Deep decarbonisation of regional energy systems: a novel modelling approach and its application to the Italian energy transition

Supplementary Material

Marcello Borasio[1] and Stefano Moret[*2]

[1] *Politecnico di Torino, Torino, Italy*
[2] *Department of Analytics, Marketing & Operations, Imperial College Business School, Imperial College London, London, UK*

Contents

[*] s.moret@imperial.ac.uk

1 Italian energy system data (years 2015 and 2050)

This Section specifies all the input data needed for the application of the EnergyScope model to the Italian energy system in the years 2015 and 2050. It complements and documents the information made available in the file `Borasio_deep_2021_data.xlsx`. In this Supplementary Material, we report and document only the data strictly related with the Italian case study, while the remaning data is considered equal to the data reported in the EnergyScope model documentation [1].

1.1 Energy demand

The Italian end-use demand (EUD) for heating, cooling, electricity and mobility in 2015 and 2050 reported in this section is the result of the collection and elaboration of data from several available sources. In case of unavailable data at the desired level of detail, we detail the assumptions we additionally made.

1.1.1 Heating and Cooling

2015

The EUD for heating and cooling in Italian households, industries and services in 2015 are calculated based on the data provided by the "Heat Roadmap Europe 2050" [2], further post-processed according to Eurostat data [3]. This data additionally indicates which types of resources (e.g. electricity, fuels, etc..) are used to supply the demand in each sector.

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

Table 1: Average efficiency/COP of different categories of technologies used to supply heating and cooling demand in Italy in 2015 from [2] unless otherwise indicated.

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

[a]From [4].

The FEC values reported in Table 2 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 by renewable energy sources (e.g. solar thermal). Thus, the EUD for heating accounts for the heat supplied by heat pumps (equal to the sum of the ambient heat and their electricity consumption, assuming a coefficient of performance (COP) of 2.6), by direct electric heating, by RES and by traditional boilers. The EUD for cooling is assumed to be entirely supplied by electric cooling systems (e.g. refrigeration cycles). As the EnergyScope model formulation distinguishes between low temperature (LT) and high temperature (HT) heating/cooling EUD a further repartition is necessary: LT heat includes the energy demand for space heating and hot water production, while HT heat includes the EUD for process heating. In the same way, LT cold considers cold for process cooling in industry and services while HT cold takes into account 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 $\%_{sh}$ and $\%_{sc}$, whose monthly distribution is reported in Table 3. Hourly time series of energy demand for space heating and cooling are evaluated differently from one modelled area to another by considering the corresponding values 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 in [5]. 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 (1). The same applies for yearly CDD definition (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.

$$
\begin{aligned}
HDD = \sum_{t \in T} (T_{comf}(t) - T_{out}(t)) \quad & if \quad T_{out}(t) < 15°C \\
HDD = 0 \quad & if \quad T_{out}(t) \geq 15°C
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
CDD = \sum_{t \in T} (T_{out}(t) - T_{comf}(t)) \quad & if \quad T_{out}(t) > 24°C \\
CDD = 0 \quad & if \quad T_{out}(t) \leq 24°C
\end{aligned}
\tag{2}
$$

2050

The EUD for heating and cooling in Italian households, industries and services in 2050 is calculated based on the projections provided by the "Heat Roadmap Europe 2050" [2]. No heating/cooling demand are assumed for farming.

Table 4 reports the percentage variation of heat and cold EUD for each type of category with respect to 2015 values. In other words, the sectoral EUD in 2050 are obtained starting from 2015 values considering the forecast relative variation. As an example, space cooling demand in households in 2050 is expected to be 143.6 TWh as a result of the increase (+97.2%) 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 [6]. Space heating demand is expected to decrease due to renovation/energy efficiency measures and better performances of new buildings in line with the Italian Action Plan for Energy Efficiency (PAEE) [7]. At the same time, the energy demand for summer cooling is assumed to nearly double due to a larger diffusion of cooling technologies caused by the higher outdoor temperatures expected as a result of global warming. The increase in heat and cold energy demand for processes is tied to the expected economic and industrial development of the Country.

