf{ship_{out}}(l,h,td,r'',r') \\ \forall l \in EXCH, h \in H, td \in TD, r' \in REG, r'' \in REG\end{gathered} \tag{2.14}$$

$$\mathbf{ship_{in}}(l,h,td,r',r'') = 0 \quad \forall l \in L \cap EXCH, r' \in REG, r'' \in REG \tag{2.15}$$

$$\begin{gathered}\sum_{(h,td) \in T\_H\_TD(t)} \mathbf{F_t}(i,h,td,r) t_{op}(h,td) \\ - \sum_{r'' \in REG} (\mathbf{ship_{in}}(l,h,td,r',r'') - \mathbf{ship_{out}}(l,h,td,r',r'')) t_{op}(h,td) \leq avail(i,r) \\ \forall i \in RES, l \in L, rinREG, r' \in REG, r'' \in REG\end{gathered} \tag{2.16}$$

Finally, since layers need to be balanced in each period, Eq. 2.17 is defined. All the energy outputs from resources/technologies (including storage) are used either to supply the regional EUD or as input to other resources/technologies. Exchanges between regions are also accounted for through the variables $\mathbf{ship_{in}}$ and $\mathbf{ship_{out}}$ previously introduced. Matrix f defines, for every technology and resource, the energy input from (negative) and output to (positive) the interested layers.

$$\sum_{(i \in RES \cup TECH \cap STO)} f(i,l)\mathbf{F_t}(i,h,td,r) + \sum_{(j \in STO} (\mathbf{Sto_{out}}(j,l,h,td,r) - \mathbf{Sto_{in}}(j,l,h,td,r))$$
$$-\mathbf{EndUses}(l,h,td,r) - \sum (\mathbf{ship_{in}}(l,h,td,r',r'') - \mathbf{ship_{out}}(l,h,td,r',r'')) = 0$$
$$\forall l \in L, h \in H, td \in TD, r \in REG \tag{2.17}$$

Storage

Regarding regional storage technologies, the level of stored energy ($\mathbf{Sto_{level}}$) at time t is equal to the level at time t-1 plus input fluxes minus output fluxes, considering the efficiencies of storage input from (or output to) each layer and the overall storage losses (Eq. 2.18). The energy level of daily and seasonal storage technologies is bonded by Eq. 2.19 and Eq. 2.20, respectively.

$$\begin{aligned} \mathbf{Sto_{level}}(j,t,r) = \mathbf{Sto_{level}}(j,t-1,r) \cdot (1 - \%sto_{loss}) \\ +t_{op}(h,td) \cdot (\sum_{(l \in L | \eta_{sto,in} > 0)} (j,l,h,td,r)\eta_{sto,in}(j,l) - \sum_{(l \in L | \eta_{sto,out} > 0)} (j,l,h,td,r)/\eta_{sto,in}(j,l) \\ \forall j \in STO, t \in T, (h,td) \in T\_H\_TD(t), r \in REG \end{aligned} \tag{2.18}$$

$$\begin{aligned} \mathbf{Sto_{level}}(j,t,r) = \mathbf{F_t}(j,h,td,r) \\ \forall j \in STODAILY, t \in T, (h,td) \in T\_H\_TD(t), r \in REG \end{aligned} \tag{2.19}$$

$$\begin{aligned} \mathbf{Sto_{level}}(j,t,r) \leq \mathbf{F}(j,r) \\ \forall j \in STODAILY, t \in T, (h,td) \in T\_H\_TD(t), r \in REG \end{aligned} \tag{2.20}$$

Since each storage technology can have input/output fluxes only from/to certain layers (e.g. pumped hydro storage can not have low temperature heat as input), Eq. 2.21 and Eq. 2.22 force storage input ($\mathbf{Sto_{in}}$) and output ($\mathbf{Sto_{out}}$) to zero if technical incompatibility is experienced. Finally, Eq. 2.23 limits the input/output energy fluxes considering the installed size of storage technologies, their availability ($\%sto_{avail}$) and both the related charging ($t_{sto_{in}}$) and discharging ($t_{sto_{out}}$) time, defined as *"the time needed to complete a full charge/discharge from empty/full storage"* [111].

$$\begin{aligned} \mathbf{Sto_{in}}(j,l,h,td,r) \cdot (\eta_{sto,in}(j,l) - 1) = 0 \\ \forall j \in STO, l \in L, h \in H, td \in TD, r \in REG \end{aligned} \tag{2.21}$$

$$\begin{aligned} \mathbf{Sto_{out}}(j,l,h,td,r) \cdot (\eta_{sto,out}(j,l) - 1) = 0 \\ \forall j \in STO, l \in L, h \in H, td \in TD, r \in REG \end{aligned} \tag{2.22}$$

$$(\mathbf{Sto_{in}}(j,l,h,td)t_{sto_{in}}(j) + \mathbf{Sto_{out}}(j,l,h,td)t_{sto_{out}}(j)) \cdot t_{op}(h,td) \leq \mathbf{F}(j)\%sto_{avail}(j)$$
$$\forall j \in STO, l \in L, h \in H, td \in TD, r \in REG \tag{2.23}$$

Infrastructure

Eq. 2.24 computes grid and district heating network losses as a share ($\%net_{loss}$) of the total energy transferred through the network itself.

$$\mathbf{Net_{losses}}(eut,h,td,r) = \Big(\sum_{i \in RES \cup TECH \cap STO | f(i,eut)>0} f(i,eut)\mathbf{F_t}(j,h,td,r)\Big) \cdot \%net_{loss}(eut) \quad \forall eut \in EUT, h \in H, td \in TD, r \in REG \tag{2.24}$$

Furthermore, the Energyscope TD formulation introduces several equations with the aim of defining the extra investments needed for a deep decarbonization of national energy systems. In this context, Limpens et al. [111] propose the Eq. 2.25, which allows an additional investment cost for the electric grid ($c_{grid,extra}$) as a result of the integration of intermittent RES (iRES) such as wind and solar.

In this context, the *Italy Energyscope* modeling framework includes two new equality constraints. Eq. 2.26 considers the total additional investments in safety and adequacy of the electric grid due to the scheduled phase-out of Italian coal power plants by 2025. $f_{max}(COAL\_US)$ and $f_{max}(COAL\_IGCC)$ represent the installed size of Ultra-Supercritical (US) and Integrated Gasification Combined Cycle (IGCC) coal plants in 2015, respectively. Basically, the lower the installed capacity of coal thermal power plants, the higher the investments needed for grid developments. Eq. 2.27 is instead added to make up for the lack of investment costs of road vehicles in the previous versions of Energyscope. The investment cost for a future huge transformation of private mobility towards a low-carbon layout (e.g. high penetration of electric or fuel cell cars) is inversely proportional to the number of traditional fossil fuel cars circulating, i.e gasoline, diesel and natural gas vehicles. Thus, similarly to Eq. 2.26, the lower the installed capacity of fossil fuel cars, the higher the economic efforts needed for the development of the mobility sector. In this context, $f_{max}(Car\_BEV, r)$ indicates the maximum circulating capacity of electric (BEV) cars, set high enough to cover the entire private passenger mobility demand.

$$\mathbf{F}(Grid,r) = \frac{c_{grid,extra}}{c_{inv}(Grid)} \frac{\mathbf{F}(Wind,r)+\mathbf{F}(PV,r)}{f_{max}(Wind,r)+f_{max}(PV,r)} \tag{2.25}$$

$$\mathbf{F}(Grid\_Coal,r) = 1 - \frac{\mathbf{F}(Coal\_US,r)+\mathbf{F}(Coal\_IGCC,r)}{f_{max}(Coal\_US,r)+f_{max}(Coal\_IGCC,r)} \tag{2.26}$$

$$\mathbf{F}(Park\_Car,r) = 1 - \frac{\mathbf{F}(Car\_Diesel,r)+\mathbf{F}(Car\_Gasoline,r)+\mathbf{F}(Car\_NG,r)}{f_{max}(Car\_BEV,r)} \tag{2.27}$$

Eq. 2.28 regionally forces the size of DHN to be equal to the summed size of all the installed centralised energy conversion technologies. Finally, Eq. 2.29 displays in a compact non-linear formulation the power-to-gas storage infrastructure, linearly implemented in the model by Limpens et al. [111] referring to Al-musleh et al. [119]. Basically, it includes two conversion units and a liquefied natural gas (LNG) storage tank: power-to-gas converts electricity to LNG while gas-to-power converts LNG to electricity.

$$\mathbf{F}(DHN, r) = \sum_{j \in TECHofEUT(HeatLowTDHN)} \mathbf{F}(j, r) \tag{2.28}$$

$$\mathbf{F}(Power\_To\_Gas, r) = max(\mathbf{F}(Power\_To\_Gas, r), \mathbf{F}(Gas\_To\_Power)) \tag{2.29}$$

Additional constraints

Limpens et al. [111] add some additional constraints to the Energyscope TD formulation in order to better represent national energy systems. Eq. 2.30 sets a constant share at each time step for all the different technologies supplying passenger mobility ($\%_{\mathbf{MobPass}}$). In this way, in an optimized-cost scenario, this share remains constant even if any investment cost for passenger and freight transport technologies is not given as input to the Energyscope TD modeling framework.

$$\begin{aligned} \mathbf{F_t}(j, h, td, r) = \%_{\mathbf{MobPass}}(j) \sum_{l \in EUTofEUC(MobPass)} \mathbf{EndUses}(l, h, td, r) \\ \forall j \in TECHofEUC(MobPass), h \in H, td \in TD, r \in REG \end{aligned} \tag{2.30}$$

Additional constraints characterise decentralise heat production technologies. Solar thermal, for instance, is always installed coupled with another decentralised technology, serving as a back-up unit during periods of low solar irradiance. Thus, the regional total installed capacity of solar thermal is equal to the sum of all the solar thermal capacities regionally associated with back-up units, as expressed in Eq. 2.31. Eq. 2.32 links instead the installed capacity of each solar thermal technology ($\mathbf{F_{sol}}$) to its actual production ($\mathbf{F_{t_{sol}}}$) through the hourly defined solar capacity factor.

$$\mathbf{F}(Dec_{solar}, r) = \sum_{j \in EUTofEUC(HeatLowTDec) \setminus DecSolar} \mathbf{F_{sol}}(j, r) \quad \forall r \in REG \tag{2.31}$$

$$\begin{aligned} \mathbf{F_{t_{sol}}}(j, h, td, r) = \mathbf{F_{sol}}(j) c_{p,t}(Dec_{solar}, h, td, r) \\ \forall j \in TECHofEUT(HeatLowTDec) \setminus DecSolar, h \in H, td \in TD, r \in REG \end{aligned} \tag{2.32}$$

Furthermore, Limpens et al. [111] suggest a new equality constraint in order to link the i-th thermal storage technology with its j-th related energy conversion technologies and the associated thermal solar plants ($\mathbf{F_{sol}}$(j)). Thus, Eq. 2.33 imposes that the use of each decentralised low temperature heat technology, plus its associated solar thermal ($\mathbf{F_{t_{sol}}}$(i)), plus the effective contribution of storage ($\mathbf{Sto_{out}}$(i) - $\mathbf{Sto_{in}}$(i)) should be a constant share ($\%_{\mathbf{HeatDec}}$(j)) of the regional decentralised heat demand. In this way, even if decentralised heat is represented in an aggregated form, heating technologies installed in one dwelling can not be used by another house and vice versa.

$$\mathbf{F_t}(j,h,td,r) + \mathbf{F_{t_{sol}}}(j,h,td,r) + \sum_{l \in L}(\mathbf{Sto_{out}}(i,l,h,td,r) - \mathbf{Sto_{in}}(i,l,h,td,r)) = \\ \%_{\mathbf{HeatDec}}(j)\mathbf{EndUses}(HeatLowT,h,td,r) \\ \forall j \in TECHofEUT(HeatLowTDec) \setminus Dec_{solar}, h \in H, td \in TD, r \in REG \tag{2.33}$$

Figure 2.6 shows dam hydro-power plants implementation: a storage unit (*StoDam*) provides energy to a power production unit (*HydroDam*). In this framework, Eq. 2.34 linearly links the size of the reservoir with the hydro dam power size ($\mathbf{F}(HydroDam)$), Eq. 2.35 sets the storage input power ($\mathbf{Sto_{in}}$) equal to the water inflow ($\mathbf{F_t}$) while Eq. 2.36 limits the storage output to the related power available. Pumped Hydro Electric Storage (PHES) is defined in a different way with respect to *StoDam*: the first one is in fact characterised by a lower and an upper reservoir without any inlet source while the second one has an inlet source.

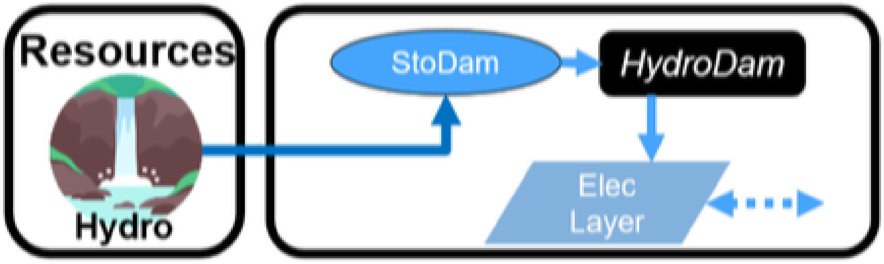


Figure 2.6: Visual representation of hydro dams implementation in the Italy Energyscope model. From Limpens et al. [111].

$$\mathbf{F}(StoDam,r) \leq f_{min}(StoDam,r) + (f_{max}(StoDam,r) \\ -f_{min}(StoDam,r))\frac{\mathbf{F}(HydroDam,r) - f_{min}(HydroDam,r)}{f_{max}(HydroDam,r) - f_{min}(HydroDam,r)} \tag{2.34}$$

$$\mathbf{Sto_{in}}(StoDam,Elec,h,td,r) = \mathbf{F_t}(HydroDam,h,td,r) \\ \forall h \in H, td \in TD, r \in REG \tag{2.35}$$

$$\mathbf{Sto_{out}}(StoDam,Elec,h,td,r) \leq \mathbf{F_t}(HydroDam,h,td,r) \\ \forall h \in H, td \in TD, r \in REG \tag{2.36}$$

Eq. 2.37 is added in order to include the vehicle-to-grid (V2G) dynamic via the V2G set of technologies in case of a large penetration of electric vehicles in the national energy system. Thus, the electricity stored in vehicle batteries ($\mathbf{F}$(i)) is given by the product of the number of circulating electric vehicles for passenger mobility times the size of battery per car ($ev_{Batt,size}$). At the same time, Eq. 2.38 forces each battery to supply at least the energy required by the related electric vehicle.

$$\mathbf{F}(i,r) = n_{car,max}\%_{\mathbf{MobPass}}(j)ev_{Batt,size}(j) \\ \forall j \in V2G, i \in V2GBATTofV2G(j), r \in REG \tag{2.37}$$

$$\begin{aligned} \mathbf{Sto_{out}}(i, Elec, h, td, r) \geq f(j, Elec, r)\mathbf{F_t}(j, h, td, r) \\ \forall j \in V2G, i \in V2GBATTofV2G(j), h \in H, td \in TD, r \in REG \end{aligned} \tag{2.38}$$

Finally, two equations bind the installed capacity of low temperature heat supply according to the peak demand ratio of space heating ($\%_{Peak_{sh}}$). Eq. 2.39 imposes that the installed capacity of decentralised low temperature heat technologies is sufficient to cover the real peak over the year. Similarly, Eq. 2.40 forces the regional centralised heating system to have a sufficient supply capacity to cover the highest possible heating demand.

$$\begin{aligned} \mathbf{F}(j) \geq \%_Peak_{sh} \max_{h \in H, td \in TD} \mathbf{F_t}(j, h, td, r) \setminus Dec_{solar} \\ \forall j \in TECHofEUT(HeatLowTDec), r \in REG \end{aligned} \tag{2.39}$$

$$\begin{aligned} \sum_{j \in TECHofEUT(HeatLowTDHN), i \in TSTECHofEUT(j)} (\mathbf{F}(j, r) + \mathbf{F}(i, r) / t_{sto_{out}}(i, HeatLowTDHN, r) \\ \geq \%Peak_{sh} \max_{h \in H, td \in TD} \mathbf{EndUses}(HeatLowTDHN, h, td, r) \\ \forall r \in REG \end{aligned} \tag{2.40}$$

Additional constraints for the Italian case study

According to the Energyscope TD formulation, two additional constraints are finally added in order to implement alternative low-carbon scenarios. Firstly, Eq. 2.41 sets an upper bound (gwp_{limit}) on total yearly emissions at a national scale, reducing the penetration of polluting and non-efficient energy conversion technologies. This constraint is particularly interesting when performing an optimized-cost scenario since it allows to limit the environmental impact of the energy system. Secondly, Eq. 2.42 is complementary to Eq. 2.11 but, in this specific formulation, the operation of each technology is regionally limited according to its layer mix between $f_{min,\%}$ and $f_{max,\%}$.

$$\mathbf{GWP_{tot}} \leq gwp_{limit} \tag{2.41}$$

$$\begin{aligned} f_{min,\%}(j, r) \sum_{j' \in TECHofEUT(eut), t \in T, (h,td) \in T\_H\_TD} \mathbf{F_f}(j', h, td, r) t_{op}(h, td) \quad \leq \sum_{j' \in TECHofEUT(eut), t \in T, (h,td) \in T\_H\_TD} \mathbf{F_f}(j', h, td, r) t_{op}(h, td) \\ \leq \quad f_{max,\%}(j, r) \sum_{j' \in TECHofEUT(eut), t \in T, (h,td) \in T\_H\_TD} \mathbf{F_f}(j', h, td, r) t_{op}(h, td) \\ \forall eut \in EUT, j \in TECHofEUT(eut), r \in REG \end{aligned} \tag{2.42}$$

2.3 Model Validation

The energy modeling practice can be generally described as a process consisting of three interrelated phases: mathematical model formulation, characteristic parameters estimation and validation of the model itself. The first two steps of this process have been fully described in Sec. 2.2. Regarding the final step, long term planning models like Energyscope TD are fundamentally non-validatable since they model an uncertain future configuration of national energy systems [152]. However, in order to verify the accuracy of the formulation adopted and the consistency of the results, such models can be used to represent a well-known state of the system related with the past or the present.

In this section, the 2015 real-world Italian energy system is firstly briefly presented and described in terms of energy supply, dependence on fossil fuels, RES penetration and electrification of end-use demand. Then, the *Italy Energyscope* modeling framework is used to replicate this specific configuration of the national energy system. This year has been chosen for the two following reasons: (i) 2015 is taken as a reference year for multiple European reports [74] and national directives [155]; (ii) the good availability of detailed data collected from online databases of public research bodies (ENEA), national operators (Terna S.p.a, GSE S.p.a and RSE S.p.a) and European associations (ENTSO-E). Finally, the LP model outputs are compared with the actual 2015 values for the Italian energy system in order to verify both the accuracy of *Italy Energyscope* and its feasibility for national energy planning.

2.3.1 The Italian energy system in 2015

Figure 2.7 shows the trend of Total Primary Energy Supply (TPES) in Italy from 1990 to 2015 divided by source. After the peak reached in 2005, the Italian TPES has constantly decreased during the last few years as result of several energetic and economic factors such as an overall increase in energy efficiency, an higher penetration of RES and lower consumption due to the economic crisis. The Italian energy system is still strongly dependent on fossil resources which account for 79.1% of TPES in 2015, broken down in natural gas (36.7%), oil (34.2%) and coal (8.2%) [94]. Figure 2.8 underlines the main role played by fossils in the power generation sector in the last few years, covering more than 65% of the national electricity production in 2015 [94]. They also supply the vast majority of the heating and mobility demand in the form of natural gas (NG) and diesel/gasoline, respectively [160, 144]. Oil products (e.g. light and heavy fuel oils) and solid fuels (i.e. coal) are nearly exclusively used to fuel thermal power plants. Finally, Italy's net electricity import accounts for 2.6% of TPES in 2015, a share that has remained relatively unchanged over the past decade [94].

Despite the still high penetration, the share of fossil resources has constantly reduced over the past decade starting from 89.8% of TPES in 2005, as renewable energy has gained a larger and larger portion of the total energy mix, with a 17.5% of TPES [155] and a 33.3% of PES for electricity production in 2015 [155], as shown in Figure 2.7 and 2.8 respectively. Table 2.6 lists each technology contributing to renewable power production in 2015. In this context, hydroelectricity and solar photovoltaic generate more than 60% of the national renewable electricity, followed

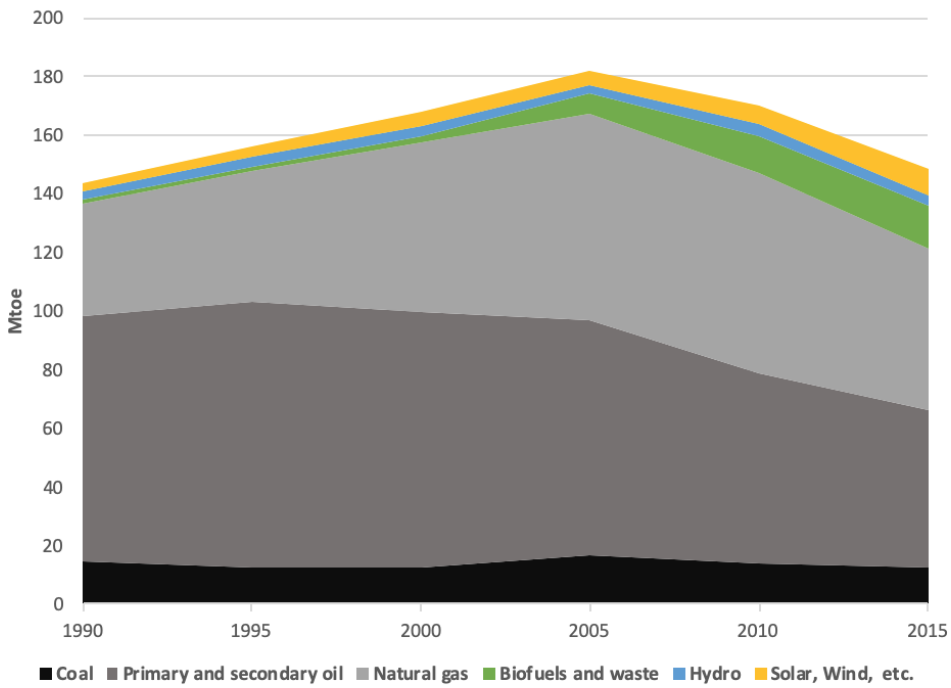


Figure 2.7: Evolution of Total primary Energy Supply by source in Italy, data extracted from IEA Statistics data browser [94].

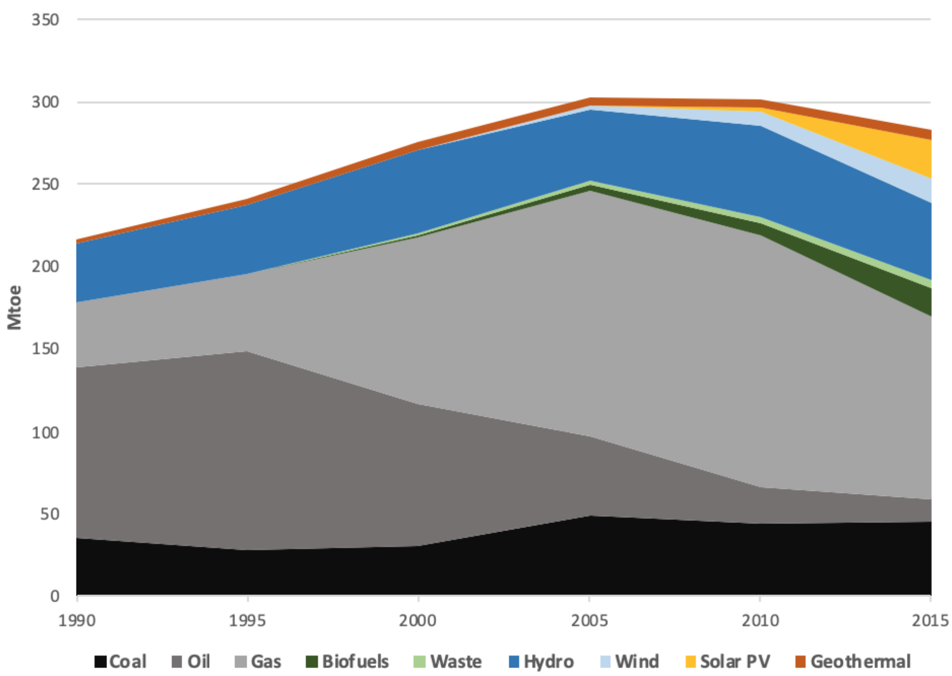


Figure 2.8: Evolution of electricity generation by fuel in Italy, data extracted from IEA Statistics data browser [94].

by bio-energies, wind and geothermal. However, despite the recent sharp increase of renewable energy production in the power sector (lead by PV and wind), RES penetration in both the heating (19.2%) and the mobility sector (6.4%) is still quite low [155].

Table 2.6: Power sector: power, net production and share of renewables technologies in the Italian energy system in 2015 [144].

Renewables	**Power** [GW]	**Net Production** [TWh]	**Share** [%]
Hydroelectic[a]	18.543	45.5	41.8
Wind[b]	9.162	14.8	13.6
PV	18.892	22.9	21.1
Geothermal[c]	0.821	6.2	5.7
Bioenergies	4.057	19.4	17.8
- Solid Biomass	1.612	6.3	
- Biogas	1.406	8.2	
- Bioliquid	1.038	4.9	

[a]Considering both hydro dam and hydro run-of-river plants.
[b]Only onshore wind turbines installed.
[c]Geothermal power plants directly using the steam that comes out of the ground.

Focusing on heat generation, the Italian energy system is dominated by decentralised boilers, mostly fueled with NG and woody biomass. The latter is in fact largely available and cheap while NG is easily accessible everywhere thanks to an efficient network of pipelines well spread over the peninsula [148]. At the same time, the large diffusion of boilers is favoured by the low penetration of cleaner and more efficient technologies such as district heating networks (DHN) (covering 3% of total low temperature heat demand), heat pumps (HPs) (covering 8% of total low temperature heat demand) or Combined Heat and Power (CHP) plants [74]. While the low penetration of HPs and CHP plants is generally due to low investments in energy efficiency, DHN development is mainly hindered by climatic reasons, which make its application suitable only in the Centre-North where winter climate is harsher [158]. So, the Italian heat generation sector is still characterised by low efficiency and poor electrification, both leading to high fossil primary energy demands and significant carbon emissions.

Also private and public mobility are generally poorly electrified (8.3%) [59] and highly polluting. Public and private passenger energy demand is in fact nearly entirely satisfied by diesel and gasoline vehicles, while the contribution of electric and hybrid means of transport is still marginal [2]. The same applies for freight mobility: electric trains cover only the 13.9% of the total demand, a percentage lower than the European average of 17.4% [59]. The remaining freight mobility demand is satisfied with diesel trucks, more flexible and affordable. Also the poor development of the Italian rail network contributes to the low electrification of transportation.

Overall, a huge and effective transformation of the Italian energy system towards an electrified low-carbon layout is needed to reduce its environmental impact. In the future context of renovation, the electrification of end-use demand will be fundamental for the spread of efficient and clean technologies: RES penetration has to sensibly increase while the general backwardness of the mobility and the heating sector must be overcome in favor of electric and efficient energy conversion technologies.

2.3.2 Comparison between model output and actual 2015 values

The *Italy Energyscope* model validation is performed as follows, adapting the procedure proposed by Moret [152]. In order to force the desired energy system configuration, given as inputs:

- the EUD values estimated from FEC data;
- the relative annual production share of each different energy conversion technology for each type of EUD;
- the share of public mobility ($\%_{\mathbf{Public}}$), of train in freight ($\%_{\mathbf{Rail}}$) and of centralised heat production ($\%_{\mathbf{Dhn}}$);
- the efficiencies of technologies characterising the Italian energy system;
- the renewable electricity production (hydro, PV, wind, biomass);

for the year 2015, the outputs of the *Italy Energyscope* model are compared to the actual values reported for that year [156]. The difference between the real-world Italian energy system in 2015 and the modeled one is assessed based on:

- primary energy consumption, global and per type of fuel;
- useful energy delivered per type of technology (CHP plants, DHN);
- national operating CO_2 emissions from both fossil fuels and biomass combustion.