Table 2: FEC and EUD in the household, industry and service sectors for the year 2015 [2, 3]. Abbreviations: Low Temperature (LT), High temperature (HT)

	Heat Roadmap Italy				
	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
		Refrigeration HPs	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
		Refrigeration HPs	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 3: Aggregated monthly distribution factors for SH demand ($\%_{sh}$) and for SC ($\%_{sc}$).

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

Table 4: Variation 2015 vs 2050 of EUD for heat and cold in each category of end use type [2]. Abbreviations: temperature (T), space heating (SC).

EUD Type of Category	**End-use Demand**		
	2015 [TWh]	2050 [TWh]	Δ^{a} [%]
Low T Heat (Hot Water)	48.4	54	+11
Low T Heat (SH)	320.1	276.3	-14
Process Heat	129.3	137.6	+6
Space Cooling	72.8	143.6	+97
Process Cooling	42.9	53.0	+23

[a]Relative variation: 2050 vs 2015

1.1.2 Electricity

2015

The values listed in Table 5 represent the electricity demand in Italy in 2015 that is not related to heating for the three considered sectors (i.e. households, services and industry) plus agriculture. The overall electricity demand is taken from "Consumi", Tab. 36 in [8], while the share of lighting with respect to the overall electricity demand is taken from [9]. The aggregated monthly distribution of electricity demand for lighting ($\%_{lighting}$) is assumed equal to the Swiss one used in [1].

Table 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

2050

The values listed in Table 6 represent the projected electricity demand in Italy in 2050 not related to heating for the three considered sectors (i.e. households, services and industry) plus agriculture, according to the scenarios elaborated by Terna, from Table 19 in [10].

Table 6: Italian electricity demand not related to heating by sector in 2050.

	Lighting [GWh]	**Others** [GWh]
Households	14504	19816
Services	29008	38069
Industry	11502	84966
Agriculture	500	4500

1.1.3 Mobility

2015

The annual passenger transport demand in Italy for 2015 is estimated to be 879.8 billions passenger-kilometers (pkms), from Tab. 7.4 in [11]. Passenger transport demand is subdivided into public and private transport. Only private transport (cars and motorcycles) and public transport on road and on rail are considered. Neither maritime transport nor aviation are included. The total number of private passenger vehicles is 37.4 Mcars [12]. The share ($\%_{public}$) of public transport is 19.3% of the annual passenger transport demand, from Table 2.3.3 in [13].

The annual freight transport demand in Italy for 2015 is estimated to be 148.8 billion-tkms from table 7.1 in [11]. 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 [13]. This means that road freight transport using trucks is predominant, bringing to relevant emissions and transportation issues (e.g. road traffic, safety).

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 [1].

2050

The annual passenger transport demand in Italy for 2050 is expected to be 1060.4 billion-pkms. This is calculated starting from the 2015 values and taking the relative variation of passenger mobility demand for 2050 from Appendix 2 in [14] (under the voice "Italy"). The increase with respect to 2015 is mainly due to an expected increase of the Italian population and the related number of vehicles, as stated in [11]. The share of public transport ($\%_{public}$) in 2050 is projected to be between 25% and 40% of the total annual passenger transport demand [13], where the lower and the upper values are our assumptions. The hourly passenger transport demand distribution in 2050 is assumed to be the same as in 2015.

The annual freight transport demand in Italy for 2050 is expected to be 204.2 billion tkms. This is calculated starting from the 2015 values and taking the relative variation of freight mobility demand for 2050 from Appendix 2 in [14] (under the voice "Italy"). In this context, the share for the use of freight trains ($\%_{rail}$) in 2050 is projected to be in between 22% and 100% (assumption) of the annual freight transport demand In the modal split of Italian freight transport on land in 2050, road freight transport using trucks will likely still be predominant. However, as a consequence of European directives and national policies, the share of trains for freight mobility could largely increase [15]: for this reason, in the scenario of deep decarbonisation the share of trains for freight is assumed to potentially increase up to 100%.

1.1.4 Summary tables: energy demand in 2015 and 2050

Table 7 and Table 8 report the EUD data for the year 2015 and 2050, respectively, calculated based on the assumptions and sources reported in the previous sections.

Table 7: 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

Table 8: End-uses demand in Italy ($endUses_{year}$) in 2050.

	Units	**Households**	**Services**	**Industry**	**Agriculture**	**Transportation**
Electricity (other)	[GWh]	19816	38069	84966	4500	0
Lighting	[GWh]	14504	29008	11502	500	0
Heat high T	[GWh]	0	5572	131528	0	0
Heat low T (SH)	[GWh]	195283	58577	22440	0	0
Heat low T (HW)	[GWh]	42199	11801	0	0	0
Cold process	[GWh]	0	26841	26159	0	0
Cold space	[GWh]	44304	75442	23854	0	0
Mobility passenger	[Mpkm]	0	0	0	0	1060365
Mobility freight	[Mtkm]	0	0	0	0	204285
Mobility farming	[Mha]	0	0	0	6.7	0

Regionalisation of demand in 2050

National EUD data for the year 2050 are listed in Table 8. Starting from national EUD, the regional values are obtained considering different factors for each sector. End-use demand for households has been weighed based on the share of the population living in the different regions, assumed to be equal in 2015 and 2050 [16]. The same applies for transportation and services. Industrial demand has been weighed based on the number of workers in the different regions in 2015 [17]. Finally, end-use demand for agriculture has been weighed considering the farming production in each area [18].

1.2 Technologies

1.2.1 Electricity production

Renewables

Data for the renewable electricity production technologies considered in the regionalised EnergyScope formulation are listed in Table 9. With respect to previous formulations of EnergyScope, the model includes the following new renewable technologies: offshore wind, CSP,

Table 9: Renewable electricity production technologies in the Italian energy system in 2050. Input values are adapted from Limpens et al. [1], unless otherwise indicated.

	f_{ref} [GW]	c_{inv} [€$_{2015}$/kW$_e$]	c_{maint} [€$_{2015}$/kW$_e$/y]	**Lifetime** [y]	c_p [%]	f_{min} [GW]	f_{max} [GW]
Solar PV	3.00e-06	560[a]	7.39[b]	30	17.0[c]	0	110[d]
Onshore Wind	3.00e-03	930[e]	21.4	25	30[f]	0	49[g]
Offshore Wind	9.00e-03	1500[h]	28.95[i]	30	38[j]	0	1.5[k]
Hydro Dam[l]	11.99	4521	22.6	40	12	11.9[m]	12.6[n]
Hydro River & pondage[l]	3.80	5045	50.5	40	44	10.2[m]	10.7[n]
Geothermal[o]	30e-03	3868	77	30	85	0	1[p]
Geothermal ORC[q]	7.6e-03	10735	435.5	30	86	0	0.9[r]
CSP[s]	50e-03	3191[t]	15[t]	25	40	0	0.3[u]
Wave Energy	30e-03	4308[t]	195[t]	20	28	0	0.3[u]
ICE Biogas[v]	1e-03	2901[t]	184[t]	20	91	0	100
ICE Bioliquid[w]	1e-03	1209[t]	164[t]	20	85	0	100
Biomass Steam Cycle[x]	5e-03	4642[t]	97[t]	22	63	0	100
Waste Incinerator[y]	10e-03	4207	357	20	84	0	100

[a] From [19]. 936.5€ in 2015 according to Limpens et al. [1].

[b] From [19]. 14.9€ in 2015 according to Limpens et al. [1].