The overall Italian energy system described in Sec. 2.3.1 is entirely modeled using only one region. This choice is motivated by the quality of data, detailed on a national scale but generally approximated regionally. Since the objective of this section is to get a validation of *Italy Energyscope* as accurate as possible, the most precise set of data is selected and then only one region is modeled. As a consequence, regionally available data such as time series of energy demand and weather conditions are computed as a weighted average of zonal values from [151, 111] in order to make them suitable to national applications. As an example, the Italian time series of solar irradiation in 2015 are calculated starting from six different zonal time series (North, Centre-North, Centre-South, South, Sicily and Sardinia) weighted on the actual PV production in each zone [151].

For model validation, Limpens at al. [111] suggest 12 TDs give the best trade-off between accuracy and computational time. The LP problem described in Sec. 2.2 is then solved using the commercial software IBM CPLEX 12.9 on an Intel Core i5 2.60 GHz, with a memory of 8 GB and a 64-bit system. For this validation, under the already specified constraints and processor, the required computational time is about 26 seconds.

The Sankey diagram in Figure 2.9 graphically illustrates the main energy flows of the modeled configuration in 2015 [6, 160, 74, 158, 156], while the corresponding numerical results are reported on Table 2.7.

In terms of energy consumption, the *Italy Energyscope* model guarantees quite a good approximation of the real-world Italian energy system in 2015 already described

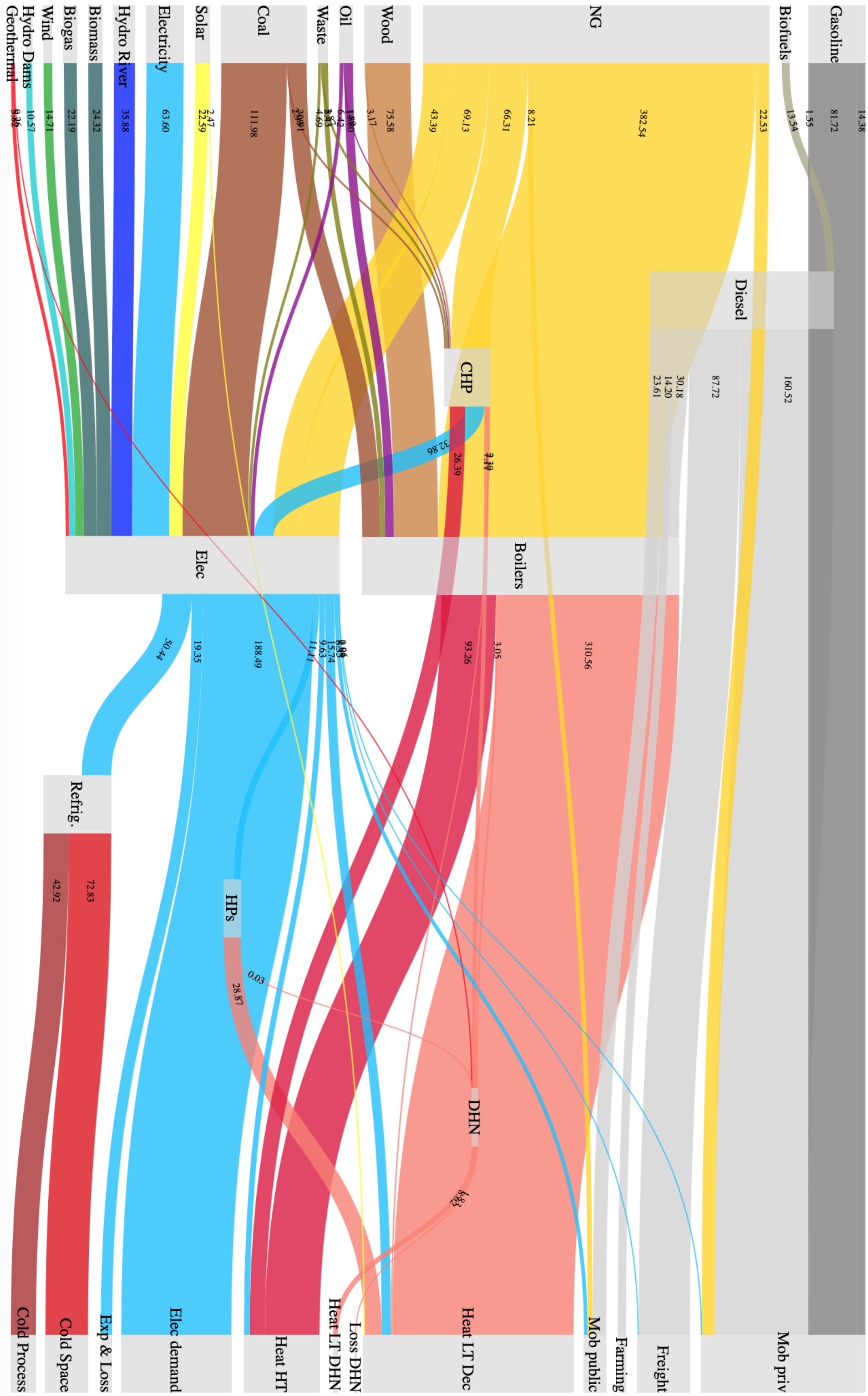


Figure 2.9: Energy flows in Italy in the year 2015. All values are in TWh. The methodology used to treat the data is documented in Appendix A.

Table 2.7: Model validation: model outputs vs. actual 2015 values for the Italian energy system. Actual values for the Italian energy system are taken from [156] unless otherwise indicated. More details provided in Sec. A.8 in Appendix A.

		Actual 2015	LP	Δ	Δ_{rel}	Units
Primary Energy Consumption	**Gasoline**	95.24	97.65	2.41	2.53 %	TWh
	Diesel	302.06	302.70	0.64	0.21 %	TWh
	- Diesel for Mobility	280.17	291.05	10.88	3.88 %	TWh
	Light Fuel Oil	14.86	14.79	-0.07	-0.47 %	TWh
	Coal	144.29	145.88	1.59	1.11 %	TWh
	- Coal for Elec.	114.00	114.97	0.97	0.85 %	TWh
	NG	617.39	602.69	-14.7	-2.38 %	TWh
	- NG for Mobility	31.56	31.25	-0.31	-0.99 %	TWh
	- NG for Elec.	196.24	189.41	-6.83	-3.48 %	TWh
	Elec. Imports	50.08	63.60	12.80	25.21 %	TWh
	Solar & Wind [a]	37.79	37.29	-0.49	-1.30 %	TWh
	Geothermal [a]	6.19	6.08	-0.10	-1.63 %	TWh
	Renewable Waste	17.16	16.99	-0.17	-0.97 %	TWh
	Wood	76.52	78.74	2.22	2.90 %	TWh
	Biomass for Elec.	42.25	46.51	4.26	10.08 %	TWh
	- Biogas	22.81[b]	22.19	-0.61	-2.68 %	TWh
	Global	1464.35	1481.15	16.8	1.15 %	TWh
Technologies Output	**DHN**	10.49[c]	10.45	-0.04	-0.36 %	TWh
	CHP	35.06[d]	35.80	0.74	2.11 %	TWh
CO_2 emissions (Fossil)		305.04[e]	310.12	5.08	1.67 %	Mt-CO_2
CO_2 emissions (Biomass)		45.99[f]	47.86	1.87	4.06 %	Mt-CO_2

[a]Data for renewable primary energy consumption are reported from [160] and from Sec. 3.1.8 in [144].

[b]From [127].

[c]From Table 9 in [6].

[d]From Fig. 17 in [158].

[e]From Table 1 (s1-s2) in [99]. Emissions of CO_2 are evaluated considering only energy-related emissions and removing fugitive emissions from fuels (no aviation/navigation).

[f]From Table 1 (s2) in [99]. Emissions data are provided separating the operating emissions from fossil fuels and the emissions from biomass.

in Sec. 2.3.1. The main differences with respect to the actual values are due to some approximations: first of all, the electricity from Combined Heat and Power (CHP) plants is underestimated since the model is not able to deduce the effective alternation between co-generative and non-cogenerative mode of production (this latter contribution is not considered). Thus, in order to fill this production gap, *Italy Energyscope* overestimates the amount of imported electricity. Ignoring the use of derived heat for DH, the contribution of some biomasses classified as "Biomass for Elec." in [156] and other minor fossil fuels such as coal by-products and half-processed oils contributes to other small differences between model outputs and the actual 2015 values in terms of energy flows.

In order to check the consistency of the environmental impact of the Italian system modeled, the actual energy related emissions from fuel combustion in 2015 are calculated in 310.12 Mt-CO_2 from [99], not including the contribution of fugitive emissions from fuels and the impact of internal navigation and aviation, not implemented into the modeling framework. This number is faithfully estimated by the *Italy Energyscope* model. The higher environmental impact of the modeled energy system is a consequence of the aforementioned approximations: principally, since imported electricity is related to an higher gwp_{op} than natural gas burned in CHP plants (see Sec. A.5 in Appendix A), the emissions obtained by the model validation are higher than reality.

Finally, the proposed LP model formulation is able to offer an accurate representation of the Italian energy system in 2015 even if it does not fully consider the climatic and technological differences at a regional scale yet. The regional configuration of Italy, in fact, needs to be further studied and modeled since it can significantly impact on national energy consumption and emissions. Nonetheless, the model validation shows the consistency of the results provided by *Italy Energyscope*, demonstrating its accuracy and reliability as modeling tool for strategic energy planning.

Chapter 3

Decarbonization pathways

Energy models can help researchers and policy-makers to identify the best pathways towards low-carbon configurations of complex and heterogeneous national energy systems during the so-called energy transition. In this context, the *Italy Energyscope* modeling framework proposed in Ch. 2 has demonstrated to be suitable for Italian applications.

In this Chapter, starting from the Italian energy system described in Sec. 2.3.1, the future national energy transition is defined as well as the sectors in which stronger efforts in decarbonization are required. Then, the developed three-regions modeling zonal division of *Italy Energyscope* is presented and applied to the Italian case study with a 15-year planning horizon. Finally, a scenarios analysis is performed aiming at defining alternative pathways of decarbonization up to 2030 and beyond. These are classified in **reference** or **policy** scenarios, while the underlying assumptions considered for their definition are fully documented.

3.1 Case study: the Italian energy system in 2030

As described in Sec. 1.1.3, Italy has recently put in place new ambitious political measures in order to actively implement energy transition policies towards a low-carbon society. The key points of these policies, listed in "NES 2017" [155] and in the most recent "Proposta di Piano Nazionale Integrato per l'Energia e il Clima" [130], are: (i) strong decarbonization of the power sector; (ii) increase of electrification in the mobility and the heating sectors; (iii) improve of energy efficiency. In this context, the 2030 is considered a reference year in both European [56] and national directives [157] to check consistency and progresses of the proposed energy strategies towards the aforementioned goals.

In order to meet the ambitious emissions targets set by the EU and to guarantee a gradual shift towards electrification, Italy has planned several actions aiming at partially decarbonizing its energy system. The priority is not only to decarbonize, but also to modernise and innovate in a less carbon- and resource-intensive direction. Firstly, a global phase-out of existing coal power plants has been scheduled by the year 2025, at the end of their technical lifetime [155, 88]. As illustrated in Figure 2.8, in 2015 thermal power plants fueled with coal had a 16% share of the total net electricity production representing an important flexible base-load capacity [160]. Thus, the planned phase-out of coal has to be reached with a parallel effort in finding alternative solutions for electricity generation. In this context, the next decade will be likely characterised by a sharp increase of both already established (i.e. PV and onshore wind) and innovative (i.e. off-shore wind, Concentrated Solar Power (CSP), wave energy) RES for power generation [130]. This energy transition will be also favoured by the progressive decrease of the investment costs for all the renewable technologies as already experienced during the last few years. At present, in fact, wind and PV are in fact already close to being cost competitive with traditional fossil-based generation options [12]. At the same time, the larger and larger availability of renewable electricity will contribute to promote the electrification of the mobility and the heating sectors through affordable and efficient technologies such as electric vehicles [26] and heat pumps [16]. The decarbonization strategy could then be extended to other fossil fuels such as petroleum products by 2050, with undoubted environmental and health benefits [45] and with an additional contribution to national objectives of increasing RES penetration and improving energy efficiency [88].

The energy transition of the Italian energy system up to 2030 will be however significantly affected by:

- regional availability and price of fossil resources, extremely difficult to predict and thus subjected by a huge uncertainty, as shown by Bezdek and Wendling [28];
- European constraints and prices related with CO_2 emissions;
- R&D efforts in storage technologies and carbon capture, able to compensate the variability of RES and to reduce the environmental impact of traditional power plants;
- the strong modernisation of the electric grid in terms of security and adequacy, to handle the increasing intermittent and distributed electricity generation from RES;
- private investments on modern energy conversion technologies to make all the end-use sectors more resource efficient and electrified.

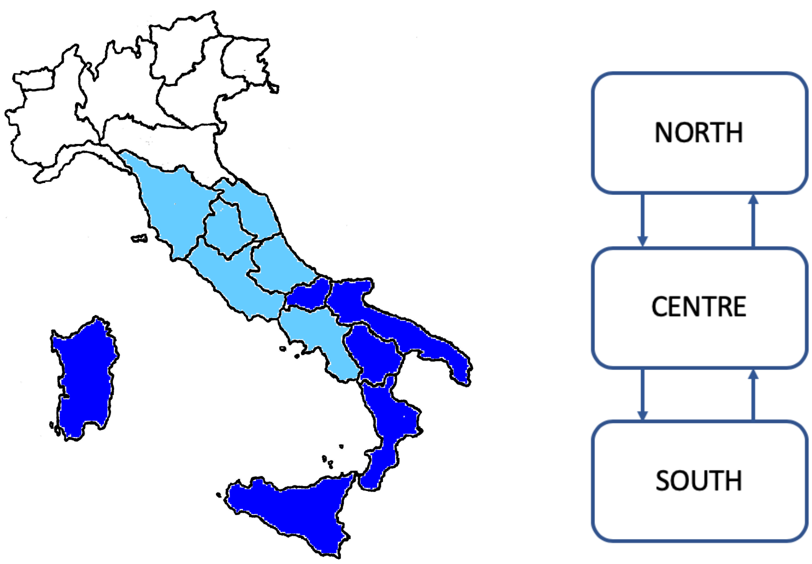
Thus, the future developments of the Italian energy system towards an efficient low-carbon configuration are multiple, hard to predict and strongly dependent on economic and technological efforts. In this context, the *Italy Energyscope* LP modeling framework described in Sec. 2.2 can be used as a supporting tool to asses and forecast which could be the most interesting pathways of decarbonization in terms of costs and environmental impact up to 2030. So, it will be applied to the Italian energy system with a 15-year planning horizon, starting from the configuration introduced in Sec. 2.3.1 and modeled in Sec. 2.3. However, identifying these alternative paths in an accurate and reliable way firstly requires further analysing the Italian energy system by taking into account the availability of resources, the efficiency of technologies, the productivity of RES and the energy demand at a (macro-)regional scale.

3.1.1 National regionalisation

Gradually decarbonizing the Italian energy system by 2030, phasing-out coal power plants and other fossil-fuel based technologies, will require a deep transformation of the national energy system towards RES. To carry out this energy-transition in safety conditions, it is necessary to implement the indispensable actions to manage the growing share of electric renewables. This new installed intermittent capacity, in fact, will generate an overproduction of electricity especially during summer time. In this context, flexibility infrastructures and power grid investments will be needed mostly in the South of the Country, where climatic conditions (i.e. solar irradiance and wind speed) make photovoltaic panels and wind turbines more efficient. At the same time, the South has a lower electricity demand than the North and the Centre of Italy, where most of the population and industrial production is concentrated: the concurrent presence of high production and low electricity demand in this zone can have significant repercussions on the national energy system.

The southern overproduction of renewable electricity is just one of the points that make the Italian energy system strongly characterised at a regional scale. The same applies for the availability of some resources such as woody and non-woody biomass or the capacity of renewable energy conversion technologies, which considerably vary from one area to another. Thus, the regionalised *Italy Energyscope* modeling framework has to carefully consider the overall energy context in which each Italian (macro-)region is inserted to develop accurate long-term planning scenarios of decarbonization.

Figure 3.1 illustrates the modeling zonal division proposed in order to take into account regional features and asses future scenarios of decarbonization up to 2030. The Italian peninsula is divided in three macro-regions according to the electrical market zones identified by GSE [143]. The resulting framework generates the North (white regions), the Centre (light-blue regions) and the South (blue-regions). More in details, the North includes Piemonte, Valle d'Aosta, Liguria, Lombardia, Veneto, Friuli Venezia Giulia and Emilia Romagna. The Centre includes Tuscany, Umbria, Marche, Lazio, Campania and Abruzzo. The South includes Molise, Puglia, Basilicata, Calabria plus the two major islands, Sardinia and Sicily.



(a) (b)

Figure 3.1: Italian zonal division: a) geographical positioning [143]; b) modelling of existing inter-zonal connections.

The choice of this specific three macro-regions repartition considers a reasonable trade-off between accuracy of available data and computational time. In fact, while time series and other parameters are regionally available with an higher degree of details (up to six macro-regions), the computational time needed with more than three zones results to be not acceptable for the purpose of this work (Table 3.1), which aims at providing a modeling tool able to produce outputs in a few minutes range.

Table 3.1: Computational time needed to process multi-regional layouts of the Italian energy system with *Italy Energyscope*.

# of Regions	Computational Time [s]	
	$\mathbf{C_{tot}}$	$\mathbf{GWP_{tot}}$
1	88	161
2	206	468
3	387	865
4	481	5478

As a consequence of the introduced regionalisation, all the model input parameters indexed over regions (r) are characterised by three different values, one for each area considered. In fact, while the parameters used for model validation in Sec. 2.3 are nationally defined (i.e. indexed over only one region standing for the whole Italian energy system), the novel configuration requires three different regionally defined values for the same parameter.

Firstly, a different $c_{p,t}$ has been regionally implemented for each renewable technology: in this way, intrinsic geographic features of solar irradiance, wind speed and hydro capacity are fully taken into account. The different $c_{p,t}$ have been regionally evaluated starting from the hourly electricity production values from 2015 time series available in [151, 70]. These values have been then divided by the actual RES capacity installed in that zone during the hour considered (i.e. the capacity which actively contributes to electricity production) in order to obtain its period capacity factor. A multiplication factor accounting for the new yearly installed capacity is also taken into account.

Secondly, due to climatic differences, hourly time series of energy demand for space heating and cooling are evaluated differently from one modeled area to another by considering a characteristic value of Heating (and Cooling) Degree Days (HDD). The methodology used for the calculation of hourly heating and cooling time series is based on the definition of HDD proposed by the Joint Research Centre (JRC) and adopted by Ispra in [97]. After having chosen a winter “comfort temperature” (T_{comf}) of 18 °C, and knowing the outdoor temperature of the investigated place (T_{out}) at a certain hour (t) of the day, the yearly HDD are given by the sum, extended to all the hours of the year, of the difference between the indoor comfort temperature and the outdoor temperature, where 15 °C is the outdoor temperature threshold (Eq. 3.1). The same applies for yearly CDD definition expressed by Eq. 3.2, in which the summer “comfort temperature” is set to 21 °C and the outdoor temperature threshold is assumed to be equal to 24 °C.

$$HDD = \sum_{t \in T} (T_{comf}(t) - T_{out}(t)) \quad if \quad T_{out}(t) < 15°C$$
$$HDD = 0 \quad if \quad T_{out}(t) \geq 15°C \tag{3.1}$$

$$CDD = \sum_{t \in T} (T_{out}(t) - T_{comf}(t)) \quad if \quad T_{out}(t) > 24°C$$
$$CDD = 0 \quad if \quad T_{out}(t) \leq 24°C \tag{3.2}$$

Figure 3.2 shows how the Italian territory is actually divided into six different climatic zones (A, B, C, D, E, F), each characterized by a certain range of degree days, according to Ispra [97]. However, since the *Italy Energyscope* model formulation only considers the three areas shown in Figure 3.1, regions belonging to different climatic zones have to be aggregated. So, regions such as Valle D'Aosta (zone I) and Liguria (zone D) have to be characterized by the same heating (cooling) time series (North region) in *Italy Energyscope*. Thus, in order to create realistic and reliable model input parameters, the average value of annual HDD (CDD) for each modeled area is determined as an average of all the different regional values from [97]. Then, the city whose temperature profile fits most the average value previously calculated is chosen as reference for each modeled macro-region. Thus, the North (zone E, 1879 HDD in 2015 [97]) is represented by the city of Mantova (1869 HDD in 2015) [131], the Centre (zone D, 1411 HDD in 2015) by Trieste (1402 HDD in 2015, chosen even if geographically located in another zone for reasons of accuracy) [132] and the South (zone B, 952 HDD in 2015) by Lecce (1014 HDD in 2015) [133].

Figure 3.2: Average climatic zones in Italy for each province, according to ISPRA [97].

Thirdly, the regional maximum potential capacity of RES has been calculated starting from national data and considering as "regionalization factor" the relative production share of 2015 [144]. As an example, if the technical maximum capacity of PV is nationally estimated in X GW in 2030 and the share of PV electricity production in the North in 2015 was Y, the technical maximum installable capacity in this zone in 2030 is given by the multiplication of X times Y (see Tables A.9-A.11 in Appendix A). Furthermore, in addition to already established technologies, new promising renewables are implemented in *Italy Energyscope*. In this context, the technical potential of offshore wind turbines is limited by the structure of the Italian coastline [125] while the regional potential of Concentrated Solar Power (CSP), wave energy and deep geothermal is assumed according to realistic considerations [155, 94]. More data and indications are provided in Sec. A.2.1 in Appendix A.

Fourthly, resources theoretically transferable from one region to another (e.g. biomass) are generally estimated as limited locally, with a specific exploitable macro-regional availability. This simplification is made for two main reasons: (i) lack of data regarding the cost for transportation of resources, the related CO_2 emissions, the efficiency of transport etc... (ii) habitual on-site exploitation of biomass for energy purposes (e.g. biogas or bioliquid) [144]. Regional availability of biomass and waste is evaluated starting from national values using several factors (see Sec. A.5 in Appendix A). Only electricity exchanges from North to Centre and from Centre to South are accounted for, as shown in Figure 3.1. Electricity import is limited by national predictions and targets and can be supplied only from the North since it has been historically imported mostly from Switzerland, France and Slovenia [160]. On the other hand, import of fossil resources is assumed to be regionally unlimited even if no fossils exchanges are possible.

Energy end-use demand is regionally estimated as well in order to represent a projection of the energy consumption of the 2030 Italian energy system and make it suitable for the elaboration of decarbonization scenarios. Starting from national data for 2015, the 2030 regional projections are evaluated considering different factors such as the population in each region, the industrial production, agricultural activities etc... More details about the procedure adopted are provided in Sec. A.9 in Appendix A.

Finally, hourly time series for freight and passenger mobility are assumed not to regionally change and are considered equal to the ones proposed by Limpens et al. for the Swiss case study [111].

3.2 Scenarios definition

In view of the uncertainties and challenges characterising the Italian energy transition, multiple scenarios can help identify robust options towards a plausible low-carbon layout in 2030 and beyond [12]. So, to better illustrates the potential of the *Italy Energyscope* model, the LP formulation described in Ch. 2 has been applied to asses several scenarios of decarbonization with a 15-year time horizon adopting the Italian zonal division of Fig. 3.1. It is assumed that the investments decisions are made today considering fuel and resources prices, end-use demand and technologies development status corresponding to the last year of the planning horizon. Elaborating feasible decarbonization pathways, in fact, requires accounting for the forecast structural features of the energy system for the investigated target year. So, the values of the input parameters of the model are the economic and technical projections for the year 2030, while the evolution of the system during this time-framework is not considered [152].

Figure 3.3 gives a general overview of the scenario-base methodology presented and adopted in this section. Starting from the *Italy Energyscope* modeling framework, each scenario is defined by an additional set of constraints fixing the use/size of certain technologies or resources in the modeled energy system (e.g. penetration of renewables, share of passenger and freight mobility, availability of fossils, etc...). By either enabling or disabling the use of some technologies, in fact, it is possible to control the use of specific resources. In the same way, it is possible to force the penetration of one technology with respect to another with the aim of limiting total investment costs and/or emissions. Then, for each scenario the optimal solution in terms of $\mathbf{GWP_{tot}}$ is defined, as already described in Sec. 2.2.2. In this way, the less efficient conversion pathways is directly eliminated by model optimization and the penetration of both biomass and clean technologies is maximized.

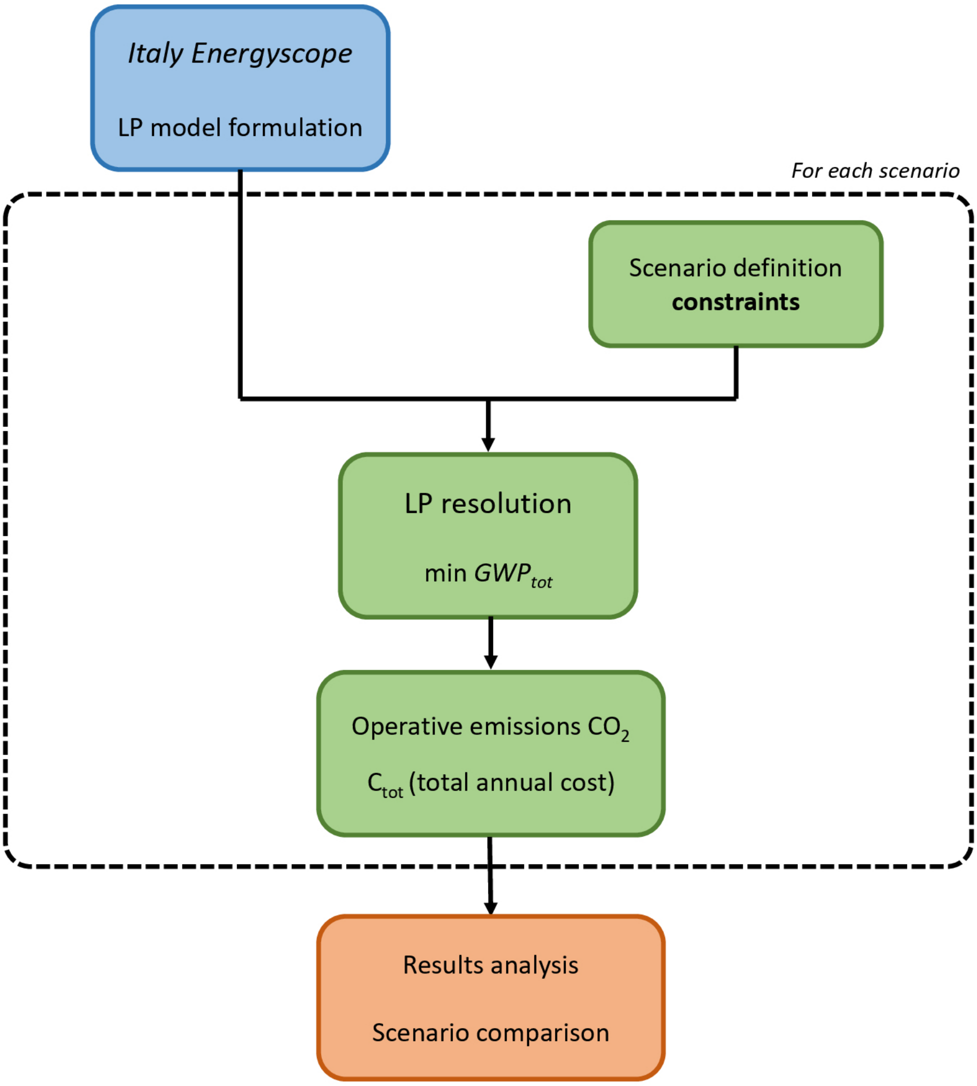


Figure 3.3: Scenario evaluation methodology. Adapted from [152, 84].