[c] For 2050, an average capacity factor of 17% is estimated from [6]. Cumulated PV installed capacity in Italy reached 18.89 GW in 2015. In the same year the overall PV production has been 22.94 TWh [4]. Considering that the Italian average utilisation in 2015 was 1225 hours [4], the average capacity factor was 14%

[d] From Colbertaldo et al. [20].

[e] From [19]. 1372€ in 2015 according to Limpens et al. [1].

[f] For 2050, an average capacity factor of 30% is estimated from [6]. The utilisation of Italian onshore wind turbines in 2015 was 1683 hours [4]. The resulting average capacity factor was 19.2%

[g] Only onshore wind turbines are considered. From Colbertaldo et al. [20].

[h] Data from [19], while for the 2015 validation a cost of 2418 €$_{2015}$/kW$_e$ is reported from [6].

[i] Data from [19] while for the 2015 validation a cost of 72€$_{2015}$/kW$_e$/y is reported from [6].

[j] This value is assumed considering the structure and configuration of the Italian coastline based on assumptions provided by [21].

[k] Assumption.

[l] Hydro-power plants are defined according to the Entso-E classification [22]. Depending on the amount of time required to fill a reservoir, hydropower plants are defined as follows: *pondage* (between 2 and 400 hours) and *dam* (more than 400 hours).

[m] Data from Terna [8].

[n] A 5% increase is assumed according to available forecasts [14].

[o] Traditional 20-30 MW geothermal power plant in 2050.

[p] From Buonasorte et al. [23].

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

[r] Assumption.

[s] Concentrated Solar Power plant.

[t] Technical and economic parameters for renewable power technologies not present in the previous Energyscope formulations are provided by Tab. 14 in [6].

[u] Since the penetration of innovative RES such as CSP and wave energy is difficult to predict due to the dependency on incentives and technical development [24], 0.3 GW has been assumed for both as the maximum installable capacity by 2050.

[v] Biogas-fuelled internal combustion engine with a 39% electrical efficiency in 2050. For the 2015 validation a 37% efficiency is considered [6].

[w] Internal combustion engine fuelled with bioliquid (especially palm oil in 2015 [4]) have a 45% electrical efficiency in 2050 [25]. For the 2015 validation a 42% electrical efficiency is assumed.

[x] Steam cycles fuelled with solid biomass with a 26% electrical efficiency in 2050 [6].

[y] 10 MW municipal solid waste incinerator with a 30% electrical efficiency in 2050 [6]. For the 2015 validation a 26% efficiency in considered.

low-enthalpy geothermal, wave energy, internal combustion engines fuelled with biogas or bioliquid, biomass steam cycle and waste incinerator.

For seasonal renewables, a capacity factor $c_{p,t}$ is defined for each time period (Table 10). In Table 9, the yearly capacity factor (c_p) is reported. The hourly values are aggregated per month and reported in Table 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 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 [8].
[b] Data for hydro-power time series provided by Entso-e [22].

Table 11 (also reported in the main manuscript) reports the regional maximum installable capacity (f_{max}) for each RES considered in the regionalised EnergyScope formulation applied to the Italian case study. f_{max} values are regionally calculated starting from national data in Table 9, scaling them according to the regional production share of each technology in 2015 from [4]. 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.

Non-renewable electricity supply technologies

Data for the fossil electricity production technologies considered in the regionalised EnergyScope model are listed in Table 12. With respect to previous formulations of EnergyScope, the regionalised model includes the following new non-renewable technologies: internal combustion engines working in a non-cogenerative mode fuelled 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 (i.e. 100 GW). For CCS technology, a 90% capture rate is assumed. In particular, the maximum available installable capacity of CCS technologies combined with gas and coal power plants in Italy is estimated to be 6 GW and 4.5 GW, respectively, in 2050 by Virdis [26].

Power-to-gas

The regionalised EnergyScope modelling framework considers the same power-to-gas seasonal storage technology described in Limpens et al. [1], consisting in the production of synthetic methane from excess of electricity.

Electricity grid

Since the total investment cost for the Italian electricity grid could not be found, it is estimated to be 500 billions €$_{2015}$ with a 80-year lifetime. This value comes from an approximate propor-

Table 11: Regional maximum capacity in 2050 for each RES considered in the regionalised EnergyScope model formulation.

RES	f_{max} [GW] 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
New Hydro Dam	0.4	0.1	0.1
Hydro River	7.9	1.0	1.2
New Hydro River	0.4	0.05	0.06
Geothermal	0	1.0[c]	0
Geothermal ORC[d]	0.3	0.3	0.3

[a]It is assumed that the 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 [20]. Data assumed from [21].

[c]The traditional geothermal potential is assumed to be 1 GW in the Centre of Italy according to the geothermal maps in Fig. 7 in [23].

[d]The geothermal ORC potential is assumed to be 0.3 GW in each region of Italy according to the geothermal maps in Fig. 7 in [23].

Table 12: Non-renewable electricity supply technologies present in the *Italy Energyscope* model. Input values are adapted from Limpens et al. [1], 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]	**Lifetime** [y]	c_p [%]	η_e [%]
CCGT	0.5	772	19.7	25	85.0	63[a]
CCGT CCS	0.5	1192	30.2	25	85.0	57[b]
U-S Coal	0.5	2517	29.7	35	86.8	43[c]
U-S Coal CCS	0.5	4052	63.29	35	86.8	35[d]
ICE NG[e]	1e-03	850[f]	10.33[f]	20	91[g]	44[f]
ICE LFO[h]	1e-03	850[i]	10.33[i]	20	88	44[f]

[a]Zanetta [27] reports that the efficiency of Italian CCGT power plants in 2015 was 54%, but in the future it could theoretically be higher than 63%. So, for the 2015 validation an electrical efficiency of 54% is assumed.

[b]CCGT with post-combustion CCS in 2025 will reportedly have a 57% efficiency (very optimistic scenario)[28].

[c]Senneca and Zanetta [29] indicate that the efficiency of Italian US coal power plants in 2015 was 34.74% but in the future it could be higher than 43%. So, for the 2015 evaluation an electrical efficiency of 35% is assumed.

[d]Pulverized coal with post-combustion CCS will reportedly have a 42% efficiency in 2025 (realistic optimistic scenario) [28]. Since the Italian efficiency is assumed to be lower, a 35% efficiency is adopted.

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

[f]1 MW$_e$ natural gas fuelled internal combustion engine [30].

[g]Same as ICE Biogas.

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

[i] 1 MW$_e$ internal combustion engine fueled with LFO is assumed to be equivalent to a 1 MW$_e$ internal combustion NG engine [30].

tion based on the dimensions and the total investment cost of the Swiss grid, estimated in 80 billions CHF_{2015} by Moret [31] for the EnergyScope implementation to the Swiss case study.

In the context of the energy transition, 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 [24]. The needed investments are expected to be 16 billion$€_{2015}$ for improving grid capacity and flexibility due to coal phase-out, from Fig. 43 in [10], plus about 20B$€_{2015}$ for grid reinforcement due to additional high RES penetration (our assumption). The lifetime of these additional investments is assumed to be 35 years.

1.2.2 Heating, cooling and cogeneration technologies

Table 13, Table 14 and Table 15 list the industrial, centralised and decentralised heat production technologies implemented in the regionalised EnergyScope model, respectively. In some cases, it is assumed that industrial (Table 13) and centralised (Table 14) technologies are the same. With respect to previous formulations of EnergyScope, the regionalised model additionally includes coal boilers for centralised heat production. Table 16 lists the new technologies available 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_{th}, respectively. The latter value is high enough for each technology to supply the entire heating and cooling demand in its layer. Thus, for heating, cooling and cogeneration technologies the maximum and minimum shares are controlled in the model by $f_{min,\%}$ and $f_{max,\%}$, respectively. In this context, $f_{min,\%}$ and $f_{max,\%}$ are set to 0 and 100, respectively, in order to let each technology free to evolve towards a deep decarbonized scenario, unless otherwise indicated.