The overall process definition is performed similarly to the model validation described in Sec. 2.3. For each scenario, given as inputs

- the regional EUD (see Sec. A.9 in Appendix A);

- the fuel efficiencies of energy conversion technologies (see Sec. A.2,A.3,A.4,A.6 and A.7 in Appendix A);
- the maximum installable capacity for each RES at a macro-regional scale;
- the regional availability of resources;
- some binding constraints in order to diversify each scenario from one another (e.g. availability of coal set to 0 if we want to represent coal-phase out, same relative annual production shares of the different technologies for each type of EUD as in 2015 if we want to force the same configuration);

for the year 2030, the results of the LP model optimization are analysed and compared to national and European energy and environmental projections [155, 130, 157]. In particular, the analysis of these scenarios aims at assessing Italy's position in relation to the three main objectives of the European climate-energy policies for 2030 [56]: (i) the 40% reduction target of GHG emissions with respect to 1990 levels, (ii) the strong development of renewable sources and (iii) the increasing energy efficiency.

Table 3.2 lists the five scenarios proposed to analyse different possible trajectories of development of the Italian energy system during the considered time horizon. Following the definitions adopted by RSE [137], three **reference** scenarios, i.e. those that trace and force the evolution of the system according to current policies and/or trends of development, and two **policy** scenarios, i.e. those built to achieve specific emission reduction objectives or penetration of technologies, are defined.

Table 3.2: List of the five alternative scenarios developed with the *Italy Energyscope* model for the year 2030.

Type	Name	Description
Reference	*ITA30-R1*	Strategy of non-acting, no development.
Reference	*ITA30-R2*	"Business as usual" (BaU) scenario [144].
Reference	*ITA30-R3*	Scenario coherent with "NES 2017" [155].
Policy	*ITA30-P1*	60% emissions reduction with respect to 1990 levels [57].
Policy	*ITA30-P2*	Maximum decarbonization of the Italian energy system.

The four main points to be assessed by the analysis of these trajectories are:

- definition of the reduction of operating emissions of CO_2 with respect to European targets;
- identification of the cleanest and most efficient technologies to invest on in order to strongly decarbonize the system;
- the analysis of the synergistic/divergent effects of energy strategies concerning different sectors;
- the quantification of economic and social repercussions of the energy policies, in terms of additional costs, penetration of fossils, energy dependence etc..

Finally, these alternative trajectories comparison has the final objective to *try to understand if the energy transition pathways up to 2030 indicated by the current national policies could meet European targets on emissions and RES penetration and to evaluate some layouts of the Italian energy system towards a deep decarbonization.*

3.2.1 Reference scenarios

The *Italy Energyscope* model formulation is used to evaluate three different reference scenarios. According to the definition provided by RSE [137], they are defined as those pathways that force the evolution of the energy system by taking into account European and national policies and/or the current trend of development of already established energy conversion technologies.

Table 3.3 briefly sums up the main features of the three reference scenarios evaluated with *Italy Energyscope* for the year 2030, according to the indications and the targets provided by "Proposta di Piano Nazionale Integrato per l'Energia e il Clima" [130], "NES 2017" [155] and "2030 Climate and Energy Framework" [56].

Table 3.3: Reference scenarios assumptions for applications of the *Italy Energyscope* model to the Italian energy system in 2030. Abbreviations used: traditional (trad), Carbon Carpture and Storage (CCS), Concentrated Solar Power (CSP), Heat Pump (HP), Combined Heat and Power (CHP), Pressure Swing Adsorption (PSA), District Heating Network (DHN). Legend: ✓ technology available; ✗ technology not available.

Sector	Technology	Scenario		
		ITA30-R1	*ITA30-R2*	*ITA30-R3*
Power	Coal Phase-out	✗	Partial[a]	Total[b]
	Trad. RES[c] development	✗	Constant	NES 2017
	Offshore Wind	✗	✗	✓
	CCS	✗	✗	✗
	CSP&Wave	✗	✗	✗
	PSA[d]	✗	✗	✓
Mobility	$\%_{\textbf{Rail}}$	0.14	0.18	0.22
	$\%_{\textbf{Public}}$	0.19	0.22	0.25
	Share trad. fossil fuel cars[e]	0.99	0.85	0.78
Heating	DHN development	✗[f]	10% increase[f]	15% increase[f]
	HPs penetration[g]	Same as 2015	Constant	NES 2017

[a] A partial coal phase-out is planned by 2025 [155, 88].

[b] Global phase-out of coal for power generation and heating by 2030, as described in scenario "SEN" proposed in [155].

[c] PV, onshore wind, hydropower, geothermal and biomass electricity production technologies.

[d] Pressure Swing Adsorption (PSA) process of available biogas resource converted to biomethane and then introduced in the NG pipelines network.

[e] Share of diesel, gasoline and NG cars over the total private passenger mobility.

[f] With respect to 2015 centralised heat production.

[g] In decentralised and centralised low temperature heat production.

The *ITA30-R1* scenario basically describes the strategy of not acting and leaving the structure of the energy system as it was in 2015. So, it assumes that the capacity of established renewables (i.e. PV, on-shore wind, hydro-power and geothermal plants) and the relative annual production share of each energy conversion technology in 2030 for each type of EUD remains constant and equal to the 2015 values. This is a very unlikely and pessimistic scenario: as national directives [155, 130] prove, in fact, major changes to the national energy system are expected in the next few years in spite of the trend recently experienced, consisting in a general slow-down of renewable technologies installations. However, even if the structure of the system is considered to be unchanged, some modifications have to be taken into account in order to generate a reliable future pathway. Firstly, regional sectors EUD are set to change with respect to 2015 (see A.9 in Appendix A). A reasonable increase of the population, alongside with a likely change of habits and climatic conditions, in fact, will generate new end-use demands of energy [88, 74]. Secondly, since European climate and energy policies suggest the need to increase the energy efficiency, it is necessary to quantify this increase with respect to 2015 values at an Italian scale and to determine how significantly it could impact in terms of emissions and primary energy saves. As an example, Senneca and Zanetta [141] suggest that the average efficiency of Italian Ultra-Supercritical (USC) Coal power plants can raise up to 40% with respect to 34.74% efficiency in 2013. The same applies for Combined Cycle Gas Turbine (CCGT), whose average efficiency in Italy was equal to 54% in 2015 but could raise up to 60% in the next few decades, according to Zanetta [79]. Table 3.4 illustrates a complete environmental impact comparison between two alternative versions of the *ITA30-R1* scenario: the first one do not consider any increase in efficiency of energy conversion technologies, while the second one does. So, the efficiency increase of energy conversion technologies supposed in *Italy Energyscope* by 2030 results in a sensible 8.1% reduction of operating emissions of CO_2 if compared to the case in which any technical development is not considered. Obviously, this efficiency increase goes in parallel with huge R&D efforts that have to be carefully considered for further technical and economic evaluations (see Sec. A.7.3 in Appendix A). So, this analysis demonstrates that a huge reduction of operating emissions would be feasible by only acting on technical efficiency of energy conversion technologies.

Table 3.4: Comparison between two versions of the *ITA30-R1* formulation considering or not the assumed increase in efficiency of energy conversion technologies for 2030.

Scenario	**Total Cost**	**Environmental Impact**		
		Operating Emissions	Variation vs 2015[a]	Variation vs *R1*
	[B€/y]	[Mt-CO_2/y]	[%]	
ITA30-R1[b]	102.0	326.7	5.4	-
ITA30-R1[c]	108.1	301.6	-2.7	-8.1

[a]Values already used for 2015 model validation are used for this comparison.
[b]Efficiency of energy conversion technologies for 2015 is considered. See values used for model validation in Appendix A.
[c]Forecast efficiency of energy conversion technologies for 2030 is considered. See Appendix A.

The *ITA30-R2* scenario is instead defined considering a constant trend of development of both RES and efficient energy conversion technologies (i.e. heat pumps, district heating network, electric vehicles etc...) and equal to the trend of growth experienced in the last fifteen years (BaU scenario) [144]. This represents a conservative scenario: in this future configuration of the Italian energy system fossil fuels still account for a large part of Country's primary energy consumption. The main assumptions and constraints used to define this decarbonization pathway are listed in Table 3.5. Renewables penetration in the electricity sector increases with respect to 2015: the RES with the highest future growth is supposed to be PV (44% increase of production with respect to 2015), followed by bioenergies (31% increase), onshore wind (26% increase) and traditional geothermal (3% increase), according to the trend of development indicated by GSE [144]. Innovative renewable technologies such as offshore wind turbines, wave energy and CSP, whose development will be strongly dependent on *ad hoc* European and national incentives and policies, are not included yet. The same applies for those technologies such as Carbon Capture and Storage (CCS) that will unlikely be available in the Italian energy context of 2030 without large R&D efforts [155].

Table 3.5: Detailed analysis of main assumptions considered for the definition of the *ITA30-R2* scenario. All the listed assumptions are based on realistic hypothesis unless otherwise indicated.

	Assumptions	
	Subject	*Description*
Resources	**Coal**	Partial phase-out in the power sector: 25% reduction vs 2015. Total phase-out in the heating sector.
	Renewables	PV production: 44% increase vs 2015 [144]. Wind production: 21% increase vs 2015 [144]. Bioenergies power production: 31% increase vs 2015 [144]. Geothermal production: 3% increase vs 2015 [144]. Off-shore wind, CSP and Wave production: technologies not available. Biogas: bio-methanation conversion not available. Biofuels use: 25% increase vs 2015. [155]
Mobility	**Freight**	Share of train freight mobility ($\%_{\textbf{Rail}}$) equal to 18%.
	Passenger	Public: Share of public passenger mobility ($\%_{\textbf{Pass}}$) equal to 22%. Private: car fleet composition in 2030 according to EC forecasts [125].
Heating	**DHN**	Centralised heat production: 10% increase vs 2015.
Other	**Innovative Tech.**	CCS: technology not available. Pyro&Gasification: technologies not available. Power-to-gas: technology not available. HPs: increased penetration both in DHN and in decen. heat production.

Finally, the *ITA30-R3* scenario is forced to be aligned with the recent Italian directives called "NES 2017" [155] and "Proposta di Piano Nazionale Integrato per l'Energia e il Clima" [130]. The main assumptions and constraints used for the definition of this final reference scenario are listed in Table 3.6. An important decarbonization characterizes both the power, the heating and the mobility sector. In this context, a significant increase of already-established and innovative RES is expected. PV power production is set to triple with respect to the 22.6 TWh of 2015, reaching approximately 72 TWh in 2030, while onshore wind production is set to more than double (40 TWh in 2030 vs. 14.7 TWh in 2015). Also innovative RES capacity such as offshore wind, CSP and wave energy actively contributes to compensate the gap in electricity production resulting from national phase-out of coal power plants. Furthermore, RES and HPs penetration in the heating sector replaces a significant fraction of pollutant and less efficient boilers fueled with LFOs and NG. DHN development helps improving the heating sector efficiency as well. Finally, Colbertaldo et al. [125] suggest a larger share of freight mobility by trains and an higher penetration of electric and innovative vehicles (BEV, Hybrid and

Table 3.6: Detailed analysis of main assumptions considered for the definition of the *ITA30-R3* scenario. All the listed assumptions are based on realistic hypothesis unless otherwise indicated.

Topic	Assumptions	
	Subject	*Description*
Resources	**Coal**	Total phase-out in the power sector [155]. Total phase-out in the heating sector.
	Renewables	PV production: following development suggested by [155]. Wind production: following development suggested by [155]. Bioenergies production: following trend suggested by [155]. Geothermal production: following trend suggested by [155]. Off-shore wind capacity: 0.3 GW. CSP&Wave energy: technologies not available. Biogas: bio-methanation conversion available. Biofuels use: 50% increase vs 2015. [155]
Mobility	**Freight**	Share of train freight mobility ($\%_{\mathbf{Rail}}$) equal to 22 %.
	Passenger	Public: Share of public passenger mobility ($\%_{\mathbf{Pass}}$) equal to 25 %. Private: car fleet in 2030 according to EC and IEA forecasts [125].
Heating	**DHN**	Centralized heat production: 15% increase vs 2015.
Other	**Innovative Tech.**	CCS: technology not available. Pyro&Gasification: technologies not available. Power-to-gas: technology not available. HPs: increased penetration according to [155].

Plug-in cars), contributing to increase the electrification in freight and passenger mobility, respectively. In this context, the relative share of private passenger mobility technologies for the Italian energy system in 2030 is given by an average between European Commission (more conservative) and IEA forecasts available in [125] (see Table A.8 in Appendix A).

3.2.2 Policy scenarios

Italy Energyscope is used to evaluate two alternative policy scenarios adopting the energy demand and efficiency of the year 2030. These scenarios have been built to represent future possible trajectories of the Italian energy system in case of deep decarbonization. Even if these low carbon layouts will unlikely be reached by 2030, due to both technical and economic limitations, their analysis is important since suggests possible future pathways of decarbonization towards and beyond the 60% and 80% emissions reduction targets set by the "Energy Roadmap 2050" for 2040 and 2050, respectively [57].

Table 3.7 briefly sums up the main assumptions made to define the two policy scenarios evaluated with the *Italy Energyscope* modeling framework.

In particular, the *ITA30-P1* scenario analyses one possible pathway towards the 60% emissions reduction target, indicated as the environmental goal to be met by 2040 [57]. Basically, the aim of this path is to investigate on a possible low-carbon development of the Italian energy system without implementing promising technologies currently at the R&D stage (e.g. CCS), and considering a reasonable electrification of mobility and heating. So, for each technology available the maximum and minimum shares are controlled in the model by $f_{min,\%}$ and $f_{max,\%}$, respectively (see Sec. A.2 in Appendix A). Furthermore, the increased shares of trains for freight ($\%_{\mathbf{Rail}}$)

Table 3.7: Policy scenarios assumptions for applications of the *Italy Energyscope* model to the Italian energy system in 2030. Abbreviations used: traditional (trad), Carbon Carpture and Storage (CCS), Concentrated Solar Power (CSP), Heat Pump (HP), Combined Heat and Power (CHP), Pressure Swing Adsorption (PSA), District Heating Network (DHN). Legend: ✓ technology available; ✗ technology not available.

Sector	**Technology**	**Scenario**	
		ITA30-P1	*ITA30-P2*
Power	Total Coal Phase-out	✓	✓
	Off-shore Wind	✓	✓
	CCS	✗	✓
	CSP&Wave	✓	✓
	PSA[a]	✓	✓
Mobility	$\%_{\textbf{Rail}}$	0.35	1.00
	$\%_{\textbf{Public}}$	0.35	0.40
Heating	DHN development	30% increase	30% increase

[a]Pressure Swing Adsorption (PSA) process of available biogas resource converted to biomethane and then introduced in the NG pipelines network.

and of public mobility ($\%_{\textbf{Public}}$) are estimated according to realistic assumptions.

The *ITA30-P2* scenario represents instead the pathway of maximum decarbonization reachable by the Italian energy system. The aim of studying this trajectory is to underline which technologies and resources will play a fundamental role in the energy transition process towards and beyond the 80% emissions reduction target set by the EU for 2050 [57]. This scenario is modeled with the highest degree of freedom, i.e. each technology is free to evolve and to cover the entire energy demand of its layer. So, the sizing parameters $f_{min,\%}$ and $f_{max,\%}$ are set to 0 and 1, respectively, for each energy conversion technology. As an example, it means that the entire private passenger mobility demand could be theoretically satisfied by electric cars only ($f_{max,\%}(FC\_BEV, r) = 1$), very efficient and characterized by zero operating emissions. The effective technical and economic feasibility of this specific scenario of decarbonization is further investigated later on in this work with the aim of evaluating if a nearly-zero carbon emissions Italian energy system could be really reached as the final step of the energy transition process.

Chapter 4

Results and discussion

The results of the previously introduced reference and policy scenarios are presented in this chapter after having been assessed with the methodology described in Sec. 3.2. A full and detailed comparison among the different outputs obtained is performed to show and quantify the environmental and economic impact of the alternative energy transition strategies indicated for the Italian energy system up to 2030 and beyond. Finally, we focus our attention on the *ITA30-P2* scenario of deep decarbonization in order to check its techno-economic feasibility by considering the modeling solutions adopted and the related results. The energy Sankey diagrams of all the scenarios proposed in this chapter are reported in Appendix B.

Table 4.1 lists the computational time needed in order to generate the results for each investigated scenario. Since the analysis is based on low-carbon energy systems projections, for each scenario the optimal solution in terms of $\mathbf{GWP_{tot}}$ is defined. In order to limit the computational burden and data requirements, thermal energy storage technologies, which have been implemented by Limpens et al. [111] in Energyscope TD for the Swiss case study, have not been considered in this analysis. So, the resulting computational time for the reference and policy scenarios developed with *Italy Energyscope* is suitable for quick forecasts and assessments of future decarbonization pathways for the Italian energy system, floating between 8 and 25 minutes.

Table 4.1: Computational time needed to process each scenario with the *Italy Energyscope* model in absence of thermal storage technologies.

Scenario	**Computational time** [s]
2015 Validation	26
ITA30-R1	462
ITA30-R2	943
ITA30-R3	1493
ITA30-P1	964
ITA30-P2	1203

4.1 Scenarios comparison

In this section, a complete comparison among the Italian energy system configurations generated by the scenarios proposed is performed. The results obtained from the "2015 model validation" described in Sec. 2.3 are also considered in order to define the starting point of each energy transition strategy. In particular, this comparison is based on the following key points: (i) estimation of the environmental impact through an analysis of operating CO_2 emissions from fuel combustion; (ii) total primary energy supply by energy source; (iii) specific focus on the electricity, mobility and heating sectors in terms of emissions, primary energy supply and main technologies adopted; (iv) economic efforts and investments needed.

4.1.1 Summary of the main results

Table 4.2 summaries the main results obtained by the scenarios analysis, highlighting the key differences among the alternative trajectories proposed in terms of emissions, primary energy supply, electrification and penetration of efficient technologies. This is a general overview that can help understand which is the actual energy system configuration for each scenario, fully described later on in this chapter and graphically represented in the energy Sankey diagrams reported in Appendix B.

Table 4.2: Key results and differences among the alternative scenarios evaluated with the *Italy Energyscope* model. Legend: ✓ criterion satisfied; ✗ criterion not satisfied.

Topic	**Unit**	**Scenario**				
		ITA30-R1	*ITA30-R2*	*ITA30-R3*	*ITA30-P1*	*ITA30-P2*
2030 Emissions Target		✗	✗	✓	✓	✓
2050 Emissions Target		✗	✗	✗	✗	✓
CCS installed		✗	✗	✗	✗	✓
TPES	[TWh]	1445.6	1407.6	1301.9	1107.8	929.5
RES over TPES	[%]	16.4	18.8	26.7	46.7	54.6
Elec. generation	[TWh]	260.0	300.7	317.6	359.7	523.4
PV&Wind generation	[TWh]	37.8	51.7	109.8	177.7	203.5
Decarbon of Elec. generation[a]	[%]	31.9	45.0	68.7	88.7	92.8
Electrification of LT heat[b]	[%]	12.0	14.8	21.3	43.6	94.9
HPs useful heat	[TWh]	28.9	37.7	61.1	139.6	342.5
Electrification of mobility[c]	[%]	9.2	21.1	28.2	49.9	96.9
Traditional cars[d]	[%]	98.9	85.5	78.3	56.8	0

[a]Decarbonization of the power generation sector vs 1990.
[b]Including both centralized and decentralized low temperature heat production.
[c]Including both passenger and freight mobility.
[d]Relative share of Diesel, Gasoline and NG cars over the total private passenger mobility.

In particular, these results introduce the layout of the reference and, above all, of the policy scenarios implemented and which are the main technologies needed in order to obtain a deep decarbonized Italian energy system. Briefly, the *ITA30-P1* scenario represents a nearly complete decarbonization of the power generation sector through a massive penetration of RES while CCS technology is not available yet. If compared to reference scenarios, this modeled energy system is characterised by an increasing overall electrification which hugely limits its fossil demand and the related environmental impact. The *ITA30-P2* scenario leads instead to a nearly complete electrification of low-temperature heat generation through HPs and of mobility through trains for freight and BEV. This major decarbonization allows to sharply cut the use of fossil fuels while the vast penetration of RES combined with the availability of CCS technology in thermal power plants significantly reduces the emissions beyond the 2050 target, while supplying the increased electricity demand.

4.1.2 Emissions

Table 4.3 summarises the GHG emissions reduction goals list in the European directives called “2030 Climate and Energy Framework” [56] and “Energy Roadmap 2050” [57]. The reported values indicate the overall expected percentage emissions reduction for the overall EU with respect to 1990 but specific targets are provided for each member state [56]. These national goals usually include the distinction between heavy energy-using installations (ETS sectors) such as thermal, refining, production of cement and steel and non-ETS sectors, i.e. small-medium industry, transport, civil, agriculture and waste [48]. As an example, focusing on non-ETS sectors, Italy has a 33% GHG emission reduction target to be achieved by 2030, compared to 2005 levels. However, since a clear distinction between ETS and non-ETS sectors is not possible in the *Italy Energyscope* modeling framework, the overall European targets reported in Table 4.3 are preferred to single state goals for a comparison with scenarios results. Furthermore, since the *Italy Energyscope* model formulation provides the emission factor of each resource (gwp_{op}) in terms of CO_2 emissions, the aforementioned targets initially defined for GHG are assumed not to change considering only carbon dioxide.

Table 4.3: Targets of emissions reduction for 2030, 2040 and 2050 according to the “2030 Climate and Energy Framework” [56] and the “Energy Roadmap 2050” [57] European directives.

	Target 2030	**Target 2040**	**Target 2050**
Reduction in GHG emissions[a]	40%	60%	80-95%

[a]With respect to 1990 levels. Italian emission data from ISPRA online database [99].

Table 4.4 reports the total annual CO_2 emissions and the corresponding percentage reduction compared to 1990 and 2015 values for each trajectory developed with *Italy Energyscope*. The environmental impact of the “2015 model validation” energy system (see Sec. 2.3) is also added in order to provide a more complete overview of the emissions trend experienced in the last few years. For the sectors considered in *Italy Energyscope*, the Italian energy related emissions of CO_2 in 1990 were equal to 368.6 Mt-CO_2 [99].

Figure 4.1 shows how emissions data listed in Table 4.4 have been graphically represented: for each scenario, the total annual CO_2 emissions from fuel combustion (y-left axis) are plotted together with their percentage reduction with respect to 1990 value (y-right axis). Finally, dashed orange and red lines represent the percentage thresholds of the emissions reduction targets indicated in Table 4.3 for 2030 and 2050, respectively.

Among reference scenarios, the analysis reports that only *ITA30-R3* reaches and overcomes the European target set for 2030 with a 40.6% CO_2 emissions reduction. As expected, the pessimistic strategy of not acting and leaving the energy system

Table 4.4: Total CO_2 emissions and percentage reduction compared to 1990 and 2015 values for each developed scenario. In bold letters the values that meet the "2030 Climate and Energy Framework" targets [56]

Scenario	**Total emissions** [Mt-CO_2/y]	**Reduction** vs 2015	vs 1990
2015 Validation	311.2		-15.9%
ITA30-R1	301.6	-2.7%	-18.2%
ITA30-R2	270.1	-12.9%	-26.7%
ITA30-R3	218.9	-29.4%	-40.6%
ITA30-P1	146.1	-52.9%	-60.4%
ITA30-P2	11.7	-96.2%	-96.8%

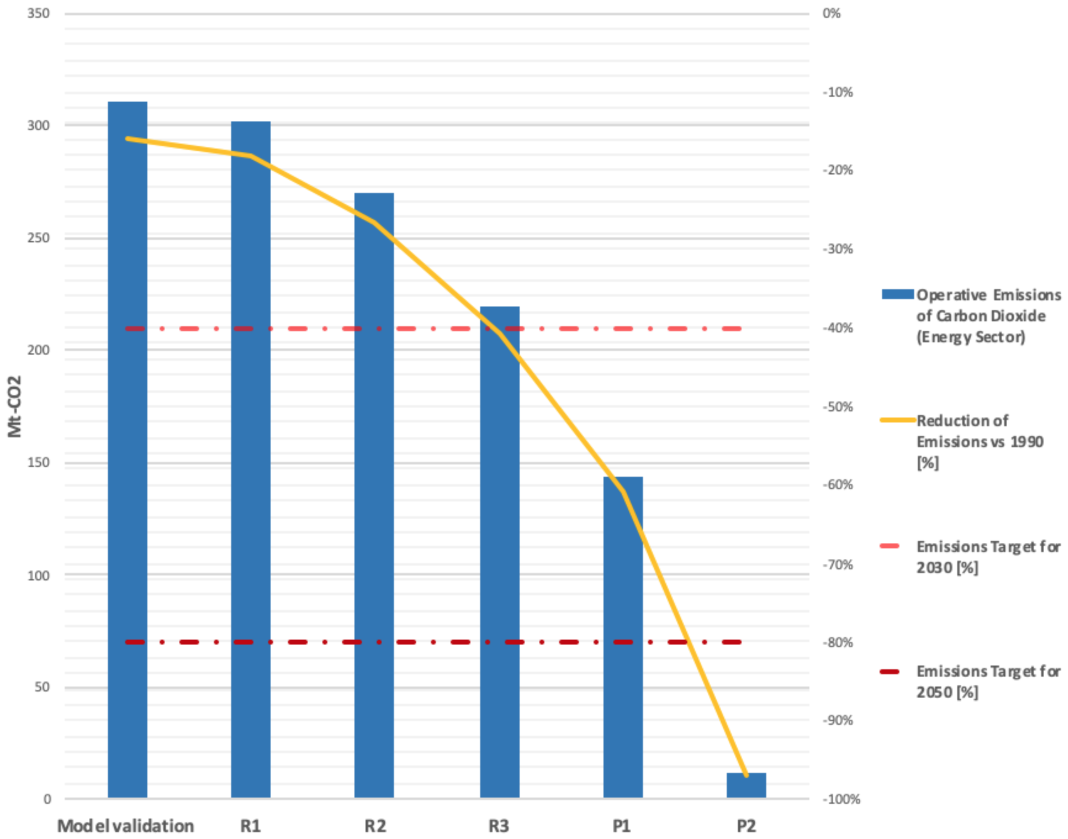


Figure 4.1: Graphical representation of total energy related CO_2 emissions and percentage reduction compared to 1990 of the Italian energy system in 2030 for each developed scenario.

as it was in 2015 (scenario *ITA30-R1*) leads to a nearly unchanged environmental impact. In this case, the increase of the end-use demand is compensated by the efficiency improvements of energy conversion technologies assumed for the next few years. So, the new system energy balance leads to a slightly decrease (-2.7% vs 2015) of operating emissions but European targets remain far from being satisfied. Also the pathway indicated by *ITA30-R2* is not able to meet European constraints on emissions. Even if the impact of the Italian policies in terms of RES penetration and environmental safety in last fifteen years has been one of the most effective in the EU [155], the related low-carbon strategy projected until 2030 can only lead to a -26.7% reduction of CO_2 emissions compared to 1990. Thus, stronger efforts in developing renewable and efficient technologies, and more specific policy planning are needed to support a deeper decarbonization since the actual energy trend is demonstrated to be not sufficient. For this reason, the *ITA30-R3* scenario traces the Italian energy system evolution according to the most recent national guidelines, specially drawn up to identify possible paths towards a low-carbon layout that meets European objectives of decarbonization (see Sec. 1.1.3). In keeping with these targets, the "NES 2017" [155] modeled guarantees a smooth and efficient transition able to get a significant decrease in the carbon intensity of energy with an overall 40.6% CO_2 emissions reduction compared to 1990.

Finally, the two policy scenarios specially created to simulate deep decarbonization layouts push the Italian energy system well below the threshold of 40% emissions reduction. Firstly, *ITA30-P1* simulates an interesting low-carbon scenario for 2040. Thus, this trajectory can be used to investigate more in details the steps needed to be taken after 2030 by Italian policy makers, i.e. in which sector the effort should be focused, which technology should be invest on etc... Secondly, the *ITA30-P2* generates a nearly-zero carbon emissions scenario corresponding to a 96.8% reduction. This latter pathway of huge decarbonization is discussed more in details later on in this chapter (Sec. 4.2). Both the proposed policy scenarios demonstrate that a deep reduction of CO_2 emissions is possible if huge efforts in trying to integrate clean and efficient technologies will be done at a national scale. Wide electrification of EUD and a larger use of RES, plus the increased penetration of more efficient technologies, could significantly help reducing the environmental impact of the Italian energy system although the overall end-use energy demand for the year 2030 is set to increase if compared to 2015 values.

4.1.3 Primary energy supply

Energy related CO_2 emissions always reflect the different fuel mixes and technology options used to convert energy in order to supply the demand. Thus, gradually decarbonizing the Italian energy system by using smarter and renewable technologies will inevitably lead to reduce the Italian primary energy supply, as shown in Figure 4.2.

In all the proposed scenarios, primary energy demand continuously decreases with respect to the energy system modeled for 2015, to achieve at least a 12% reduction in the *ITA30-R3* scenario, close to the 13% reduction indicated in [155]; and up to a 37% maximum decrease in the *ITA30-P2* scenario of deep decarbonization. This reduction in primary energy supply is not related to economic downturn or lower levels of sectoral activities, not accounted for in the *Italy Energyscope* model. The TPES contraction is instead exclusively due to technological changes and improvements in energy efficiency, expected to be the main drivers of decarbonization until 2030 and beyond: HPs in the heating sector and electric vehicles in transportation could lead to huge energy savings due to their high level of development in terms of energy consumption. As an example, considering a house with a 100 J heat demand, the primary energy needed to satisfy it with a traditional NG boiler (90% efficiency) would be 111 J of NG. In an electrified energy system, if the same heat demand would be instead supplied by an HP (COP = 4) powered with photovoltaic electricity (100% efficiency), only 25 J of solar resource would be needed.

Furthermore, fuel shifting from high-carbon fossils (e.g. coal or LFO) to cleaner

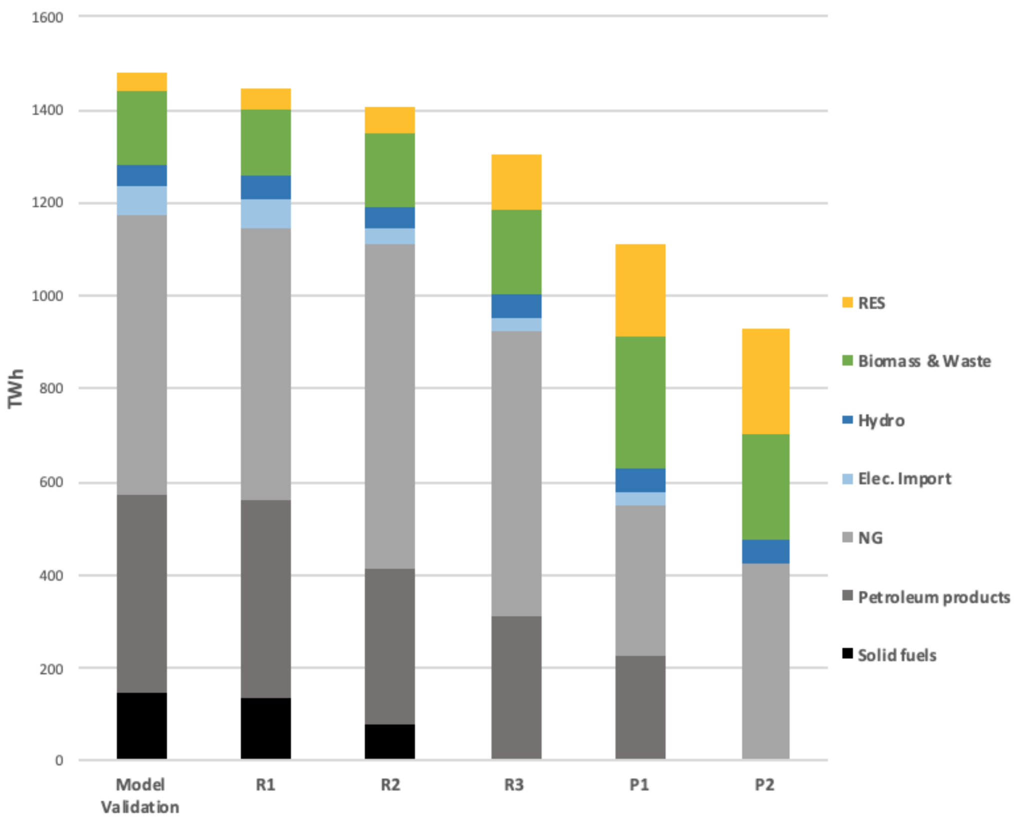


Figure 4.2: Total primary energy supply (TPES) by energy source in each developed scenario.

and/or renewable sources, can also guarantee significant energy savings and emissions reductions. The analysis, in fact, shows that the reduction of TPES goes hand in hand with the gradual phase-out of fossil fuels, which are usually used in low-efficient direct combustion processes, while RES, hydro and biomass hugely increase their share covering 27% of TPES in *ITA30-R3* (close to the target of 28% indicated in [155]); and up to 55% in *ITA30-P2*. Limiting fossil fuel penetration can play a significant role not only on energy source diversification but also on energy security: while in 2005 Italian import dependence reached 87% [12], in 2030 it could drop below 50%. So, it is clear that a shift towards innovative and renewable solutions strongly increases the overall efficiency of the energy system, reducing emissions, TPES and guaranteeing huge advantages in terms of energy dependence and security.

4.1.4 Power generation sector

The almost-complete decarbonization of the power generation sector is one of the key points to be achieved during the energy transition in order to significantly reduce the environmental impact of the Italian energy system. In this context, the "Energy Roadmap 2050" [57] indicates that the Italian power sector could reduce emissions by 96-98% by 2050, despite the higher and higher electrification of end-use demand and the related increase of electricity production. Table 4.5 confirms these projections showing that operating CO_2 emissions in the power generation sector could decrease up to 93% in the *ITA30-P2* scenario compared to 1990 values, estimated in 126.2

Mt-CO_2 [99]. Furthermore, the results demonstrate the inversely proportional trend between emissions and electrification of the Italian energy system, confirmed as one of the key drivers of the future energy transition. In fact, while the electricity production (and the related demand) is projected to increase by 28% in *ITA30-R3* and up to 111% in *ITA30-P2* compared to 2015 levels, the related CO_2 emissions keep reducing, as already described in Sec. 4.1.2.

Table 4.5: Impact of the Italian power generating sector in terms of electricity production and operating CO_2 emissions for each scenario.

Scenario	**Elec. Production**		**Emissions**	
	[TWh]	Variation vs 2015	[Mt-CO_2/y]	Variation vs 1990
Model Validation	247.5	-	87.74	-30.5%
ITA30-R1	260.0	5.1%	86.00	-31.9%
ITA30-R2	300.7	21.5%	69.45	-45.0%
ITA30-R3	317.6	28.4%	39.51	-68.7%
ITA30-P1	359.7	45.3%	14.26	-88.7%
ITA30-P2	523.4	111.5%	9.11	-92.8%

Figure 4.3 shows the electricity production by type of resource used for each developed scenario. The structure of the power generation sector significantly changes from reference to policy scenarios, progressively moving electricity production towards natural gas and renewable sources. The first step to be taken during this cleaning-up process is the national phase-out of coal for power production, as proposed in [155] and modeled in *ITA30-R3* and in the two policy scenarios. At the same time, RES penetration is set to increase providing a growing share of electricity production, passing from 89.56 TWh in 2015 to 164.6 TWh in *ITA30-R3*. In this scenario, the sharp growth of RES is lead by PV, whose production pass from 22.6 TWh in 2015 to 71.2 TWh in 2030, and by wind, whose production is set to more than double passing from 14.7 TWh to 38.6 TWh (on-shore plus off-shore wind turbines considered). Hydro-power generation remains rather constant at 46-50 TWh meaning that its potential is already now well exploited. Biomass use in non-CHP plants (i.e. ICEs or rankine cycles) is instead projected to decrease. As a result of this transition, RES account for 56% of total net generation in *ITA30-R3*, perfectly fitting the national target of 55% listed in [155].

The contribution of intermittent RES grows more rapidly in the deep decarbonised policy scenarios, accounting for 242.6 TWh and 268.4 TWh in *ITA30-P1* and *ITA30-P2*, respectively. Wave energy, high-enthalpy deep geothermal and CSP actively contribute to electricity production up to 8 TWh. Furthermore, in *ITA30-P2* the generation capacity is strongly affected by the availability of Carbon Capture and Storage (CCS) technology, providing 251 TWh of low-carbon fossil electricity.

Finally, the shift towards a deeper electrification also guarantees to sharply cut the primary energy supply of the electricity sector, as already introduced in Sec. 4.1.3. The larger penetration of RES substituting fossil fuels, in fact, reduces the PES since conventionally many RES have an efficiency factor of 100% while Italian traditional thermal power plants are generally characterised by low efficiencies (see Sec. A.2.2 in Appendix A). A lower consumption of fossil fuels also allows to reduce the Italian dependence on import, indicated in [155] as one of the keys point to be achieved in the next future: in this context, the *ITA30-R3* is characterised by a 17% energy savings in the power generation sector alone. The policy scenarios

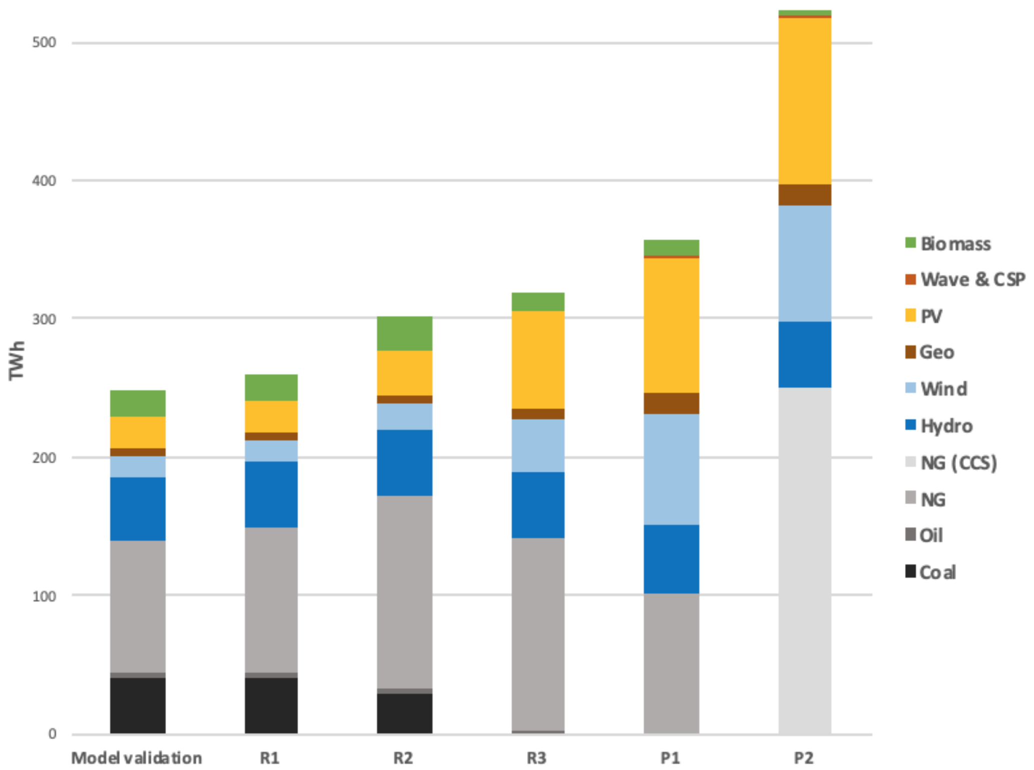


Figure 4.3: Electricity production in all the developed scenarios by type of resource used. Renewable energy sources are further divided in wind, PV, hydro, geothermal and wave plus CSP.

do not respect this PES reduction trend since the electricity demand is too high to be satisfied only with RES: the remaining part is supplied by NG CHP or thermal power plants (combined with CCS), whose efficiency is assumed to be quite low (see Table A.12, Appendix A).

4.1.5 Transport sector

Decarbonizing the transport sector contributes to strongly mitigate the environmental impact of the Italian energy system. Phasing-out automotive fuels such as diesel and gasoline will reduce the atmospheric pollution characterising vast areas of the Country, especially the main cities of the Northern regions, and locally improve the air quality [113, 150].

Table 4.6 shows how transport sector emissions from fuel combustion are divided among freight, public and private transportation in each investigated scenario. The Italian transport sector in 2030 can emit up to 101.5 Mt-CO_2 in the *ITA30-R1* scenario, with a slight increase with respect to 2015 values as result of the forecast higher mobility demand. Nonetheless, developing electric and hybrid means of transport, eco-sustainable fuels, and promoting modal shift towards collective and rail mobility can strongly decrease the environmental impact of the mobility sector. In particular, it is possible to reach a 14% emissions reduction in *ITA30-R3* with respect to 2015 and up to a carbon-free transport sector in *ITA30-P2*. The increased share of efficient electric and hybrid cars to the detriment of fossil fuel vehicles (Fig-

Table 4.6: Impact of the Italian transport sector (public, private and freight) in terms of operating CO_2 emissions in each developed scenario.

Scenario	Transport Emissions			
	Public [Mt-CO_2/y]	Private [Mt-CO_2/y]	Freight [Mt-CO_2/y]	Total [Mt-CO_2/y]
Model Validation	7.9	69.1	23.3	100.3
ITA30-R1	8.1	72.5	20.8	101.5
ITA30-R2	8.2	64.6	19.9	92.7
ITA30-R3	8.2	58.9	18.6	85.8
ITA30-P1	9.6	38.9	15.7	64.3
ITA30-P2	0	0	0	0

ure 4.4) is fundamental for this achievement. In *ITA30-R3* innovative vehicles cover only the 12% of total private passenger mobility demand, with an 8% penetration of electric and plug-in cars, while in *ITA30-P2* the whole demand is satisfied only with BEV. Furthermore, in this latter layout, electric trains satisfy all the freight mobility demand while public vehicles are either electrified or fueled with biofuels. This particular low-carbon configuration allows such a high level of electric means of transport because of the large availability and diffusion of renewables and CCS technology for electricity production, as shown in Figure 4.3. Moreover, it is interesting to notice that electricity demand for private and public mobility (accounting for 89.67 TWh in *ITA30-P2*) is usually nearly exclusively concentrated during daylight hours, so in phase with PV production: this can guarantee a more efficient use of renewable electricity with undoubted advantages also in terms of costs. From this perspective, the development of new infrastructure for electric vehicles (e.g. charging stations, electric storage etc...) is essential since it can further increase the efficiency of transport sector and can also help stabilizing the power grid during periods of peak generation from RES, reducing the excess production and losses.

Finally, Figure 4.5 demonstrates how this shift from conventional to electric and plug-in hybrids cars, plus a gradual shift from road to rail transport and an increased share of public mobility, leads to a significant reduction in primary energy supply for the transport sector compared to 2015 values (10% reduction in *ITA30-R3* and up to 69% in *ITA30-P2*). Focusing on the private passenger mobility, this results mainly from the higher efficiency of innovative vehicles than traditional ones. As an example, a BEV is assumed to have a 0.095 kWh/pkm efficiency in 2030 while a diesel car will likely have a four times lower efficiency, accounting for 0.381 kWh/pkm (see Table A.18 in Appendix A).

4.1.6 Heat generation sector

Table 4.7 lists the CO_2 emissions related with low and high temperature heat generation processes for space heating/hot water and industrial applications, respectively.

At present, the heat generation sector results to be the most polluting one in the Italian energy system: in 2015, it has a 16% higher impact than transports and a 32% higher impact than electricity production, with a 36% contribution on national emissions. In particular, low temperature heat production for space heating and hot water stands for 66% of the overall emissions of the sector. This high environmental impact comes from the four following reasons: (i) the large use of fossil

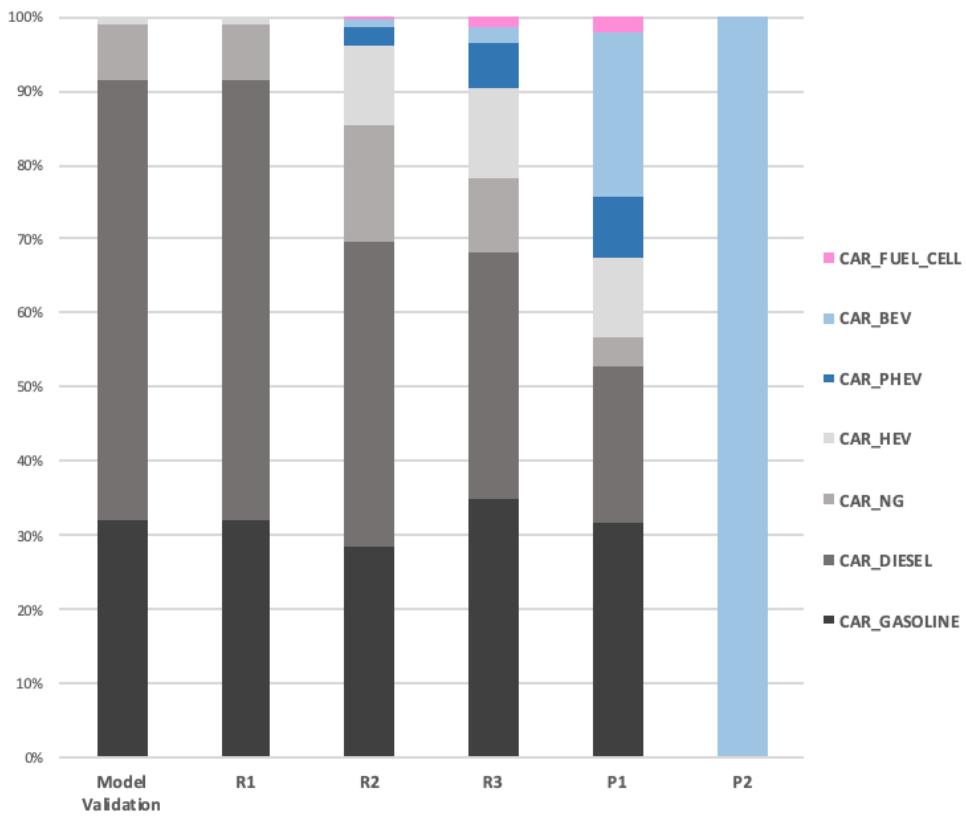


Figure 4.4: Demand for private passenger mobility by type of cars.

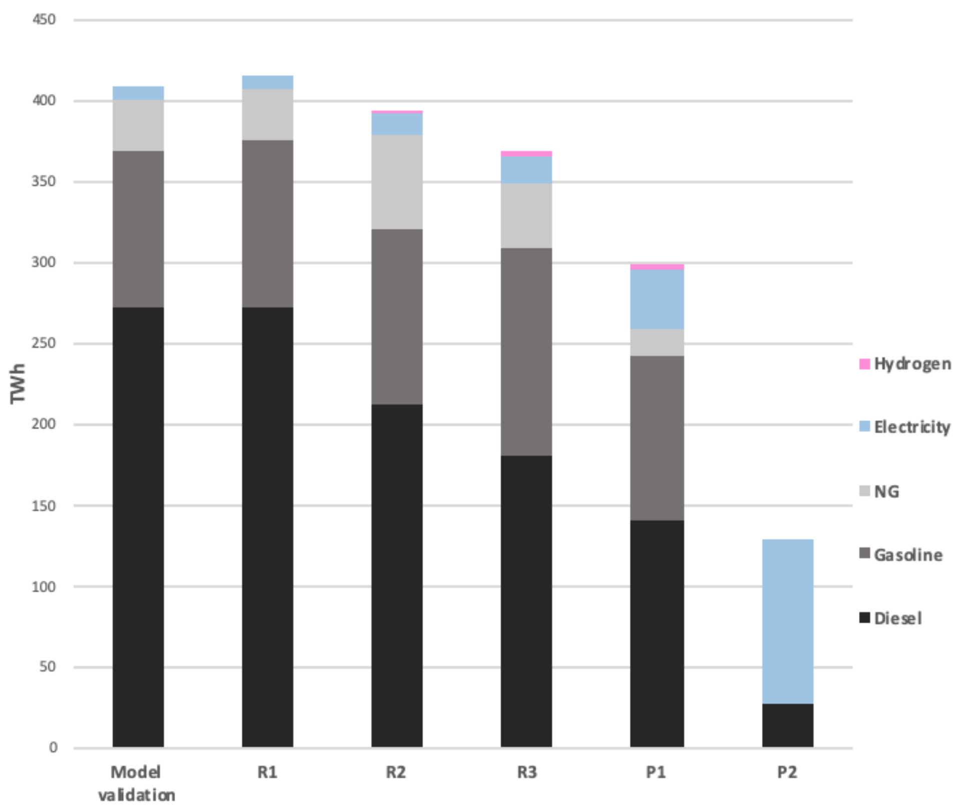


Figure 4.5: Primary energy supply by energy source in the transport sector for each developed scenario.

Table 4.7: Impact of the Italian heat generation sector in terms of operating CO_2 emissions for each scenario.

Scenario	**Emissions**		
	Low T Heat [Mt-CO_2/y]	**High T Heat** [Mt-CO_2/y]	**Total** [Mt-CO_2/y]
Model Validation	76.8	39.7	116.5
ITA30-R1	71.2	38.8	110.1
ITA30-R2	67.9	37.1	105.0
ITA30-R3	61.4	37.6	98.9
ITA30-P1	42.8	40.4	83.2
ITA30-P2	0.2	0	0.2

fuels (especially NG and heating oil) in low-efficient decentralised boilers; (ii) low penetration of DHN (only 2% of the total LT heat demand is supplied by centralised technologies); (iii) poor electrification of heat end-use demand due to the current low affordability of efficient technologies such as heat pumps; (iv) bad performances of buildings envelope in households and services. Through the *Italy Energyscope* model the influence of the first three points can be evaluated. The impact of building retrofitting in household and services, which can strongly contribute to reduce primary energy demand for heating (and cooling) in the next future through improved thermal insulation [12] is instead not considered.

Starting from the *ITA30-R1* scenario, the analysis shows that emissions tied to LT heat generation start decreasing with respect to 2015 as a consequence of the reduced primary energy demand (Figure 4.6). This results mainly from the increased energy efficiency of traditional boilers (see Table A.15 in Appendix A) and from the gradual switch from fossil fuels to electricity and renewable energy. In this context, Figure 4.6 shows how the gradual phase-out of oil and NG low-efficient boilers, with the higher and higher penetration of decentralised HPs and solar thermal panels, reduces the LT heat primary energy demand by 14% in *ITA30-R3* and by 72% in *ITA30-P2* compared to 2015, passing from 472 TWh to a minimum of 134.6 TWh. As already explained in Sec. 4.1.3, the penetration of smart technologies guarantees in fact high efficiencies and low energy consumption.

The reduction trend of emissions and primary energy demand experienced for LT heat is not so well defined in the process heat generation. Also in this context the increased HT heat demand assumed for 2030 as a consequence of a higher national industrial production is compensated by the assumed improvement in energy efficiency. However, due to the expected increase of electricity demand in deep decarbonized scenarios, HT heat is often supplied in combination with electricity in NG and biomass fueled CHP plants. Furthermore, in this sector the impact of RES (e.g. solar thermal) and HPs is hindered by the range of temperatures needed for process applications (from 100 °C to 500 °C). Thus, the impact of the energy transition in this branch of the Italian energy system is rather limited especially in reference scenarios, where appreciable decreases neither in PES nor in emissions are not experienced. Focusing on policy scenarios, emissions sharply reduce only in the *ITA30-P2*. In this low-carbon configuration, in fact, CHP plants are neither energetically nor economically convenient anymore due to the large availability of cheaper electricity from renewables: so, HT heat is exclusively provided by biomass and biomethane boilers, which are usually less efficient but cleaner and more affordable.

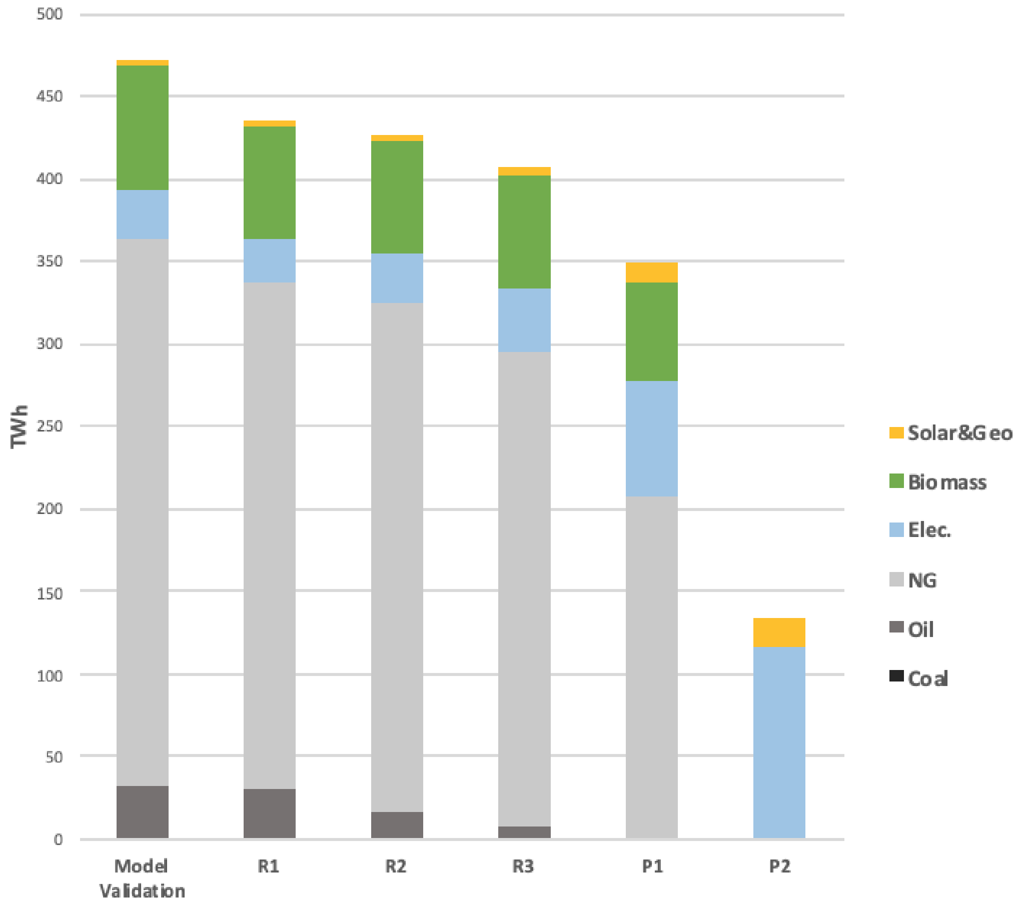


Figure 4.6: Primary energy supply by energy source in the low temperature heating generation sector for each developed scenario.

The gradual modifications of the overall heat generation sector towards an electrified configuration is graphically represented in Figure 4.7, illustrating the relative share of the different energy conversion technologies used in each scenario.

The Italian diffusion of CHP plants is usually limited with respect to other realities (see the Swiss case in [111, 152]), while biomass and waste are mainly used to fuel decentralised boilers for low and high temperature heat production, respectively. The gradual transition from traditional fossil fuel boilers to more efficient technologies such as heat pumps and RES goes together with an increased electrification of the Italian energy system. As a consequence, these smart technologies have a 25% share in *ITA30-R3* (coherent with the results proposed in the "BASE" scenario in [155]), and up to a 95% penetration in the *ITA30-P2* scenario.

Finally, the comparison demonstrates that a huge decarbonization of the heat generation sector can be achieved through the large electrification of the energy system and will be lead by heat pumps and biomass technologies. However, especially for HT heat production, the transition towards a low-carbon layout is generally slower and the use of some technologies strongly depends on other sectors end-use energy demand.