For the DHN, the specific investment cost (c_{inv}) is estimated to be 825.9 $€_{2015}/kW_{th}$. This value is adapted from the value proposed by Limpens et al. [1] for the Swiss case considering a full load hours of 1535 per year and a lifetime of 60 years. The regional lower ($\%_{dhn,min}$) and upper bounds ($\%_{dhn,max}$) for the use of the DHN in Italy for 2050 are assumed to be 15% and 48% of the annual low temperature heat demand in the North, 2% and 57% in the Centre, respectively. The South is not considered suitable to DHN due to climatic reasons. The values for $\%_{dhn,min}$ are based on the actual 2015 DHN penetration rate; the values of $\%_{dhn,max}$ represent the maximum penetration that could be reached if all the low temperature heat EUD in every Northern and Centre Italian city with more than 15000 inhabitants (where DHNs are economically feasible, data from [16]) was to be satisfied only by centralised heating technologies.

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

1.2.3 Transport

For transport technologies, only the operating costs associated with fuel consumption are considered. Investment, O&M costs and emissions associated to the construction are not accounted for due to the difficulty in finding consistent data. Furthermore, the model does not consider maritime and air transport of both passengers and freight. With respect to previous formulations, the regionalised EnergyScope model additionally includes motorcycles for private passenger mobility and farm tractor for farming mobility.

The efficiencies for passenger vehicles in 2050 (Table 18) are provided in [20] unless otherwise indicated. For private mobility, the average occupancy in Italy in 2050 is assumed to

Table 13: Industrial heating and cogeneration technologies in the regionalised EnergyScope model. Input values are adapted from Limpens et al. [1], unless otherwise indicated. The indicated values for 2015 are used for model demonstration in Appendix B.1 (main article).

	f_{ref} [MW]	c_{inv} [€$_{2015}$/kW$_{\mathrm{th}}$]	c_{maint} [€$_{2015}$/kW$_{\mathrm{th}}$/y]	Lifetime [y]	c_p [%]	η_e [%]	η_{th} [%]	$f_{min,\%}$ [%]	$f_{max,\%}$ [%]
CHP NG	20	1408	92.6	20	85	44	46	0	100
CHP Wood	20	1081	40.5	25	85	18	53	0	0[a]
CHP Waste	20	2928	111.3	25	85	20	45	0	0[a]
Boiler NG	10	58.9	1.18	17	95	0	93[b]	0	100
Boiler Wood[c]	10	115.18	2.2	17	90	0	86[d]	0	0[a]
Boiler Oil	10	54.9	1.18[e]	17	95	0	87[f]	0	100
Boiler Coal	1	115.18[g]	2.3[g]	17	90	0	82[h]	0	100
Boiler Waste	1	115.18[g]	2.3[g]	17	90	0	82[i]	0	100
Direct Elec.	0.1	332.36[j]	1.51[j]	15	95	0	100[k]	0	100

[a] Some technologies are phased-out for industrial heat production in order to account for a more efficient and rational use of local available resources such as wood and waste.

[b] According to [2], the Italian average efficiency of NG boilers for process heat was 75% in 2015.

[c] Biomass boilers for process heat fuelled with wood and other solid-liquid biomasses (biogas, bioliquids) described by [2] are consider equivalent to an industrial wood boiler.

[d] According to [2], the Italian average efficiency of biomass boilers for process heat was 85% in 2015.

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

[f] According to [2], the Italian average efficiency of LFO boilers for process heat was 75% in 2015.

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

[h] According to [2], the Italian average efficiency of Coal boilers for process heat was 75% in 2015.

[i] According to [2], the Italian average efficiency of Waste boilers for process heat was 75% in 2015.

[j] Industrial large direct electric heating.

[k] According to [2], the Italian average efficiency of direct electric heaters for process heat was 61% in 2015.