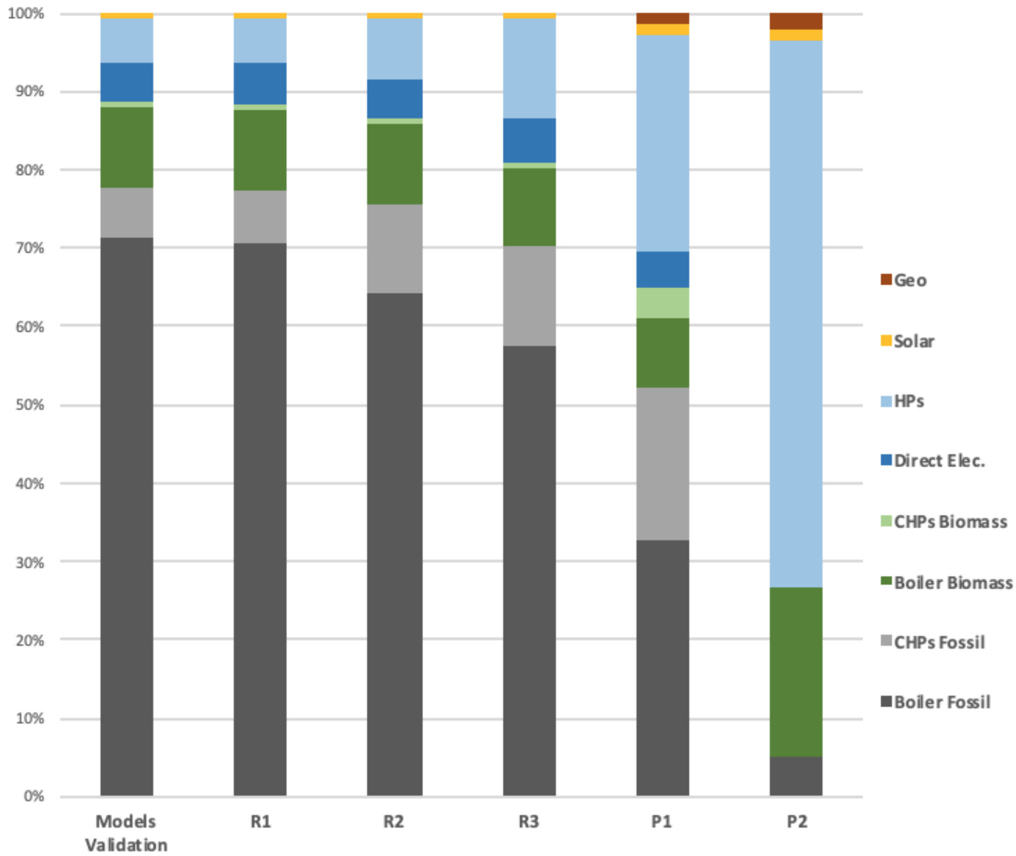


Figure 4.7: Demand for heat at high and low temperature (decentralized and centralized) by type of technology used.

4.1.7 Costs and investments

Deep decarbonizing the Italian energy system requires considerable effort in terms of low-carbon resources and smart technologies as so far described, and also in economic terms. Table 4.8 lists the total annual cost ($\mathbf{C_{tot}}$) for each investigated scenario divided into investment ($\mathbf{C_{inv}}$), maintenance ($\mathbf{C_{maint}}$) and operating costs of resources $\mathbf{C_{op}}$. Then, the percentage variation with respect to the computed 2015 total cost is reported. The analysis shows that the annual cost of the modeled energy systems keeps growing while increasing the penetration of renewable and efficient technologies, and decreasing CO_2 emissions. So, the deep decarbonization of Italy is not cost-free but requires huge specific investments in order to change the current fossil-based energy system. In particular, the analysis shows that the low-carbon energy transition shifts a major part of the costs from resources (OPEX) to capital (CAPEX) expenditure due to the lower penetration of fossil fuels and the higher penetration of RES, electric technologies and CCS. However, the OPEX still increases in all the reference scenarios even if fossil fuels consumption is decreasing: this is due to the likely increased cost of fossils assumed for the next few years (see Table A.5 in Appendix A) and to the increased exploitation of expensive biomass such as wood and biogas.

In this analysis, the cost of electricity generation includes only technology investments and O&M costs (variables and fixed). Transmission and distribution costs are not considered, as well as the cost of CO_2 emission. Investments on the electric grid due to an higher penetration of RES are accounted for. In the scenarios characterised by high electrification and high penetration of intermittent and variable renewables, it is in fact crucial to invest in the overall strengthening, safety and modernizing of the power grid. This allows Italy to theoretically exploit the full potential of electric renewables, while improving service quality and efficiency. However, the costs of transportation infrastructure (e.g. railways) as well as investments on trains for freight and on public means of transport, set to significantly contribute to lower the emissions in both the policy scenarios, are not considered. So, the results obtained are, especially for the policy scenarios, just a lower estimation of the costs associated with the decarbonization of the Italian energy system.

Table 4.8: Total annual costs for the Italian energy system in each scenario.

Scenario	**Costs Analysis**				
	$\mathbf{C_{inv}}$ [B€$_{2015}$/y]	$\mathbf{C_{maint}}$ [B€$_{2015}$/y]	$\mathbf{C_{op}}$ [B€$_{2015}$/y]	$\mathbf{C_{tot}}$ [B€$_{2015}$/y]	**Variation vs 2015** [%]
Model Validation	41.4	5.4	47.9	94.6	
ITA30-R1	43.5	5.7	58.9	108.1	+14.2
ITA30-R2	47.0	6.3	53.7	107.0	+13.0
ITA30-R3	53.3	8.0	51.3	112.7	+19.0
ITA30-P1	63.5	9.8	42.5	115.8	+22.3
ITA30-P2	83.3	10.7	26.8	120.9	+27.7

Figure 4.8 illustrates the cumulated costs variation by type of category for each scenario with respect to the 2015 model validation results. Only relative cost variations of imported fossil resources, exploited biomass, private cars fleet renovation, heat generating technologies, RES and fossil electricity generation are taken into account. In this context, passing from reference to policy scenarios the emphasis gradually switches from fossil fuels and imported electricity costs towards investments in renewable power generation capacity, biomass and more efficient electric technologies. From one hand, in fact, the gradual electrification of the energy system strongly contributes to sharply cut the TPES of the Country (see Figure 4.2) and the related costs for importing fossil resources. From the other hand, a larger penetration of biomass and electric technologies leads instead to increase the total annual cost of the energy system by 19.0% in *ITA30-R3* and up to 27.7% in *ITA30-P2* compared to 2015. These costs are mainly associated to the large penetration of BEV cars, supposed to be still costlier than traditional fossil-based vehicles in the short-to medium term (until 2030) [12], and to the huge increase of RES and the related costs in safety and adequacy of the electric grid. The development fo DHN and of HPs contributes to slightly increase the costs related to the heating systems: in this context, HPs are considered to be cost-competitive with fossil boilers in 2030. So, in reference scenarios the still low electrification of mobility and heating guarantees a reasonable growth of total annual costs related with RES and biomass, reaching a 18.1 B€/y increase in *ITA30-R3*, while the higher electrification modeled in *ITA30-P1* and *ITA30-P2* leads to an overall system costs increase of 26.3 B€/y in the nearly-zero emissions scenario.

Finally, the investments on private passenger mobility and decentralised heating technologies that characterise the *ITA30-R3* and both the policy scenarios underline one the biggest challenge towards a low-carbon configuration of the Italian energy system: the need to finance the energy transition by involving the private sector.

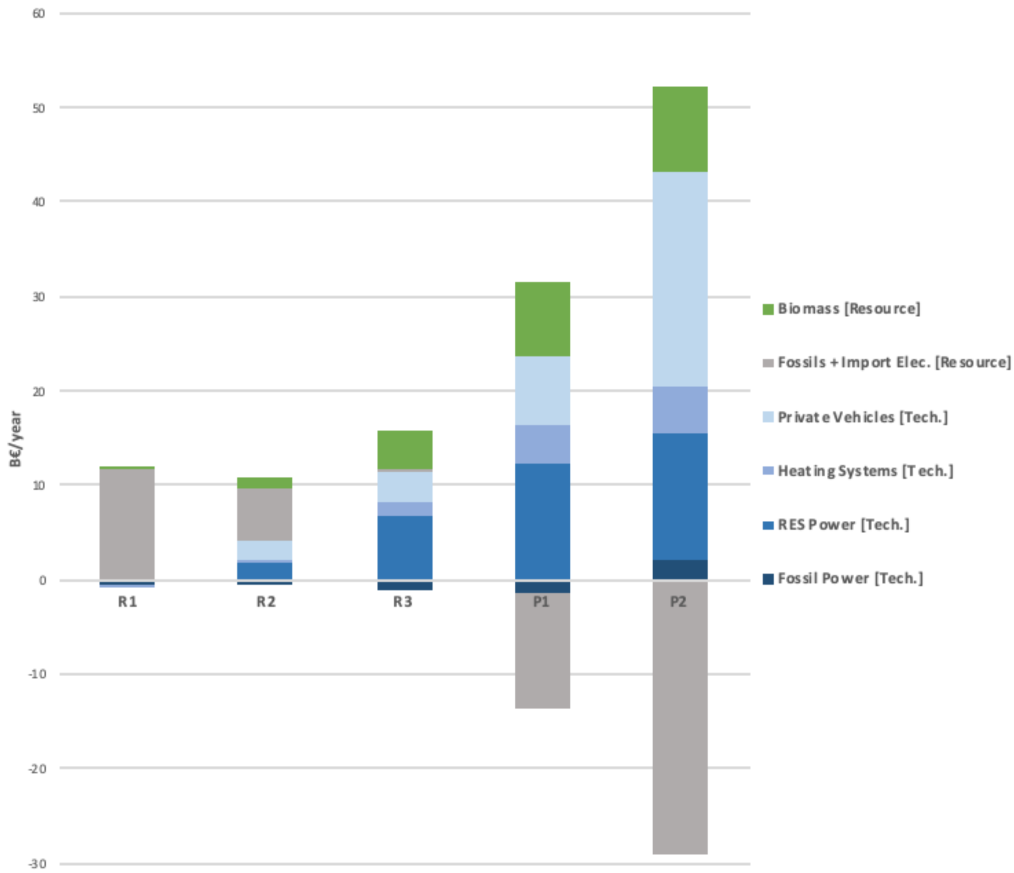


Figure 4.8: Cumulated costs change in all the developed scenarios vs 2015 model validation.

In fact, if it looks apparently "easy" to act on the national electricity generation sector by increasing RES penetration, the same cannot be said about decarbonizing private sector technologies, which obviously strongly depend on private initiatives and investments. So, the Italian deep decarbonization planned up to and after 2030 can be feasible only through the development of specific policies and energy strategies and with appropriate financing schemes that would provide the necessary up-front capital to firms and households so they can actively play a primary role in the future energy transition.

4.2 Feasibility of nearly-zero emissions pathway

The analysis performed in Sec. 4.1 has demonstrated that the modeled *ITA30-P2* scenario could theoretically lead to an energy system with nearly-zero CO_2 emissions meeting the 80 to 95% reduction target set by the EU for 2050. As already stated, the aim of studying this trajectory is to underline which technologies and resources could play a fundamental role in the energy transition process towards a deep decarbonization. However, this specific low-carbon layout is the results of several social, technical and economic considerations and assumptions whose feasibility needs to be further demonstrated in this section. The Sankey diagram in Figure 4.9 graphically illustrates the main energy flows modeled in this specific pathway. The key hypothesis contributing to this particular layout are: (i) major electrification of

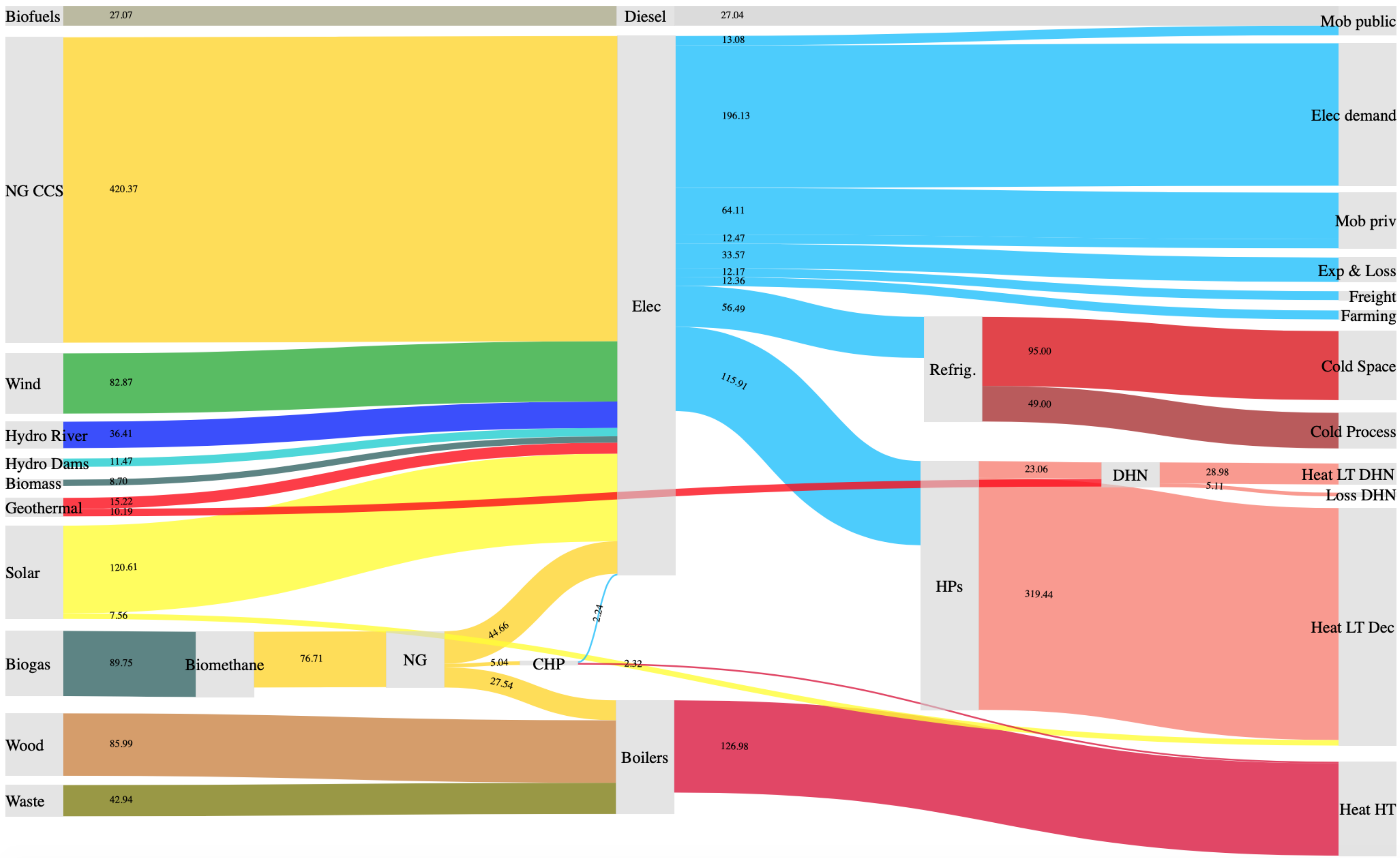


Figure 4.9: Energy flows in Italy in the year 2030 according to the *ITA30-P2* scenario. All values are in TWh. The methodology used to treat the data is documented in Appendix A.

the energy system maximising RES production; (ii) availability of CCS technology for power generation; (iii) less tight constraints on relative share of technologies in each layer (e.g. the possibility to have a complete freight mobility on rails or a private passenger mobility demand satisfied by only BEV).

In this context, the *ITA30-P2* scenario is characterised by a high level of electrification of the end-use demand, especially in heating and transport services. This configuration is only possible by powering the energy system with a large share of renewable electricity: solar PV production provides the largest RES contribution, with 120.6 TWh, while wind provides 77.6 TWh from onshore and 5.3 TWh from offshore plants, respectively. So, compared to 2015 values, the production of electricity from PV and wind is projected to grow by more than five times, passing from 37.8 TWh to 203.5 TWh. Other minor RES such as wave energy and CSP contribute with a quite low share as well. In this context, Table 4.9 lists the renewable power generation capacity installed for these technologies in the *ITA30-P2* scenario, comparing it with model validation and *ITA30-R3*.

Table 4.9: Renewable power generation capacity installed for some RES in the *ITA30-P2* scenario with respect to *Model Validation*, *ITA30-R3* and to the maximum available potential.

RES	**Installed Power**			**Max. Potential**
	Model Validation [GW]	*ITA30-R3* [GW]	*ITA30-P2* [GW]	$\boldsymbol{f_{max}}$ [GW]
PV	18.9	60	95	110.2
Onshore Wind	9.1	24	45	49.1
Offshore Wind	0.0	0.5	1.5	1.5
CSP&Wave	0.0	0.0	0.6	0.6

The outputs demonstrate that the growing trend necessary to reach and overcome the 80% emissions reduction target set for 2050 is coherent with the one indicated by "NES 2017" with respect to the Italian energy system in 2015. Obviously, further increasing the RES power generation capacity means exploiting a major part of their potential. As an example, since the $\boldsymbol{f_{max}}$ of the Italian photovoltaic is estimated from the available roofs and façades surface of all the buildings considering the current average module efficiency (Table A.9 in Appendix A), imagining an 86.2% exploitation as indicated in *ITA30-P2* strongly depends on public acceptance and technical limitations. The variability of RES such as PV, in fact, can generate problems of adequacy and safety for traditional electric grid: significant investments will therefore be required for the improvement of the so-called Smart Grids, storage systems (batteries, pumped-hydro) and also for power reserve capacities as reported shown in Figure 4.8. Also landscape protection and the Italian territory configuration can limit a large diffusion of PV and wind technologies. Thus, passed a certain threshold of installable capacity to be determined, the electricity production from RES is likely expected to grow due to efficiency increase and technical improvements than by installing new units. Furthermore, the installable capacity assumed for innovative technologies such as CSP and wave energy will be hugely influenced by their technical developments and future affordability. However, the results obtained in this scenario in terms of power generation from RES are similar to the ones available in literature regarding alternative low-carbon configurations of the Italian energy system, reported in [12, 13]. So, fully exploiting solar and wind resources is generally considered feasible and it is modeled as a necessary step in order to achieve ambitious decarbonization targets.

Furthermore, the Sankey diagram in Figure B.5 shows that a large power generation from intermittent RES is not enough to satisfy the electricity demand required by an energy system able to meet the 80% emissions reduction target if not coupled with thermal power plants with CCS. This technology is still at the development stage but Italy is one of the few countries where pilot plants have been already established [53]: for this reason, a future use of this technology for electricity generation is likely to happen even if concerns exist over its viability, due to the expected cost of transporting the CO_2 through pipelines [12]. At the same time, another key point that needs to be further investigated is the quantification of how much CCS could we reasonable deploy in Italy.

Moreover, the maximum available exploitation of woody biomass, biogas and waste modeled in the *ITA30-P2* scenario can be reached only by rationally managing woody by-products from agricultural and industrial processes, wet biomass from breeding and sewage sludge, and recycling (Table A.19 in Appendix A), respectively.

Finally, some considerations about the results obtained for heating and mobility (Table 4.2) are necessary. From one hand, the slight cost increase related with the strong development of HPs and DHN shown in Figure 4.8 demonstrates that an high electrification and development of the heating sector towards efficient and clean technologies is economically feasible. From the other hand, a vast electrification of mobility results instead more difficult to be met in short-to medium terms due to both economic and technical limitations. Focusing on freight mobility, the Italian industrial system layout is characterised by a large number of medium-small firms heterogeneously distributed over the Country, so on-road means of transport are usually more flexible and adapted than on-rails transportation. Electric trains covering the entire freight demand, as modeled in *ITA30-P2*, would also require strong investments on specific infrastructures, not accounted for in *Italy Energyscope* but which can further burden the energy transition process. However, even if a complete on-rails mobility is unlikely, trying to get close to a more efficient and less polluting freight transportation sector is possible by focusing the attention on gradual developing railways infrastructure and improving truck efficiency. The same applies for private passenger mobility, modeled to be satisfied only with electric cars. A future layout with a large penetration of BEV circulating could be feasible in an high electrified energy system only by improving their technical features and, above all, decreasing their investment costs (Sec. 4.1.5). The economic analysis shown in Figure 4.8, in fact, demonstrates that BEV are still costlier than traditional fossil-based vehicles in the short-to medium term (until 2030).

Finally, this feasibility analysis demonstrates that the 80% to 95% emission reduction target set by the “Energy Roadmap 2050” [57] is a realistic goal for the Italian energy system. Even if some of the outputs of the *ITA30-P2* scenario cannot be fully achieved, we have to consider this layout as a future projection of the Italian energy system up to 2050 and beyond. In this context, a further reduction of the energy demand with respect to the input values used for 2030 is reasonable and can be achieved through additional efforts in increasing the efficiency, improving thermal performances of buildings, encouraging the use of trains and public transports, and through a more rational exploitation of the energy sources. In the same way, technologies that are not considered to be cost-competitive with traditional fossil-based ones in 2030 are likely to become so by 2050. Furthermore, the future efficiency increase of RES such as PV and wind could allow to find a good trade-off among installed capacity, social acceptance and safeguarding of the environment, while the development of promising technologies (e.g. CCS, deep geothermal, wave energy) could guarantee additional carbon-free sources for electricity and heat generation by the end of the energy transition process. As a consequence, the emissions related with the energy sector will further decrease during the next decades even if some fossil technologies will still likely be part of the Italian system.

Chapter 5

Conclusions

Through this work of thesis an open source modeling framework called Energyscope TD has been implemented to make it suitable to Italian applications with the aim of identifying multiple low-carbon scenarios for national energy planning during the so-called energy transition up to 2030 and beyond.

With respect to previous works using the Energyscope TD model, the solution proposed in this thesis, called *Italy Energyscope*, present several novelties such as the spatial characterisation of the problem by dividing the modeled area in different regions (regionalisation), new energy conversion technologies and new end-use demands that define the Italian energy system. Once presented the mathematical LP formulation adopted (Ch. 2), the *Italy Energyscope* modeling framework has been applied to the real-world condition of Italy in 2015 in order to validate it. The consistency of the obtained results comparing model outputs with the known energy values demonstrates the accuracy and reliability of *Italy Energyscope*. The validated model has been further implemented with a three-regions zonal division (Ch. 3) to carefully consider RES capacity, availability of resources and energy demand regionally. Then, multiple low-carbon scenarios for the Italian energy transition up to 2030 have been assessed. This scenarios analysis has the final objective to try to understand if the energy transition pathways indicated by current national policies or trends of development (the so-called reference scenarios) could meet European targets on emissions and RES penetration and, if not, to evaluate some configurations of the system able to satisfy them and reach a deep decarbonization (the so-called policy scenarios). The results have been determined in Ch. 4 through a constrained optimisation in terms of global emissions and then they have been analysed and compared.

The scenarios comparison has demonstrated that deep modifications have to be planned in the next few years in order to significantly reduce emissions and to increase RES penetration nationally. Without acting the impact of the Italian energy system on the environment is set to increase as a consequence of the supposed overall growth of the energy demand. In the same way, the current trend of development of RES and efficient technologies results to be not sufficient to sharply cut emissions. However, the *ITA30-R3* scenario forced to be aligned with the recent national directives is able to embrace European policies, leading the energy system to pass the target of 40% reduction of CO_2 emissions compared to 1990 values. This configuration also allows to reduce the TPES by 17% and then energy dependence of the Country. These achievements are based on three main pillars: (i) complete phase-out of coal in the electricity generation sector; (ii) overall increase of the energy efficiency; (iii) higher electrification of the energy system through a larger penetration of RES in the power generation sector, and HPs and electric vehicles in heating and mobility, respectively.

Once demonstrated the reliability of the strategy indicated by the recent national directives, two scenarios of deep decarbonization are analysed. In this context, the *ITA30-P1* scenario allows a 60% emissions reduction and further saves in TPES beacause of a huge penetration of RES (specially PV and onshore wind) in the power generation sector. However, if we want to achieve the minimum target of 80% emissions reduction set for 2050, decarbonizing the electricity generation sector has to go in parallel with further efforts in electrifying heating and mobility. In this context, the *ITA30-P2* scenario of maximum decarbonization can lead to hugely decreasing the emissions (97% reduction with respect to 1990) and the primary energy supply (37%). This promising layout could be an interesting guide-line for decision makers to understand how the Italian energy system is likely to evolve by 2050 and beyond. Even if some of the outputs are technically and economically difficult to be reached (e.g. vast electrification of private passenger and freight mobility), a nearly-zero carbon emissions configuration is demonstrated to be feasible by further increasing RES penetration and energy efficiency, by developing promising technologies such as CCS, and by decreasing both the energy demand and the investment costs of electric technologies. The results from policy scenarios show, in fact, that deep decarbonizing the Italian energy system requires considerable efforts not only in terms of low-carbon resources and technologies, but also in economic terms. The total annual cost of the system keeps growing while decreasing CO_2 emissions, bringing to a 27.7% increase in the *ITA30-P2* scenario with respect to 2015. This is mainly due to the large penetration of RES for power generation, the vast exploitation of wood and biogas and, finally, the increased share of HPs and BEV. The role played by the latter efficient and electric technologies underlines, therefore, the primary importance to finance the energy transition by involving the private sector. Without specific energy strategies and policies that would guarantee access to credit for firms and households, an overall deep decarbonization of the Italian energy system will not be economically feasible in the short-to medium term.

Overall, the *Italy Energyscope* modeling framework proves to be a valuable and reliable tool able to quickly assess future scenarios of decarbonization for the Italian energy system, effectively evaluating energy transition pathways towards an high penetration of both RES and smart and innovative technologies. Its intuitive and linear formulation can then help Italian students, researchers and energy planners to evaluate future alternative low-carbon configurations of the Italian energy system.

In the next future more end-use energy demands (e.g. navigation, aviation), investment costs for mobility and energy conversion technologies can be added to the proposed framework. Clearly this will increase the computational time, but also the accuracy of the modeling results. Moreover, accounting for uncertainties is important in long term energy planning. Data about costs and energy demand can be different than the considered ones since their actual trend is likely to deviate from hypothesis assumed. With an uncertainty analysis it will be then possible to determine which are the most affecting parameters and which are the best configurations of the Italian energy system if demands and costs change in order to avoid wrong strategic energy planning decisions.

Appendix A

Italian Energy System data

All the resources and energy conversion technologies represented in Figure 2.3 are characterised in this Appendix in terms of energy and mass balances within the national energy system's boundaries, cost (operating and investment), and environmental impact through either Global Warming Potential (GWP) or operating CO_2 emissions from fuel combustion. For GHG emissions, the GWP related with the construction of each technology is assesed with the "GWP100a - IPCC2013" indicator as reported in [152]. For technologies, the GWP indicator accounts for the technology construction; for resources, only operating CO_2 emissions from fuel combustion are considered, in order to make possible a comparison with available data from ISPRA [99].

For the cost, the reported data are the nominal values for Italy in the year 2030, unless otherwise indicated. All costs are expressed in real Euro (€) for the year 2015 ($_{2015}$). All cost data originally expressed in other currencies (e.g. Swiss Francs in the Energyscope TD model [111]) or referring to another year are converted to €$_{2015}$ to offer a coherent comparison. The method used for the conversion is reported by Eq. A.1.

$$c_{inv}[EURO_{2015}] = c_{inv}[C_y] \cdot \frac{USD_y}{C_y} \cdot \frac{CEPCI_{2015}[USD_{2015}]}{CEPCI_y[USD_y]} \cdot \frac{EURO_{2015}}{USD_{2015}} \quad \text{(A.1)}$$

Where C and y are the currency and the related year in which the original cost data are expressed, respectively, USD is the symbol of the American Dollars and the Chemical Engineering's Plant Cost Index (CEPCI) [69] is a particular index considering the evolution of the equipment cost. Although this conversion method was originally defined for technology-related costs, in this work it is applied also for the cost of resources as a simplification [152].

Generally, in this thesis the same cost data used in previous works with the Energyscope model [152, 111] are assumed for energy conversion technologies unless otherwise indicated, while for imported resources new costs related with the Italian energy system are considered.

A.1 Energy Demand

The Italian EUD for heating, cooling, electricity and mobility in 2015 and 2030 showed in this section is the result of the collection and elaboration of data from several available sources. Some assumptions have been made in order to represent a simplified yet complete configuration of the Italian energy system and make it suitable for validation and scenarios assessment with the *Italy Energyscope* model.

A.1.1 Heating and Cooling

2015

The EUD for heating and cooling in Italian households, industries and services in 2015 is calculated based on the data provided by the "Heat Roadmap Europe" [74], further post-processed according to Eurostat indications [75]. The energy profiles also show which types of resources (e.g. electricity, fuels, etc..) are used to supply the demand in each sector.

Table A.2 reports input data for final energy consumption and the resulting values for the heating and cooling EUDs. The calculation of the end-use demand starts from the FEC data by type of heat usage, available in [74]. The average efficiencies assumed for each type of end-use technology in order to pass from FEC to EUD are shown in Table A.1.

Table A.1: Average efficiency/COP of different technology categories used to supply heating and cooling demand in Italy in 2015 [74].

	Efficiency [%]	**COP [-]**
Households Boilers	73	
Services Boilers	83	
Industries Boilers (LT heat)	87	
Industries Boilers (HT heat)	73	
Elec. Direct Heating (LT heat)	89	
Elec. Direct Heating (HT heat)	83	
Decentralised HPs		2.6
Elec. Space Cooling		2.4
Elec. Process Cooling		2.0

The reported FEC values are the sum of the fuel consumption in boilers, the electricity consumption for direct electric heating/cooling and for HPs, the ambient heat used by the latter and the contribution provided by renewable energy sources (e.g. solar thermal). Thus, the EUD for heating accounts for the heat supplied by the heat pumps (equal to the sum of the ambient heat and their electricity consumption assuming a coefficient of performance (COP) of 2.6, the heat provided by direct electric heating system (equal to their electricity consumption), the heat supplied by RES and by traditional boilers. The EUD for cooling is assumed entirely covered by electric cooling system (e.g. refrigeration cycles). Since in the Energyscope model formulation there is a clear distinction between low temperature (LT) and high temperature (HT) heating/cooling EUD a further classification is necessary. Thus, LT heat includes the energy demand for space heating and hot water while

HT heat includes the EUD for process heating. In the same way, LT cold considers cold for process cooling in industries and services while HT cold takes into account only space cooling demand. The yearly shares of process heating and cooling are considered constant, while space heating (SH) and space cooling (SC) demands are shared over the year according to $\%_{heating}$ and $\%_{cooling}$, whose monthly distribution is reported in Table A.3.

2030

The EUD for heating and cooling in Italian households, industries and services in 2030 is calculated based on the projections provided by the "Heat Roadmap Europe 2050" [16]. Neither heating nor cooling demand are assumed for farming. The resulting trends provide help to understand how heat and cold are going to be used and in which sector they will be relevant in the next future after additional decarbonization efforts.

Table A.4 reports the percentage variation of heat and cold end-use demand for each type of category with respect to 2015 values. So, the sectoral EUD in 2030 are obtained starting from 2015 values considering the forecast relative variation. As an example, space cooling demand in households in 2030 is expected to be 95 TWh as a result of the increase (+30.4%) of the 2015 demand (72.8 TWh). In this context, the higher energy demand for hot water is tied to the assumed growth of the Italian population and the hypotheses concerning the evolution of the number of people per family, provided by the European Commission [137]. The heat demand related with space heating is expected to reduce due to residential houses renovation and better performances of new buildings in line with the Italian Action Plan for Energy Efficiency (PAEE) [65]. At the same time, the energy demand for summer cooling is assumed to grow both due to the increased number of families and under the hypothesis of a larger diffusion of cooling technologies due to the expected higher outdoor temperatures. Regarding heat and cold energy demand for processes, the increase of the EUD is tied to the economic and industrial development of the Country.

A.1.2 Electricity

2015

The values listed in Table A.5 represent the electricity demand in Italy in 2015 that is not related to heating for the three sectors considered previously (i.e. households, services and industry) plus agriculture. The overall electricity demand is taken from "Consumi", Tab. 36 in [160] while for lighting demand refer to from Fig. 1 in [20]. The aggregated monthly distribution of electricity demand for lighting ($\%_{lighting}$) is assumed equal to the Swiss one proposed by Limpens et al. [111], reported in Table A.3.

2030

The values listed in Table A.6 represent the projected electricity demand in Italy in 2030 that is not related to heating for the three sectors previously considered (i.e. households, services and industry) plus agriculture, according to the scenarios

Table A.2: FEC and EUD in the household, industry and service sectors. Abbreviations: Low Temperature (LT), High temperature (HT).

			Heat Roadmap Italy [74]		
	EUD type	**Technology/Source**	**Households** [GWh/y]	**Industry** [GWh/y]	**Services** [GWh/y]
FEC	Space heating		280089	29541	78313
	Space cooling		10935	4839	10867
	Hot water		43643	0	11596
	Process heating		0	172449	5883
	Process cooling		0	10442	10867
FEC[a]	Space heating	Fuels	266535	28579	74433
		RES	650	138	3018
		Elec. heat pumps	8340	0	795
		Ambient heat	22118	0	1451
		Elec. direct heating	4563	823	68
	Space cooling	Fuels	0	0	0
		RES	0	0	0
		Elec. heat pumps	0	0	0
		Ambient heat	22471	12098	38263
		Elec. direct heating	10935	4839	14717
	Hot water	Fuels	31111	0	10901
		RES	1004	0	559
		Elec. heat pumps	1144	0	125
		Ambient heat	3033	236	
		Elec. direct heating	10384	0	10
	Process heating	Fuels	0	15855	0
		RES	0	0	0
		Elec. heat pumps	0	0	0
		Ambient heat	0	0	0
		Elec. direct heating	0	13894	5883
	Process cooling	Fuels	0	0	0
		RES	0	0	0
		Elec. heat pumps	0	0	0
		Ambient heat	0	21182	21734
		Elec. direct heating	0	10442	10866
EUD[a]	Space heating		226273	26001	67873
	Space cooling		22471	12098	38263
	Hot water		37861	0	10588
	Process heating		0	124043	5255
	Process cooling		0	21182	21734
EUD[a]	Heat LT		264134	26001	78461
	Heat HT		0	124043	5255
	Cold LT		0	21182	21734
	Cold HT		22471	12098	38263

[a]Calculated values.

Table A.3: Aggregated monthly distribution factors for SH demand ($\%_{heating}$), for SC ($\%_{cooling}$) and for electricity demand for lighting ($\%_{lighting}$).

	Yearly share (adding up to 1) of space heating and lighting [-]											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
$\%_{heating}$	0.211	0.193	0.131	0.063	0.010	0.000	0.000	0.000	0.008	0.051	0.131	0.200
$\%_{cooling}$	0.000	0.000	0.000	0.004	0.049	0.156	0.406	0.279	0.100	0.005	0.001	0.000
$\%_{lighting}$	0.091	0.081	0.089	0.079	0.081	0.079	0.078	0.080	0.082	0.084	0.086	0.089

Table A.4: Variation of EUD for heat and cold in each category of end use type [16, 74]. Abbreviations: temperature (T), space heating (SC).

EUD Type of Category	**End-use Demand**		
	2015 [TWh]	2030 [TWh]	Variation [%]
Low T Heat (Hot Water)	48.4	52	7.3
Low T Heat (SH)	320.1	304.0	-5.0
Process Heat	129.3	150	16.0
Space Cooling	72.8	95.0	30.4
Process Cooling	42.9	49	14.2

Table A.5: Electricity demand not related to heating by sector in 2015.

	Lighting [GWh]	**Others** [GWh]
Households	9266	21555
Services	25784	33873
Industry	11013	81350
Agriculture	569	5120

of development elaborated by Terna S.p.a, from Table 19 in [88]. The expected increased electricity demand not related to heating, especially in households, is tied to the higher number of families while for the other sectors is mainly due to the overall economic development of the Country.

Table A.6: Italian electricity demand not related to heating by sector in 2030.

	Lighting [GWh]	**Others** [GWh]
Households	10066	23416
Services	27664	36305
Industry	11169	82506
Agriculture	500	4500

A.1.3 Mobility

2015

The annual passenger transport demand in Italy for 2015 is estimated to be 879.8e09 passenger-kilometers (pkms), from Tab. 7.4 in [17]: only private transports (cars and motorcycles) and public transports on road and on rail are considered. Neither navigation nor aviation are included. The Energyscope TD further divides passenger transport demand in public and private transport. The share ($\%_{public}$) of public transport is roughly 19% of the annual passenger transport demand, from Table 2.3.3 in [59].

The annual freight transport demand in Italy for 2015 is estimated to be 148.8e09 tkms from table 7.1 in [17]. This is shared between road (trucks) and rail (train) freight transport: the share of freight trains ($\%_{rail}$) is 14% of the total annual freight transport demand, from Table 2.2.3 in [59]. So, regarding the modal split of Italian freight transport on land in 2015, road freight transport using trucks is predominant, bringing to relevant emissions and transportation issues (e.g. traffic, security).

Table A.7 indicates the hourly passenger transport demand share. Due to the lack of consistent data for the Italian case, hourly time series for private and public mobility are assumed to be equal to the ones proposed for the Swiss case in [111], derived from [118]. Furthermore, hourly time series for freight mobility are assumed to be constant over the whole year.

Table A.7: Hourly passenger transport demand share.

	Hourly passenger transportation demand ($\%_{pass}$)[a][%]											
	1	2	3	4	5	6	7	8	9	10	11	12
a.m.	0.21	0.09	0.04	0.51	1.37	3.43	6.65	5.79	5.36	6.00	6.86	7.55
p.m.	6.86	6.95	7.80	8.15	8.15	6.00	4.29	3.22	2.14	1.37	0.86	0.34

[a] Data from Figure 12 of [118]

2030

The annual passenger transport demand in Italy for 2030 is expected to be 978.e09 passenger-kilometers (pkms). Starting from the 2015 values previously reported, the relative variation of passenger mobility demand for 2030 derives from Appendix 2 in [13] under the voice "Italy". The trend of increase with respect to 2015 will be mainly due to a supposed rise of the Italian population and the related number of vehicles, as stated in [17]. The share of public transports ($\%_{public}$) in 2030 is projected to be in between 19% and 35% of the total annual passenger transport demand [59], where the lower value is obtained from 2015 calculations and the upper one is a realistic assumption. Focusing on private mobility, Colbertaldo et al. [125] report two different trends of evolution of the Italian car fleet by 2030 (see Table A.8) proposed by the European Commission (EC) and by the International Energy Agency (IEA), respectively. Both the projections show an increase penetration of efficient and less pollutant innovative electric and plug-in vehicles, more pronounced in the IEA scenario.

The hourly passenger transport demand share in 2030 is assumed to be the same as 2015.

Table A.8: Mobility forecasts data of the Italian car fleet in 2030. Adapted from Colbertaldo et al. [125]

	Share of vehicles		
	Today 2015	**EC forecasts** 2030	**IEA forecasts** 2030
Gasoline car	49.71%	28.33%	41.73%
Diesel car	41.96%	41.44%	25.18%
NG-LPG[a] car	8.09%	15.73%	4.32%
HEV[b] (Gasoline)	0.22%	5.13%	8.63%
HEV[c] (Diesel)	0.01%	5.54%	5.04%
PHEV[d] car	0.01%	2.60%	9.36%
BEV[e] car	-	1.00%	3.60%
FC[f] car	-	0.24%	2.16%

[a]Natural Gas (NG) or Liquefied Petroleum Gas (LPG).
[b]Hybrid Electic Vehicle (HEV) fueled with gasoline.
[c]Hybrid Electic Vehicle (HEV) fueled with diesel.
[d]Plug-in hybrid Electric Vehicle (PHEV).
[e]Battery Electric Vehicle (BEV).
[f]Fuel Cell (FC).

The annual freight transport demand in Italy for 2030 is expected to be 178.2e09 tkms. Starting from the 2015 values previously reported, the relative variation of freight mobility demand for 2030 derives from Appendix 2 in [13] under the voice "Italy". In this framework, the share for the use of freight trains ($\%_{rail}$) in 2030 is projected to be in between 14% and 30% of the annual freight transport demand. Regarding the modal split of Italian freight transport on land in 2030, road freight transport using trucks will still be predominant. However, as a consequence of European directives and national policies, the share of trains for freight mobility is set to increase [8].

A.2 Electricity production and storage

A.2.1 Renewables

Data for the renewable electricity production technologies considered in the Energyscope TD formulation are listed in Table A.9. With respect to previous formulations of Energyscope, the *Italy Energyscope* model includes the following new renewable technologies: offshore wind, CSP, low-enthalpy geothermal, wave energy, internal combustion engines fueled with biogas or bioliquid, biomass steam cycle and waste incinerator. Furthermore, in this modeling framework hydro capacity is not split in already-installed and new capacity as it is in [152, 111] due to the lack of precise data for the Italian energy system.

As described in Section 2.2, for seasonal renewables the capacity factor $c_{p,t}$ is defined for each time period (Table A.10). In Table A.9, the yearly capacity factor (c_p) is reported. For these technologies, the relation between $c_{p,t}$ and c_p is expressed by Eq. A.2.

$$c_{p,t} = \frac{c_p \cdot 365 \cdot dist_t}{days_t} \tag{A.2}$$

In which $dist_t$ is the share of electricity production in period t (summing up to 1) and $days_t$ is the number of days in month t. The hourly values are aggregated per month and reported in Table A.10. For all the other electricity supply technologies (renewable and non-renewable) with a uniform monthly distribution, $c_{p,t}$ is equal to the default value of 1.

Table A.11 reports the regional maximum installable capacity (f_{max}) for each RES considered in the three-regions *Italy Energyscope* formulation proposed in Sec. 3.1.1. f_{max} values are regionally calculated starting from national data in Table A.9, scaling them according to the regional production share of each technology in 2015 from [144]. As an example, the share of PV electricity production in the North in 2015 was equal to 44% so the f_{max} of PV in the North is assumed to be 48.44 GW, or 44% of 110.2 GW.

A.2.2 Non-renewable electricity supply technologies

Data for the fossil electricity production technologies considered in the Energyscope TD model are listed in Table A.12. With respect to previous formulations of Energyscope, the *Italy Energyscope* model includes the following new non-renewable technologies: internal combustion engines working in a non-cogenerative mode fueled with natural gas and light fuel oil. The maximum installed capacity (f_{max}) is set to a value high enough for each technology to potentially cover the entire regional demand singularly. Thus, 100 GW_e is assumed for the North, 55 GW_e for the Centre and 66 GW_e for the South, taking as reference the power capacity regionally installed in the *ITA30-P2* scenario of high electrification developed in 3.2. For CCS technology, a 90% capture rate is assumed.

A.2.3 Seasonal storage

The Energyscope TD modeling framework presents a seasonal storage for electricity, consisting in the production of synthetic methane from the excess of electricity

Table A.9: Renewable electricity production technologies in the Italian energy system [160, 144]. Input values are adapted from Moret [152], unless otherwise indicated.

	f_{ref} [GW]	c_{inv} [€$_{2015}$/kW$_e$]	c_{maint} [€$_{2015}$/kW$_e$/y]	gwp_{constr} [kgCO$_2$-eq./kW$_e$]	Lifetime [y]	c_p [%]	f_{min} [GW]	f_{max} [GW]
Solar PV	3.00e-06	936.5	14.9	2081	25	14.0[a]	0	110.2[b]
Onshore Wind	3.00e-03	1372	21.4	622.9	20	19.2[c]	0	49.1[d]
Offshore Wind	9.00e-03	2418[e]	72[e]	685.2[f]	30	40[g]	0	1.5[h]
Hydro Dam[i]	11.99	4521	22.6	1693	40	23.4	11.99[j]	11.99[j]
Hydro River & poundage[i]	3.80	5045	50.5	1263	40	48.4	10.07[j]	10.2 [j]
Geothermal[k]	30e-03	3868	77	2.493e01	30	85	0	0.9[l]
Geothermal ORC[m]	7.6e-03	10735	435.5	2.493e01	30	86	0	2[n]
CSP[o]	50e-03	3191[p]	15[p]	-	25	40	0	0.3[q]
Wave Energy	30e-03	4308[p]	195[p]	-	20	28	0	0.3[q]
ICE Biogas[r]	1e-03	2901[p]	184[p]	-	20	91	0	10
ICE Bioliquid[s]	1e-03	1209[p]	164[p]	-	20	85	0	10
Biomass Steam Cycle[t]	5e-03	4642[p]	97[p]	-	22	63	0	10
Waste Incinerator[u]	10e-03	4207	357	-	20	84	0	10

[a] Cumulated PV installed capacity in Italy reached 18.89 GW in 2017. In the same year the overall PV production has been 22.94 TWh [144]. Considering that the Italian avarage value of utilization in 2015 was 1225 hours [144], the average capacity factor was 14.0.

[b] The solar photovoltaic maximum theoretical potential is evaluated from the available roofs and façades surface of buildings, considering the average irradiation (i.e. the value in central Italy, 1854.2 kWh/m^{2}y), a reference average module efficiency (19.7%), and an average system performance ratio (80%). From [125].

[c] The avarage value of utilization of Italian onshore wind turbines in 2015 was 1683 hours [144]. The resulting average capacity factor was 19.2.

[d] Only onshore wind turbines are considered. From [125].

[e] Investment and O&M costs are reported from [137].

[f] A 10% increase of emissions related to construction is assumed for offshore wind turbines with respect to onshore ones.

[g] This values is assumed considering the structure and configuration of the Italian coastline based on assumptions provided by [105].

[h] Realistic assumption.

[i] Hydro-power plants are defined according to Entso-e classification [128]. Depending on the period required to fill a reservoir, hydro power plants are defined as follows: poundage (between 2 and 400 hours) and dam (more than 400 hours).

[j] Data from Terna [160].

[k] Traditional 20-30 MW geothermal power plant in 2030.

[l] Buonasorte et al. [33] estimate the traditional low enthalpy geothermal potential in Italy.

[m] ORC cycle at 6 km depth for electricity production.

[n] Buonasorte et al. [33] estimate the theoretical geothermal ORC potential in Italy.

[o] Concentrated Solar Power plant in 2030.

[p] Technical and economic parameters for renewable power technologies not present in the previous Energyscope formulations are provided by Tab. 14 in [137].

[q] Since the penetration of innovative RES such as CSP and anergy from waves is really difficult to predict due to the tight relationship with incentives and technical development [155], 0.3 GW has been assumed for both as the maximum installable capacity by 2030.

[r] Biogas fueled internal combustion engine with a 39% electrical efficiency in 2030. For 2015 model validation a 37% efficiency is considered [137].

[s] Internal combustion engine fueled with bioliquid (especially palm oil in 2015 [144]) have a 45% electrical efficiency in 2030 [7]. For 2015 model validation a 42% electrical efficiency is assumed.

[t] Steam cycles fueled with solid biomass with a 26% electrical efficiency in 2030 [137].

[u] 10 MW municipal solid waste incinerator with a 30% electrical efficiency in 2030 [137]. For 2015 model validation a 26% efficiency in considered.

Table A.10: Aggregated monthly electricity production share from established renewable energy sources in Italy in 2015.

	Monthly electricity production share ($dist_t$) [-]											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Solar PV[a]	0.050	0.057	0.084	0.103	0.112	0.117	0.122	0.112	0.096	0.060	0.047	0.040
Wind[a]	0.136	0.105	0.136	0.093	0.078	0.059	0.049	0.049	0.091	0.092	0.075	0.037
Hydro Dam[b]	0.073	0.083	0.069	0.076	0.094	0.107	0.132	0.087	0.082	0.082	0.069	0.044
Hydro River[b]	0.071	0.069	0.074	0.089	0.125	0.118	0.099	0.084	0.081	0.087	0.059	0.043

[a] Italian production profiles for electricity generation is obtained considering an average among six macro-regions time series (North, Centre-North, Centre-South, South, Siciliy and Sardinia). Data from online Terna database [151].

[b] Data for hydro-power time series provided by Entso-e [70].

Table A.11: Regional maximum capacity for each RES considered in the three-regions *Italy Energyscope* model formulation.

	f_{max} [GW]		
RES	North	Centre	South
PV	48.4	29.6	31.9
CSP	0	0	0.3[a]
Onshore Wind	0.6	11.4	36.9
Offshore Wind	0	0	1.5[b]
Wave	0	0	0.3[a]
Hydro Dam	8.4	1.9	1.6
Hydro River	7.9	1.0	1.2
Geothermal	0	0.9	0
Geothermal ORC[c]	0	1	1

[a]It is assumed that the eventual development of CSP and of wave energy would be possible only in the South of Italy for geographical and climatic reasons.

[b]The technical potential of off-shore wind turbines is limited by the structure of the Italian coastline [125]. Data assumed from [162].

[c]The geothermal ORC potential is assumed to be 1 GW both in the Centre and in the South of Italy according to the geothermal maps in Fig. 7 in [33].

Table A.12: Non-renewable electricity supply technologies present in the *Italy Energyscope* model. Input values are adapted from Moret [152], unless otherwise indicated. Abbreviations: Combined Cycle gas Turbine (CCGT), Carbon Capture and Storage (CCS), Ultra-Supercritical (US), Integrated Gasification Combined Cycle (IGCC).

	f_{ref} [GW]	c_{inv} [€$_{2015}$/kW$_e$]	c_{maint} [€$_{2015}$/kW$_e$/y]	gwp_{constr} [kgCO$_2$-eq./kW$_e$]	**Lifetime** [y]	c_p [%]	η_e [%]
CCGT	0.5	772	19.7	183.8	25	85.0	58[a]
CCGT CCS	0.5	1192	30.2		25	85.0	53[b]
U-S Coal	0.5	2517	29.7	331.6	35	86.8	40[c]
U-S Coal CCS	0.5	4052	63.29		35	86.8	31[d]
IGCC	0.5	3246	48.9		35	85.6	54
IGCC CCS	0.5	5661	69.2		35	85.6	48
ICE NG[e]	1e-03	850[f]	10.33[f]	-	20	85	44[f]
ICE LFO[g]	1e-03	850[h]	10.33[h]	-	20	85	44[f]

[a]Zanetta [79] reports that efficiency of Italian CCGT power plants in 2015 was 54% but in the future they could theoretically pass 63%. So, for 2015 model validation an electrical efficiency of 54% is assumed while for 2030 scenarios assessment a 58% efficiency is considered as a good trade-off.

[b]CCGT with post-combustion CCS in 2025 will reportedly have a 58% efficiency (very optimistic scenario)[24]. Since Italian efficiency is assumed to be quite lower, a 53% efficiency is adopted in this work.

[c]Senneca et al. [141] indicates that efficiency of Italian US coal power plants in 2015 was 34.74% but in the future they could pass 43%. So, for 2015 model evaluation an electrical efficiency of 35% is assumed while for 2030 scenarios evaluation a 39% efficiency is considered as a good trade-off.

[d]Pulverized coal with post-combustion CCS will reportedly have a 42% efficiency in 2025 (realistic optimistic scenario) [24]. Since Italian efficiency is assumed to be quite lower, a 32% efficiency is adopted.

[e]Internal combustion engine NG system operating in a non-cogenerative mode.

[f] 1 MW$_e$ natural gas fueled internal combustion engine [71].

[g]Internal combustion engine LFO system operating in a non-cogenerative mode.

[h] 1 MW$_e$ internal combustion engine fueled with LFO is assumed to be equivalent to a 1 MW$_e$ internal combustion NG engine [71].

through the so-called power-to-gas technology [67]. This synthetic methane is then used for producing electricity during periods of deficit in electricity supply. The seasonal storage modeled is based on the liquified CH_4-CO_2 system presented by Al-musleh et al. [119] and carefully described by Moret [152] for Energyscope applications.

A.2.4 Electricity grid

Since the replacement cost for the Italian electricity grid is not available in literature, the related investment cost is estimated on roughly 500 billions €$_{2015}$ and its lifetime is 80 years. This value comes from an approximate proportion starting from the dimensions and the replacement cost of the Swiss grid, estimated in 80 billions CHF$_{2015}$ by Moret [152] for the Energyscope implementation.

Furthermore, the Italian electricity grid will need additional investments depending on the penetration level of decentralised and stochastic electricity production technologies especially after the coal phase-out planned for 2025 [155]. The needed investments are expected to be 16 B€$_{2015}$ for improving grid capacity and flexibility, from Fig. 43 in [88]. The lifetime of these additional investments is assumed to be 80 years.

A.3 Heating, cooling and cogeneration technologies

Table A.13, Table A.14 and Table A.15 list the industrial, centralised and decentralised technologies for heat generation implemented in Energyscope TD, respectively. In some cases, it is assumed that industrial (Table A.13) and centralised (Table A.14) technologies are the same. With respect to previous formulations of Energyscope, the *Italy Energyscope* model additionally includes coal boiler for centralized heating generating. Furthermore, Table A.16 lists the new technologies available in *Italy Energyscope* able to provide cold for industrial/services processes and for space cooling.

Regional f_{min} and f_{max} for heating and CHP technologies are 0 and 220 GW$_{\text{th}}$, respectively. The latter value is high enough for each technology to supply the entire heat demand in its layer. Thus, for heating and cogeneration technologies the maximum and minimum shares are controlled in the model by $f_{min,\%}$ and $f_{max,\%}$, respectively.

For the DHN, the specific investment cost for network realization (c_{inv}) is estimeted in 825.9 €$_{2015}$/kW$_{\text{th}}$. This value is adapted from the value proposed by Moret [152] for the Swiss case considering a full load hours of 1535 per year. The lifetime of the DHN is expected to be 60 years [152]. The lower ($\%_{dhn,min}$) and upper bounds ($\%_{dhn,max}$) for the use of the DHN in 2030 are assumed to be 3% and 22% of the annual low temperature heat demand, respectively. The latter is a theoretical value that could be reached if all the low temperature end-use heat demand in every Northern Italian city with more than 15000 inhabitants (where DHNs are economically feasible for climatic reasons, data from [102, 50]) would be satisfied only by centralised heating technologies. However, MISE [158] indicates that the current Italian DHN has a 30% residual capacity with respect to the 2015 installed size.

Table A.13: Industrial heating and cogeneration technologies present in the *Italy Energyscope* model. Input values are adapted from Moret [152], unless otherwise indicated.

	f_{ref} [MW]	c_{inv} [€$_{2015}$/kW$_{th}$]	c_{maint} [€$_{2015}$/kW$_{th}$/y]	gwp_{constr} [kgCO$_2$-eq./kW$_{th}$]	Lifetime [y]	c_p [%]	η_e [%]	η_{th} [%]	$f_{min,\%}$ [%]	$f_{max,\%}$ [%]
CHP NG	20	1408[a]	92.6[a]	1024.3	20	85	44	46	0	50
CHP Wood[b]	20	1081	40.5	165.3	25	85	18	53	0	100
CHP Waste	20	2928	111.3	647.8	25	85	20	45	0	50
Boiler NG	10	58.9	1.18	12.3	17	95	0	80[c]	0	80
Boiler Wood[d]	10	115	2.2	28.9	17	90	0	85[e]	0	100
Boiler Oil	10	54.9	1.18[f]	12.3	17	95	0	80[f]	0	50
Boiler Coal	1	115.18[g]	2.3[g]	48.2	17	90	0	80[f]	0	20
Boiler Waste	1	115.18[g]	2.3[g]	28.9[g]	17	90	0	80[f]	0	100
Direct Elec.	0.1	332.36[h]	1.51[h]	1.47	15	95	0	100	0[i]	100

[a] Calculated as the average of investment costs for 50 kW$_e$ and 100 kW$_e$ internal combustion engine cogeneration systems [71].

[b] Biomass cogeneration plant (medium size) in 2030-2035.

[c] According to [74], the Italian average efficiency of NG boilers for process heat was 75% in 2015. This value is used for Model validation in Subsection 2.3. For 2030 scenarios evaluation a 5% increase of efficiency is assumed taking into account NES 2017 [155] suggests an overall increase of efficiency for heat technologies.

[d] Biomass boilers for process heat fueled with wood and other solid-liquid biomasses (biogas, bioliquids) described by [74] are assimilated to an industrial wood boiler.

[e] According to [74], the Italian average efficiency of biomass boilers for process heat was 85% in 2015. This value is used for Model validation in Subsection 2.3 and for 2030 scenarios evaluation since no significant efficiency increase is assumed for next years [152].

[f] Assumed to be equivalent to a NG boiler.

[g] Assumed to be equivalent to a wood boiler.

[h] Industrial large direct electric heating.

[i] According to [74], the Italian average efficiency of direct electric heaters for process heat was 61% in 2015. This value is used for Model validation in Subsection 2.3. For 2030 scenarios evaluation a 5% increase of efficiency is assumed taking into account NES 2017 [155] suggests an overall increase of efficiency for heat technologies.

Table A.14: District heating technologies present in the *Italy Energyscope* model. Input values are adapted from Moret [152], unless otherwise indicated.

	f_{ref} [MW]	c_{inv} [€$_{2015}$/kW$_{th}$]	c_{maint} [€$_{2015}$/kW$_{th}$/y]	gwp_{constr} [kgCO$_2$-eq./kW$_{th}$]	Lifetime [y]	c_p [%]	η_e [%]	η_{th} [%]	$f_{min,\%}$ [%]	$f_{max,\%}$ [%]
HP	1	344.8	12	174.8	25	95	0	400	0	50
CHP NG	20	1254[a]	37.5[a]	490.9	25	85	50	40	0	60
CHP Wood[b]	20	1080.8	40.5	165.3	25	85	18	53	0	100
CHP Waste[b]	20	2928	111.3	647.8	25	85	20	45	0	50
Geothermal Deep[c]	23	1517	56.3	808.8	30	85	0	100	0	50
Geothermal LowT[d]	10	340[e]	20[f]	808.8[g]	30[g]	85[g]	0	100	0	50
Boiler Wood[b]	10	115	2.3	28.9	17	90	0	86.4	0	100
Boiler Oil[b]	10	54.9	1.18	12.3	17	95	0	87.3	0	10
Boiler Coal[h]	10	54.9	1.18	12.3	17	95	0	87.3	0	10

[a] CCGT with cogeneration [3].

[b] Assumed same technology as for industrial heat and CHP (Table A.13).

[c] Direct use of a geothermal well at 4.2 km depth.

[d] Direct use of low-enthalpy geothermal energy available on surface (dwellings depth 100-300m).

[e] Investment cost for a low enthalpy 9.98 MW$_{th}$ geothermal district heating scenario evaluation in Greece [107].

[f] Realistic assumption for lack of data.

[g] Assumed the same environmental impact as a geothermal deep district heating plant.

[h] District heating boiler fueled with coal [6] is assumed to be equivalent to a DH oil boiler.

Table A.15: Decentralised heating and cogeneration technologies present in the *Italy Energyscope* model. Input values are adapted from Moret [152], unless otherwise indicated.

	f_{ref} [MW]	c_{inv} [€$_{2015}$/kW$_{th}$]	c_{maint} [€$_{2015}$/kW$_{th}$/y]	gwp_{constr} [kgCO$_2$-eq./kW$_{th}$]	Lifetime [y]	c_p [%]	η_e [%]	η_{th} [%]	$f_{min,\%}$ [%]	$f_{max,\%}$ [%]
HP	0.01	492[a]	21[b]	164.9	18[b]	28.5[c]	0	290[d]	0	50
Thermal HP	0.01	315.7	9.5	381.9	20	28.5[c]	0	150	0	20
CHP NG[e]	0.005	1408	92.6	1024	20	28.5[c]	44	46	0	40
CHP Oil	0.01	1305.6[f]	81.9[g]	1024[h]	20	28.5[c]	39	43	0	40
FC NG	0.01	7242	144.8	2193	20	28.5[c]	58[i]	22[i]	0	20
FC H_2[j]	0.01	7242	144.8	2193	20	28.5[c]	58	22	0	20
Boiler NG	0.01	158.9	4.76	21.1	17	28.5[c]	0	83[k]	20	80
Boiler Wood	0.01	462.5	16.2	21.1[l]	17	28.5	0	63[m]	0	100
Boiler Oil	0.01	142.4	8.54	21.1	0	82[n]	10	40		
Solar Th.	0.01	719	8.09	221.2	20	9.0[o]	0	-	0	20
Direct Elec.	0.01	39.9[p]	0.18	1.47	15	28.5[c]	0	95[q]	0	30

[a] 10.9 kW$_{th}$ Belaria compact IR heat pump [138].

[b] 6 kW$_{th}$ air-water heat pump [10].

[c] 2500 h/y of operation (assumption).

[d] According to [74, 144], the Italian average Coefficient of Performance (COP) of decentralised heat pumps for space heating and hot water production was 270 in 2015. This value is used for model validation in Sec. 2.3. For 2030 scenarios evaluation a increase of COP up to 290 is assumed taking into account NES 2017 [155] suggests an overall increase of efficiency for heating technologies.

[e] Assumed same technology as for industrial CHP NG (Table A.13)

[f] Assumed to be equivalent to a 100 kW$_e$ internal combustion engine cogeneration NG system [58].

[g] Assumed to be equivalent to a 100 kW$_e$ internal combustion engine cogeneration NG system.

[h] Assuming same impact as decentralised NG CHP.

[i] Solid-oxide FC coupled with a NG turbine, values for very optimistic scenario in 2025 [14].

[j] Assumed to be equivalent to FC NG.

[k] According to [74, 144], the Italian average thermal efficiency of decentralised natural gas boilers was 78.5% in 2015. This value is used for Model validation in Subsection 2.3. For 2030 scenarios evaluation a 5% increase of efficiency is assumed taking into account NES 2017 [155] suggests an overall increase of efficiency for heat technologies.

[l] Assuming same impact as NG and oil decentralised boilers.

[m] According to [74, 144], the Italian average thermal efficiency of decentralised wood boilers was 58% in 2015. This value is used for Model validation in Subsection 2.3. For 2030 scenarios evaluation a 5% increase of efficiency is assumed taking into account NES 2017 [155] suggests an overall increase of efficiency for heat technologies.

[n] According to [74, 144], the Italian average thermal efficiency of decentralised heating oil boilers was 77% in 2015. This value is used for Model validation in Subsection 2.3. For 2030 scenarios evaluation a 5% increase of efficiency is assumed taking into account NES 2017 [155] suggests an overall increase of efficiency for heat technologies.

[o] The calculation of the capacity factor for solar thermal in Italy is related to the evaluations made by Moret [152] for the Swiss case.

[p] Resistance heaters with fan assisted air circulation in [58].

[q] According to [74, 144], the Italian average thermal efficiency of electric heaters was 90% in 2015. This value is used for Model validation in Subsection 2.3. For 2030 scenarios evaluation a 5% increase of efficiency is assumed taking into account NES 2017 [155] suggests an overall increase of efficiency for heat technologies.

Table A.16: Industrial and decentralised cooling technologies present in the *Italy Energyscope* model. Input values are adapted from Moret [152], unless otherwise indicated.

	f_{ref} [MW]	c_{inv} [€$_{2015}$/kW$_{th}$]	c_{maint} [€$_{2015}$/kW$_{th}$/y]	gwp_{constr} [kgCO$_2$-eq./kW$_{th}$]	Lifetime [y]	c_p [%]	η_e [%]	η_{th} [%]	$f_{min,\%}$ [%]	$f_{max,\%}$ [%]
HP[a]	0.1	1000	16.85	174.8	25	0.95	0	250[b]	0	100
HP[c]	0.01	492	21	164.9	18	28.5	0	290[d]	0	50
Thermal HP[c]	0.01	315.7	9.5	381.9	20	28.5	0	150	0	20

[a] 1 MW electrical HP for cooling processes, From Table 14 in [91]. From [74], the 85% of cold for processes in Italian industries and services is at a temperature between 0 °C and 15 °C, so it is assumed that all the demand can be supplied by HPs.

[b] According to [74, 144], the Italian average Coefficient of Performance (COP) of industrial heat pumps for process cooling was 200 in 2015. This value is used for Model validation in Subsection 2.3. For 2030 scenarios evaluation a increase of COP up to 230 is assumed taking into account the evolution trend proposed by [155].

[c] Same HP considered in Table A.15.

[d] According to [74, 144], the Italian average Coefficient of Performance (COP) of decentralised heat pumps for space cooling was 240 in 2015. This value is used for Model validation in Subsection 2.3. For 2030 scenarios evaluation a increase of COP up to 270 is assumed taking into account NES 2017 [155] suggests an overall increase of efficiency for cooling technologies.

Table A.17 reports the monthly distribution factors used for the calculation of solar thermal $c_{p,t}$ according to equation A.2. For all the other heat supply technologies (renewable and non-renewable), $c_{p,t}$ is equal to the default value of 1.

Table A.17: Monthly heat production share from decentralised solar thermal panels in Italy in the year 2015.

	Monthly heat production share ($dist_t$) [-]											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Solar Thermal[a]	0.012	0.027	0.065	0.109	0.155	0.163	0.158	0.144	0.077	0.058	0.020	0.013

[a] The calculation of the monthly share for solar thermal is based on the calculation performed by Limpens et al. [111]. Starting from the Swiss time series, an Italian time series has been calculated considering the yearly difference of solar thermal production between the two Countries.

A.4 Transport

In the Energyscope TD model, for transport technologies only the operating cost related with fuel consumption is considered. Investment, O&M costs and emissions associated to the construction are not accounted for due to the lack of reliable data. Furthermore, the model does not consider inland navigation and aviation of both passenger and freight. With respect to previous formulations of Energyscope, the *Italy Energyscope* model additionally includes motorcycles for private passenger mobility and farm tractor for farming mobility.

The efficiencies for passenger vehicles in 2030 (Table A.18) are calculated with a linear interpolation between the 2010 and 2050 values presented in Table 6 in [85] unless otherwise indicated. For private mobility, the average occupancy in Italy in 2030 is assumed to be 1.8 passenger/vehicle for cars and 1 passenger/vehicle for motorcycles (in 2015 an average occupancy of 1.7 passenger/vehicle for cars is reported, see Table V.1.2.4 in [17]).

The efficiency of farming machines is instead calculated considering which is the average fuel consumption per hectare for the principal Italian cultivations reported in Allegato 1 in [142], and is equal to 1844 $GWh_{fuel}/M\text{-}hectare_{cultivated}$.

The technologies available Energyscope TD for freight transport are trains and trucks. Trains are considered to be only electric. Their efficiency in 2030 is 0.068 kWh/tkm. The efficiency for freight transport by truck is 0.51 kWh/tkm based on the weighted average of the efficiencies for the vehicle mix (see Table 6 in [85]).

Table A.18: Fuel and electricity consumption for transport technologies in 2030, and minimum/maximum shares allowed in the *Italy Energyscope* model formulation.

Vehicle type	**Fuel** [kWh/pkm]	**Electricity** [kWh/pkm]	$f_{min,\%}$ [a] [%]	$f_{max,\%}$ [a] [%]
Gasoline car	0.360[b]		25	100
Diesel car	0.381[c]		25	100
NG car	0.429[d]		5	50
HEV[e]	0.220		10	30
PHEV[f]	0.156	0.040	0	30
BEV		0.095[g]	5	30
FC car	0.159		0	30
Motorcycle	0.352[h]		0	10
Tram and Trolley Bus		0.165	0	30
Diesel Bus and Coach	0.265		0	30
Diesel HEV Bus and Coach	0.183		0	30
NG Bus and Coach	0.306		0	30
FC Bus and Coach	0.225		0	20
Train		0.092	0	80
Truck	0.5126[i]		0	80

[a] Assumed values considering 2015 car fleet composition and forecasts from [125].

[b] Gasoline car efficiency is calculated as the average between the values proposed by Codina et al. [85] and Colbertaldo et al. [125]. For the 2015 model validation, an efficiency of 0.3861 kWh/pkm is considered with an average occupancy of 1.7 passenger/vehicle.

[c] For the 2015 model validation, an efficiency of 0.4032 kWh/pkm is considered with an average occupancy of 1.7 passenger/vehicle.

[d] For the 2015 model validation, an efficiency of 0.4546 kWh/pkm is considered with an average occupancy of 1.7 passenger/vehicle.

[e] Using gasoline as only fuel. For the 2015 model validation, an efficiency of 0.2325 kWh/pkm is considered with an average occupancy of 1.7 passenger/vehicle.

[f] It is assumed that electricity is used to cover 40% of the total distance and petrol to cover the remaining 60%.

[g] For the 2015 model validation, an efficiency of 0.1001 kWh/pkm is considered with an average occupancy of 1.7 passenger/vehicle.

[h] Motorcycle efficiency is calculated as an average between scooters and motorcycles fuel consumption s(gasoline) provided by [68]. The same efficiency is assumed for the 2015 model validation.

[i] For the 2015 model validation, an efficiency of 0.7394 kWh/tkm is used (see Table 6 in [85]).

A.5 Resources

With respect to previous formulations of Energyscope, the *Italy Energyscope* model excludes uranium and adds the following two new resources: biogas and biomass for electricity (i.e. bioliquid).

The availability of all the resources, except for wood, waste, biogas and biomass for electricity, considered as local and/or limited, is set to a value high enough to allow unlimited import in each region of the modeled Italian energy system. No import of hydrogen or biofuels is accounted in *Italy Energyscope* and any national production of fossil resources is not taken into account as well (i.e. fossils are assumed to be entirely imported). National availability of woody biomass is calculated in 90633 GWh/y from "Italy Sustainable Scenario" in [9] (forest wood, round-wood, forestry residues, industrial wood residues, landscape care wood), while Municipal Solid Waste (MSW) is limited to 53820 GWh. For the calculation of the national MSW availability it is considered that the 47.5% of the total production of waste (Table 2.16 in [98]) is recycled and the average LHV is assumed to be equal to 12.35 MJ/kg (from [152]). For the calculation of the biogas availability at a national scale, it is considered that the potential of biomethane supplying the NG network in 2030 is estimated to be around 8.5 Nm^3 (see Table 1 in [15]) and the average LHV is 36.1 MJ/Nm^3 from [104]. So, considering that the average efficiency of PSA technology upgrading biogas to biomethane is 85.5% [166], the resulting national availability of biogas is 99726 GWh/y. These national values are then further processed in order to be regionally defined according to the three-zones division of Sec. 3.1.1 (Table A.19): wood is scaled proportionally to its regional forest availability (see Table 2.20 in [11]), while waste and biogas are scaled according to their regional distribution of production in 2015, from Table 2.16 in [98] and from Figure 3.5.16 in [144], respectively.

Table A.19: Regional availability of local and limited resources considered in *Italy Energyscope.*

	avail [GWh]		
Resources	North	Centre	South
Wood	43436	24864	22333
Bio-gas	79781	9973	9973
Waste	25009	17934	10877
Electricity	31017[a]	0	0

[a]Maximum values of imported electricity in 2030 according to available forecasts (see Tab. 49 in [130]). Electricity imported in Italy in 2015 was equal to 63594 GWh according to model validation (see Sec. 2.3).

Table A.20 details the import price of each resource (c_{op}) and its CO_2 emission factor (gwp_{op}) from combustion according to [136]. c_{op} for imported biofuels is assumed to be equal to the price of the respective fossil equivalent. No cost is associated to the waste, as it is assumed that it should be collected anyway. Export of electricity is possible, but it is associated to a zero selling price. Regional exchanges of electricity are possible as well, but they are not associated to neither any cost nor emissions for lack of detailed data.

Table A.20: Price and CO_2 emissions of principal resources considered in the *Italy Energyscope* modeling framework.

Resources	$\boldsymbol{c_{op}}$ [€$_{2015}$/MWh$_{\text{fuel}}$]	$\boldsymbol{gwp_{op}}$ [kgCO_2-eq./MWh$_{\text{fuel}}$]
Electricity Import	83.7[a]	345[b]
Gasoline	73.8[c]	262.6[b].
Diesel	66.3[d]	265.1[b]
LFO	54.5[e]	275.8[b]
NG	26.7[f]	205.9[b]
Wood	44.5	307.2[b]
Waste[g]	0	150
Coal	13.0[h]	345.4[b]
Biogas	90.00[i]	307.2[b]
Biomass for elec.[j]	27.3[k]	307.2[b]

[a]Based on electricity traded price in Italy in the year 2015 (65 €$_{2015}$/MWh, from Figure 26 in [60]). Projected from 2010 to 2030 using a multiplication factor of 1.29 following the assumptions proposed by Moret [152].

[b]From [99].

[c]Based on oil products price without VAT and taxes for Italy in 2015 (61.9 €$_{2015}$/MWh, from [66]). Projected from 2015 to 2030 using a multiplication factor of 1.19 following the assumptions proposed by Moret [152].

[d]Based on oil products price without VAT and taxes for Italy in 2015 (55.6 €$_{2015}$/MWh, from [66]). Projected from 2015 to 2030 using a multiplication factor of 1.19 following the assumptions proposed by Moret [152].

[e]Based on oil products price without VAT and taxes for Switzerland in 2010 (45.7 €$_{2015}$/MWh, from [152]). The Italian price is considered to be the same for lack of data. Projected from 2015 to 2030 using a multiplication factor of 1.19 following the assumptions proposed by Moret [152].

[f]Average import price of NG in Italy considering estimations of border prices from Russia, Algeria, Norway, Netherlands in the whole 2015 (average of prices in the four quarters of the year is 18.5 €$_{2015}$/MWh, from Map 1 in [61]). Projected from 2015 to 2030 using a multiplication factor of 1.44 from Table 2 in [88].

[g]Renewable and non-renewable municipal solid waste (MSW).

[h]Based on coal price without VAT and taxes for Italy in 2015 (13.0 €$_{2015}$/MWh, from [66]). Projected from 2015 to 2030 using a multiplication factor of 1.17 from Table 2 in [88].

[i]From [135].

[j]The reported values are calculated for Italian imported bio-liquid.

[k]Considering average import price of palm oil in Italy in 2015 equal to 850 €/t [43]. Assuming a $LHV_{\text{palm oil}} = 36.6$ MJ/kg, the price is estimated equal to 23.2 €$_{2015}$/MWh. For 2030 the import price is assumed equal to 1000 €/t.

A.6 Storage

Tables A.21 and A.22 list the storage technologies data used in Energyscope TD. As already stated, *Italy Energyscope* does not consider thermal storage technologies due to the lack of reliable data consistent with previous formulations of Energyscope.

Table A.21: Storage technologies in Energyscope TD. Input values are adapted from Limpens et al. [111].

	f_{ref} [MW]	c_{inv} [€$_{2015}$/kW$_{th}$]	c_{maint} [€$_{2015}$/kW$_{th}$/y]	gwp_{constr} [kgCO$_2$-eq./kW$_{th}$]	**Lifetime** [y]	f_{min} [GWh]	f_{max} [GWh]
Li-on batt.[a]	1e-6	374.6	46.8	61.3	15	0	∞
PHS[b]	1	4.66	0.02	8.33	40	2000[c]	8000[d]

[a]Lithium-ion battery.
[b]Pumped Hydro Storage.
[c]Electricity (GWh) produced by PS in Italy in 2013 (minimum production during the last 20 years) [39].
[d]Electricity (GWh) produced by PS in Italy in 2002 (maximum production during the last 20 years) [39].

Table A.22: Storage technologies Technical features of storage technologies in Energyscope TD. Input values are adapted from Limpens et al. [111].

	$\eta_{sto,in}$ [-]	$\eta_{sto,out}$ [-]	$\mathbf{t_{sto,in}}$ [h]	$\mathbf{t_{sto,out}}$ [h]	$\mathbf{\%_{sto,loss}}$ [s^{-1}]	$\mathbf{\%_{sto,avail}}$ [s^{-1}]
Li-on batt.	0.95	0.95	4	4	2e-4	1
BEV batt.[a]	0.95	0.95	4	4	2e-4	0.2
PHEV batt.[a]	0.95	0.95	4	4	2e-4	0.2
PHS	0.9	0.9	203	203	0	1

[a] Other data not necessary because depending on the number of cars.

A.7 Other parameters

A.7.1 Hydrogen production

Table A.23 lists the data for the hydrogen production technologies. In the Energyscope TD model three technologies are considered for hydrogen production: electrolysis, fuel (NG) reforming and biomass gasification. The last two alternatives include CCS technology for reducing the CO_2 emissions.

A.7.2 Biomass and Biogas to synthetic fuels

In Energyscope TD two different technologies are implemented for the conversion of woody biomass to synthetic fuels: pyrolysis and gasification. The main output of the pyrolysis process is bio-oil, which is considered equivalent to fossil LFO. The main product of the gasification process is SNG, which is considered equivalent to fossil

Table A.23: Hydrogen production technologies. Data from Moret [152].

	c_{inv} [€$_{2015}$/kW$_{H2}$]	c_{maint} [€$_{2015}$/kW$_{H2}$/y]	**Lifetime** [y]	c_p [-]	η_{H2} [%]
Electrolysis	307.6	30.8	15	0.9	85
CH_4 reforming	681.3	64.4	25	0.86	73
Biomass gasification	2525.5	195.7	25	0.86	43

NG. Table A.24 reports the data characterising the aforementioned technologies. In the table, "fuel" corresponds to the main synthetic fuel given as product.

Furthermore, *Italy Energyscope* considers a new technology able to allow the injection of biomethane (considered equivalent to fossil NG) into the grid. In fact, since the biogas usually produced by anaerobic digestion processes is a mixture of methane and carbon dioxide (approximately 60 and 40% respectively), it is necessary to upgraded it to biomethane to make it suitable for a grid-injection (injection of biogas into the natural gas grid). Several technologies are available for this purpose, the most widely adopted is Pressure Swing Adsorption (PSA) [166], whose data are reported.

Table A.24: Woody biomass to synthetic fuels plus PSA conversion technologies. Data from Moret [152], unless otherwise indicated.

	c_{inv} [€$_{2015}$/kW$_{fuel}$]	c_{maint} [€$_{2015}$/kW$_{fuel}$/y]	**Lifetime** [y]	c_p [-]	η_{fuel} [%]	η_e [%]	η_{th} [%]
Pyrolysis	1344.3	67.2	25	0.85	66.6	1.58	-
Gasification	2743.9	139.9	25	0.85	74	3.15	9.01
PSA[a]	444.35[a]	64.14[a]	20[a]	0.85	0.85[a]	-	-

[a]41.5 MW Pressure Swing Adsorption (PSA) unit [166].

A.7.3 Additional cost for national improvements

The Italian energy system is set to consistently change in the next future due to the energy transition [155, 130]. Forecast modifications of the energy system will require specific investments: in particular, huge efforts will be made in order to decarbonize both the power generation (see Sec. A.2.4) and the mobility sector. In this context, a deep decarbonization of mobility is set to require up to a maximum 140 B€$_{2015}$ by 2030 (from Table 4 in [154]). Since these investments can vary with the electrification and decarbonization rate of the related 2030 scenario, they are quantified by Eq. 2.27 as described in 2.2.2. Furthermore, the energy demand reduction cost due to an overall increase of efficiency of energy conversion technologies is estimated in 130 B€$_{2015}$ (see Table 4 in [154]). Since in the *Italy Energyscope* model an efficiency improvement by 2030 is expected, this is considered as a fixed cost.

A.7.4 Other

The real discount rate for the public investor i_{rate} is fixed to 3.215%, average of the range of values used to define the corresponding uncertainty range in [152].

Losses ($\%_{loss}$) in the electricity grid are fixed to 6.4% in 2030 [88] and 6.2% in 2015 [160]. This is the ratio between the losses in the grid and the total annual electricity production in Italy in 2030 and 2015, respectively. The DHN losses are assumed to be 15% of the total centralised heat production in 2030 while for 2015 they stand for 18.5% of the centralised heat production (see Table 9 in [6]).

The input and output efficiency of each storage technologies for electricity production ($\eta_{sto,in}$ and $\eta_{sto,out}$) is defined to allow the connection between the storage itself (*StoHydro* and *Power2Gas*) and its respective layers (electricity and LNG, respectively). The efficiency is 1 for both the *StoHydro* unit, representing a "shift" in the monthly production of the dams, and the LNG storage tank, assumed to have no losses.

A.8 2015 data for model validation

This section details the data of the Italian energy system in the year 2015 used to validate the LP model formulation described in Chapter 2.

The input data necessary to replicate the Italian energy system in 2015 are: (i) the yearly EUD values in the different sectors ($endUses_{year}$) (ii) the relative annual production share of the different technologies for each type of EUD, e.g. 66.7% yearly shares of DHN low temperature heat provided by CHPs technologies for the Italian energy system in 2015; (iii) the share of public mobility ($\boldsymbol{\%_{Public}}$), train in freight ($\boldsymbol{\%_{Rail}}$) and centralised heat production ($\boldsymbol{\%_{Dhn}}$); (iv) the fuel efficiency for mobility, heating and power generation technologies.

The EUD data are listed in Table A.25, previously calculated in Sec. A.1.1; ($\boldsymbol{\%_{Public}}$), ($\boldsymbol{\%_{Rail}}$) and ($\boldsymbol{\%_{Dhn}}$) are reported in Table A.26.

Table A.25: End-uses demand in Italy ($endUses_{year}$) in 2015.

	Units	**Households**	**Services**	**Industry**	**Agriculture**	**Transportation**
Electricity (other)	[GWh]	21555	33873	81350	5120	0
Lighting	[GWh]	9266	25784	11013	569	0
Heat high T	[GWh]	0	5255	124043	0	0
Heat low T (SH)	[GWh]	226273	67873	26001	0	0
Heat low T (HW)	[GWh]	37861	10588	0	0	0
Cold process	[GWh]	0	21734	21182	0	0
Cold space	[GWh]	22471	38263	12098	0	0
Mobility passenger	[Mpkm]	0	0	0	0	879864
Mobility freight	[Mtkm]	0	0	0	0	148777
Mobility farming	[Mha]	0	0	0	8	0

The annual gross electricity production share for power technologies derives from data provided by Terna S.p.a [160] and GSE [144]. The yearly shares of mobility and heating&CHP technologies per type of EUD are reported in Tables A.29, A.30 and A.31.

For private passenger mobility (Table A.27), the repartition among the different types of vehicles available in the *Italy Energyscope* model is not estimated based on

Table A.26: ($\%_{\mathbf{Public}}$), ($\%_{\mathbf{Rail}}$) and ($\%_{\mathbf{Dhn}}$) for the Italian energy system in 2015.

	Share [%]
$\%_{\mathbf{Public}}$	19.3
$\%_{\mathbf{Rail}}$	14.0
$\%_{\mathbf{Dhn}}$	2.3

their effective number in Italy in 2015 but on the actual journeys by road. According to the data provided by ACI [2], for instance, 50% of Italian cars are fueled with gasoline but they only satisfy 30% of the global private passenger demand [82]. Plug-in hybrid vehicles (PHEV) and fuel cell cars are not present in the 2015 Italian car fleet. Natural Gas (NG) cars include both methane and liquefied petroleum gases (LPG) vehicles. Motorcycles passenger mobility data are reported in Tab. 7.4 in [17].

Table A.27: Yearly shares of private vehicles technologies for the Italian energy system in 2015 [2, 82].

	Share Mpkm [%]
Gasoline car	30.16
Diesel car	56.07
NG car	6.97
HEV	0.94
PHEV	0.00
BEV	0.09
FC car	0.00
Motorcycle	5.76

For public mobility (Table A.28), the reported values are obtained firstly considering the modal split of passenger transport on land among buses&coaches (12.2%), railways (6.2%) and tram/metro (0.8%), from Table 2.3.3 in [59]. Secondly, in order to further differentiate all the available technologies for public mobility on road, a specific report from ISTAT [101] have been consulted: in 2015 diesel buses and coaches are the most widely used (75.4%), followed by NG buses and coaches (22.5%) and diesel HEV buses (2.1%). NG buses and coaches category includes also means of transport fueled with LPG.

Regarding low and high temperature heat/cold production, the yearly shares have been calculated based on report of the Heat Roadmap Europe Website called "D 3.1: Profile of heating and cooling demand in 2015" [74], further implemented with the data provided by MISE [158] and AIRU [6] for cogeneration plants and DHNs, respectively. The efficiencies of energy conversion technologies in 2015 reported in Tables A.29, A.30 and A.31 are used.

As expected, looking at the national heat production, the largest contribution is given by natural gas, predominantly burned in boilers in order to provide both heat at low and high temperature for heating, hot water and for industrial/services processes. Furthermore, oil and coal are still present as energy sources for heat production: in particulars, coal still accounts for a relevant role in the production

Table A.28: Yearly shares of public mobility technologies for the Italian energy system in 2015 [59, 101].

	Share Mpkm [%]
Tram and Trolley Bus	4.4
Diesel Bus and Coach	47.3
Diesel HEV Bus and Coach	1.3
NG Bus and Coach	14.1
FC Bus and Coach	0.0
Train/Metro	32.9

Table A.29: Yearly shares of decentralised low temperature heat & CHP technologies for the Italian energy system in 2015 [74, 145].

	Share heat [%]
HP	8.0
Thermal HP	0.0
CHP NG	0.4
CHP Oil	0.2
FC NG	0.0
FC H_2	0.0
Boiler NG	68.2
Boiler Wood	11.7
Boiler Oil	6.4
Solar Th.	0.7
Direct Elec.	4.4

Table A.30: Yearly shares of DHN low temperature heat & CHP technologies for the Italian energy system in 2015 [74, 145, 6].

	Share heat [%]
HP	0.3
CHP NG	51.4
CHP Wood	6.3
CHP Waste	10.3
Boiler NG	22.2
Boiler Wood	6.2
Boiler Oil	0.0
Boiler Coal	0.8
Geothermal	2.5

Table A.31: Yearly shares of services and industrial high temperature process heat & CHP technologies for the Italian energy system in 2015 [74, 145].

	Share heat [%]
CHP NG	17.6
CHP Wood	0.8
CHP Waste	0.5
CHP Coal	1.5
Boiler NG	39.2
Boiler Wood	1.6
Boiler Oil	8.6
Boiler Coal	17.9
Boiler Waste	4.9
Direct Elec.	7.5

of industrial high temperature heat. Regarding the penetration of renewable energy sources such as solar thermal and biomass or the use of efficient and clean technologies (e.g. heat pumps), the reported data suggests that their role is not relevant yet. Focusing on DHN, the thermal energy produced by RES and biomass that directly supply the networks in 2015 amounts to approximately 21% [145]. Most of these networks are concentrated in the mountainous areas, where the methane networks are less developed and the availability of biomass is larger. The DHNs fed by RES are also present in Tuscany where traditional geothermal energy is exploited. Finally, the use of MSW results to be quite limited if compared to other Countries (in Switzerland it accounts for more than 70% of centralised heat production [152]).

A.9 2030 data for scenarios assessment

National EUD data are listed in Table A.32 while regional values used for scenarios evaluations are listed in Tables A.36, A.37 and A.38. Briefly, with respect to the 2015 energy system configuration described in Sec. A.8,

- the overall electricity demand is increasing due to an overall higher electrification of the energy system [88];
- low temperature heat demand for space heating and hot water is decreasing, as result of the average higher outdoor temperatures and the better performances of building envelopes [74];
- as a consequence of the previous point, space cooling demand is significantly increasing [74];
- passenger/freight mobility, heat and cold demand for processes are increasing over the next few years as a result of economic and social growth [74, 46, 59].

Starting from national EUD, the regional values are obtained considering different factors for each sector. In this context, energy end-uses demand for households has been weighed taking into account the population share of the corresponding

Table A.32: End-uses demand in Italy ($endUses_{year}$) in 2030.

	Units	Households	Services	Industry	Agriculture	Transportation
Electricity (other)	[GWh]	23416	36305	82506	5120	0
Lighting	[GWh]	10066	27664	11169	500	0
Heat high T	[GWh]	0	5255	124043	0	0
Heat low T (SH)	[GWh]	214861	64450	24689	0	0
Heat low T (HW)	[GWh]	40636	11364	0	0	0
Cold process	[GWh]	0	24815	24185	0	0
Cold space	[GWh]	29310	49909	15781	0	0
Mobility passenger	[Mpkm]	0	0	0	0	978640
Mobility freight	[Mtkm]	0	0	0	0	178217
Mobility farming	[Mha]	0	0	0	7	0

zone with respect to the national value, considered constant and equal to 2015 value (Table A.33). The same applies for transportation and services. End-uses demand for industry has been weighed taking into account the number of workers in the corresponding zone in 2015 (Table A.34). Finally, end-use demand for agriculture has been weighed considering the farming production in each area (Table A.35).

The values used to characterise the availability of resources and the capacity of RES regionally are listed in Table A.19 and A.11, respectively. Obviously, for all the other parameters used in *Italy Energyscope* which cannot be estimated or forecast such as hourly time series of RES production or energy demand, the same values as 2015 are used.

Table A.33: Italian population in 2015 in each area considered by the *Italy Energyscope* model formulation [102].

Region	Population [M-people]	Share [%]
North	27.75	45.8
Centre	19.66	32.2
South	13.35	22.0

Table A.34: Italian workers in industries in 2015 in each area considered by the *Italy Energyscope* model formulation [5].

Region	Workers [M-people]	Share [%]
North	9.37	57.5
Centre	4.89	30.0
South	2.03	12.5

Table A.35: Italian agricultural production in 2015 in each area considered by the *Italy Energyscope* model formulation (form Table 4.5 in [100]).

Region	**Production** [B€$_{2015}$]	**Share** [%]
North	25.61	51.8
Centre	11.06	22.4
South	12.78	25.8

Table A.36: End-uses demand in the North of Italy ($endUses_{year}(NO)$) in 2030.

	Units	**Households**	**Services**	**Industry**	**Agriculture**	**Transportation**
Electricity (other)	[GWh]	10713	16610	47445	2330	0
Lighting	[GWh]	4605	12656	6423	259	0
Heat high T	[GWh]	0	2404	71331	0	0
Heat low T (SH)	[GWh]	98299	29486	14198	0	0
Heat low T (HW)	[GWh]	18591	5199	0	0	0
Cold process	[GWh]	0	11353	13908	0	0
Cold space	[GWh]	13409	22834	9075	0	0
Mobility passenger	[Mpkm]	0	0	0	0	447729
Mobility freight	[Mtkm]	0	0	0	0	81534
Mobility farming	[Mha]	0	0	0	3	0

Table A.37: End-uses demand in the Centre of Italy ($endUses_{year}(CN)$) in 2030.

	Units	**Households**	**Services**	**Industry**	**Agriculture**	**Transportation**
Electricity (other)	[GWh]	7549	11704	24763	1007	0
Lighting	[GWh]	3245	8918	3352	112	0
Heat high T	[GWh]	0	1694	37229	0	0
Heat low T (SH)	[GWh]	69266	20777	7410	0	0
Heat low T (HW)	[GWh]	13100	3663	0	0	0
Cold process	[GWh]	0	8000	7259	0	0
Cold space	[GWh]	9449	16090	4736	0	0
Mobility passenger	[Mpkm]	0	0	0	0	315491
Mobility freight	[Mtkm]	0	0	0	0	57453
Mobility farming	[Mha]	0	0	0	3	0

Table A.38: End-uses demand in the South of Italy ($endUses_{year}(SO)$) in 2030.

	Units	**Households**	**Services**	**Industry**	**Agriculture**	**Transportation**
Electricity (other)	[GWh]	5154	7991	10298	1163	0
Lighting	[GWh]	2216	6089	1394	129	0
Heat high T	[GWh]	0	1157	15483	0	0
Heat low T (SH)	[GWh]	47295	14187	3082	0	0
Heat low T (HW)	[GWh]	8945	2501	0	0	0
Cold process	[GWh]	0	5462	3019	0	0
Cold space	[GWh]	6452	10986	1970	0	0
Mobility passenger	[Mpkm]	0	0	0	0	215420
Mobility freight	[Mtkm]	0	0	0	0	39229
Mobility farming	[Mha]	0	0	0	2	0

Appendix B

2030 Sankey Diagrams

Section 3.2 described how reference and policy scenarios of deep decarbonization of the 2030 Italian energy system are assessed and described. Since the *Italy Energyscope* model formulation is also able to represent Sankey diagrams of energy flows of the modeled energy system, Figures B.1, B.2, B.3, B.4 and B.5 show the energy flows resulting from the *ITA-R1*, *ITA-R2*, *ITA-R3*, *ITA-P1* and *ITA-P2* scenario, respectively. These graphical representation of the Italian energy system allow to easily show the most important resources supplied (left side), the weight of the different layers/technologies (centre) and how each end-use demand (right side) is satisfied for the modeled scenario of decarbonization.

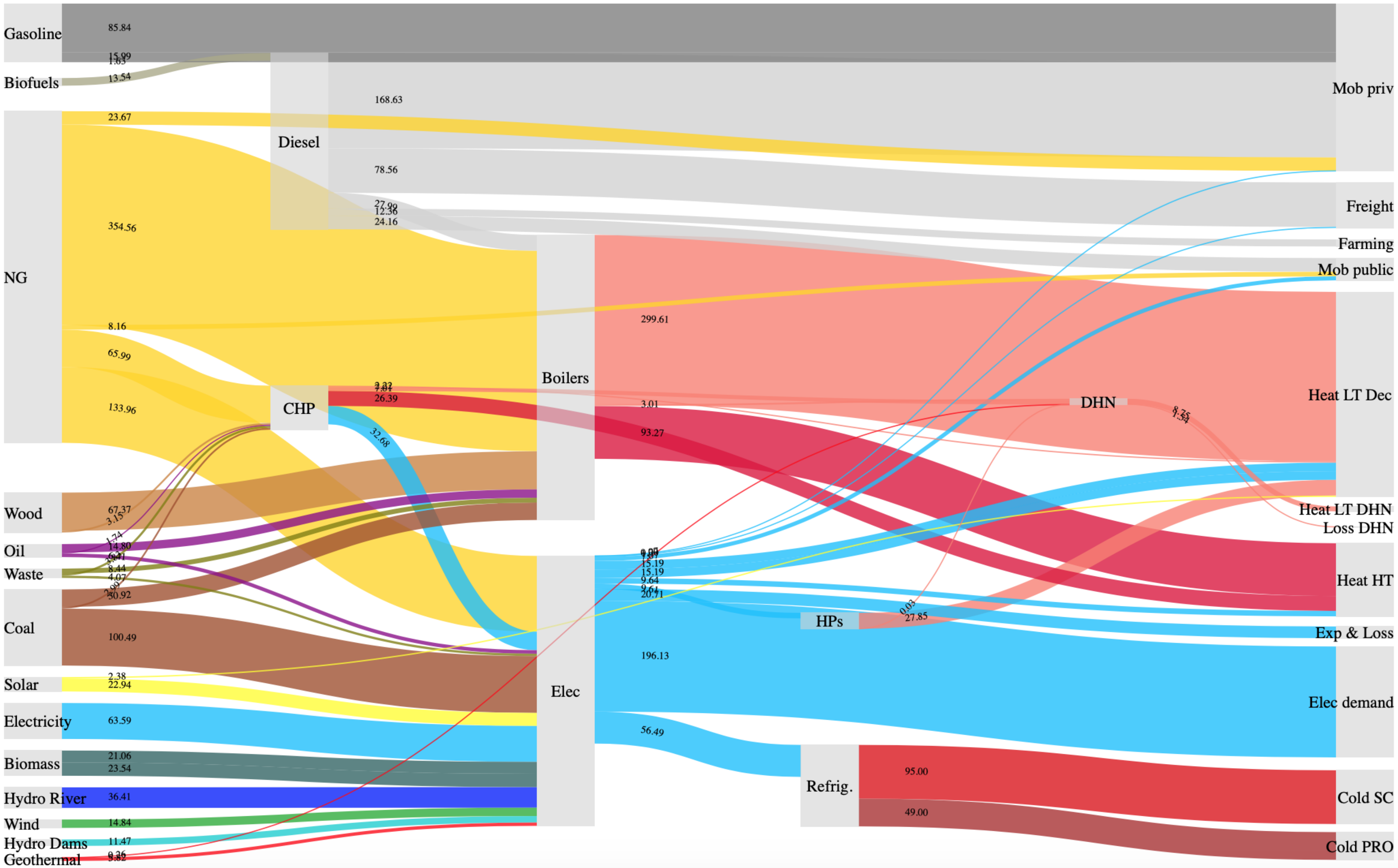


Figure B.1: Energy flows in Italy in the year 2030 according to the *ITA30-R1* scenario. All values are in TWh. The methodology used to treat the data is documented in in Appendix A.

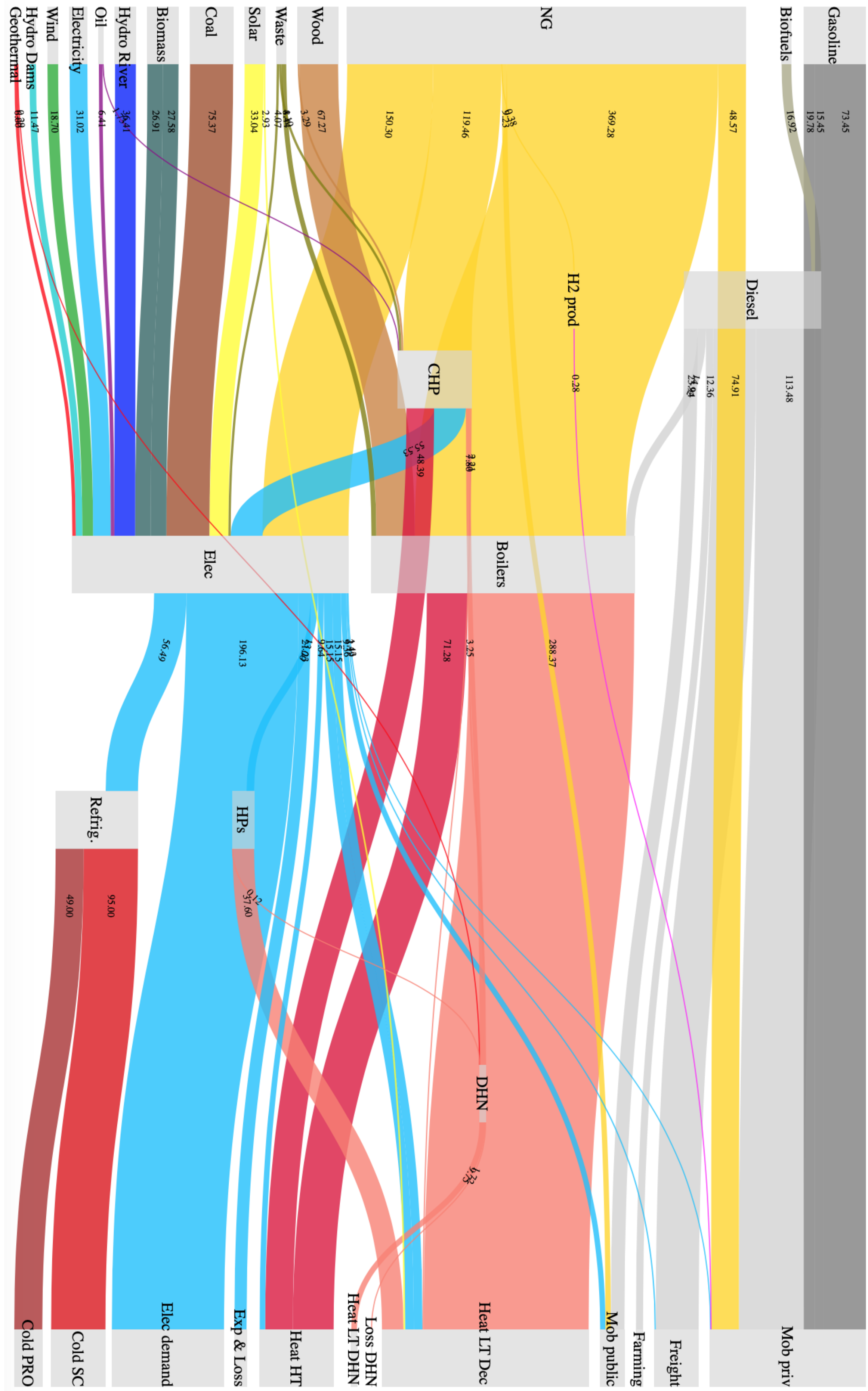


Figure B.2: Energy flows in Italy in the year 2030 according to the *ITA30-R2* scenario. All values are in TWh. The methodology used to treat the data is documented in Appendix B.

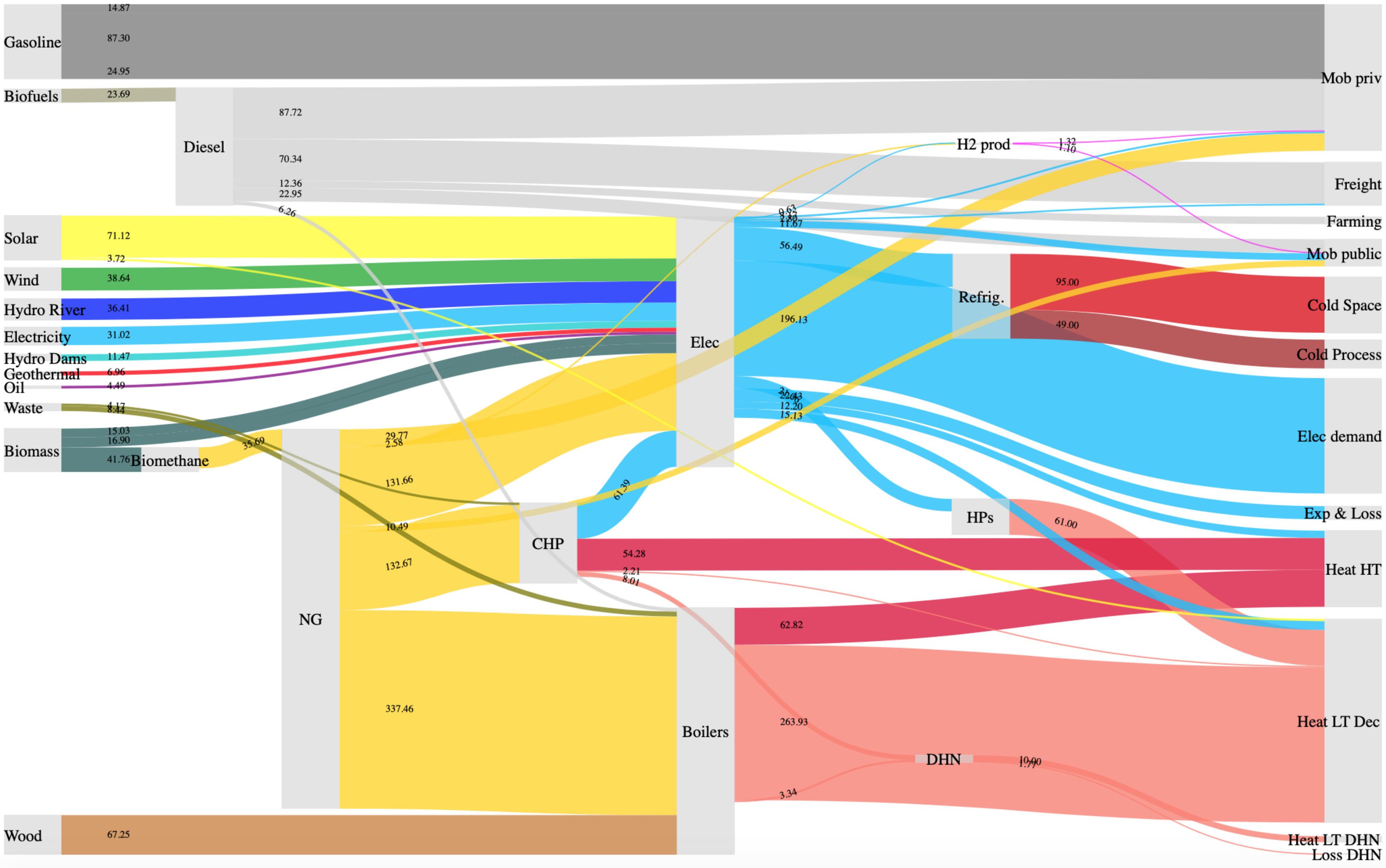


Figure B.3: Energy flows in Italy in the year 2030 according to the *ITA30-R3* scenario. All values are in TWh. The methodology used to treat the data is documented in in Appendix A.

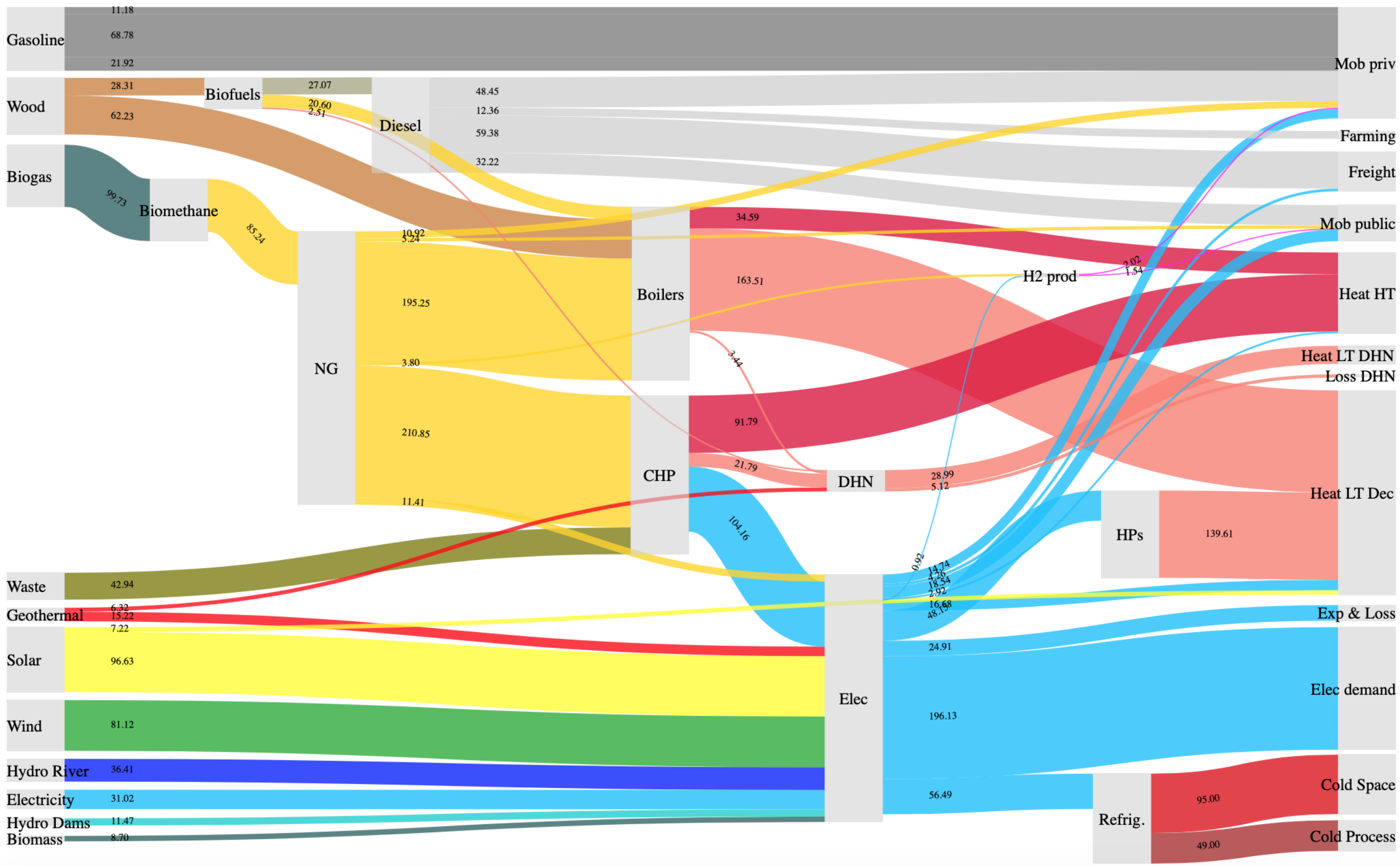


Figure B.4: Energy flows in Italy in the year 2030 according to the *ITA30-P1* scenario. All values are in TWh. The methodology used to treat the data is documented in in Appendix A.

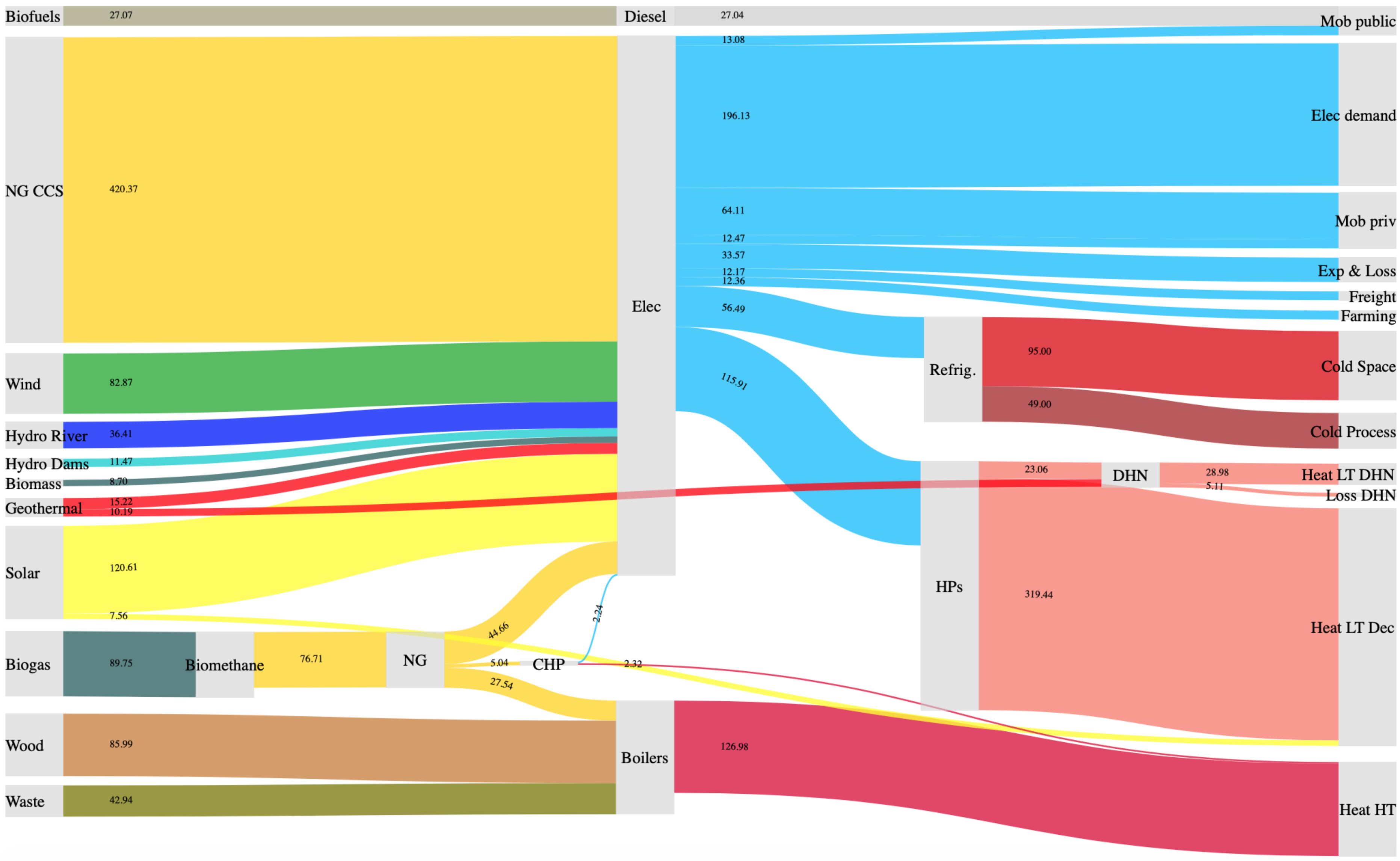


Figure B.5: Energy flows in Italy in the year 2030 according to the *ITA30-P2* scenario. All values are in TWh. The methodology used to treat the data is documented in Appendix A.

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