Table 14: District heating technologies in the regionalised EnergyScope model. Input values are adapted from Limpens et al. [1], unless otherwise indicated. The indicated values for 2015 are used for model demonstration in Appendix B.1 (main article).

	f_{ref} [MW]	c_{inv} [€$_{2015}$/kW$_{\mathrm{th}}$]	c_{maint} [€$_{2015}$/kW$_{\mathrm{th}}$/y]	Lifetime [y]	c_p [%]	η_e [%]	η_{th} [%]	$f_{min,\%}$ [%]	$f_{max,\%}$ [%]
HP	1	344.8	12	25	95	0	400	0	100
CHP NG	20	1254	37.5	25	85	50	40	0	100
CHP Wood	20	1080.8	40.5	25	85	18	53	0	0[a]
CHP Waste	20	2928	111.3	25	85	20	45	0	100
Geothermal Deep	23	1517	56.3	30	85	0	100	0	20[b]
Geothermal LowT[c]	10	340[d]	20[e]	30[f]	85[f]	0	100	0	100
Boiler Wood	10	115	2.3	17	90	0	86.4	0	100
Boiler Oil	10	54.9	1.18	17	95	0	87.3	0	100
Boiler Coal[g]	10	115.18	2.3	17	95	0	82	0	100

[a] CHP plants fuelled with wood are phased-out for centralised heat production in order to promote a more efficient and rational use of wood.

[b] Due to the lack of reliable data for high enthalpy geothermal in centralised heat production, a 20% maximum penetration is assumed.

[c] Direct use of low-enthalpy geothermal energy (dwellings depth: 100-300m).

[d] Investment cost for a low enthalpy 9.98 MW$_{\mathrm{th}}$ geothermal district heating scenario evaluation in Greece [32].

[e] Assumption.

[f] Assumed to be equal to deep geothermal

[g] District heating boiler fuelled with coal [33] is assumed to be equivalent to an industrial coal boiler.

Table 15: Decentralised heating and cogeneration technologies present in the regionalised EnergyScope model. Input values are adapted from Limpens et al. [1], unless otherwise indicated. The indicated values for 2015 are used for model demonstration in Appendix B.1 (main article).

	f_{ref} [MW]	c_{inv} [€$_{2015}$/kW$_{\text{th}}$]	c_{maint} [€$_{2015}$/kW$_{\text{th}}$/y]	**Lifetime** [y]	c_p [%]	η_e [%]	η_{th} [%]	$f_{min,\%}$ [%]	$f_{max,\%}$ [%]
HP	0.01	492	21	18	28.5	0	400[a]	0	100
Thermal HP	0.01	315.7	9.5	20	28.5	0	150	0	100
CHP NG	0.005	1408	92.6	20	28.5	44	46	0	100
CHP Oil	0.01	1305.6	81.9	20	28.5	39	43	0	100
FC NG	0.01	7242	144.8	20	28.5	58	22	0	100
FC H_2	0.01	7242	144.8	20	28.5	58	22	0	100
Boiler NG	0.01	158.9	4.76	17	28.5	0	90[b]	20	100
Boiler Wood	0.01	462.5	16.2	17	28.5	0	85[c]	0	10[d]
Boiler Oil	0.01	142.4	8.54	0	85[e]	0	85	0	100
Solar Th.	0.01	719	8.09	20	9.0[f]	0	100	0	25[g]
Direct Elec.	0.01	39.9	0.18	15	28.5	0	100[h]	0	100

[a]According to [2, 4], the Italian average Coefficient of Performance (COP) of decentralised heat pumps for space heating and hot water production was 2.6 in 2015.

[b]The Italian average thermal efficiency of decentralised natural gas boilers was 78.5% in 2015 [2].

[c]The Italian average thermal efficiency of decentralised wood boilers was 58% in 2015 [2].

[d]Realistic assumption considering a lower and lower use of wood for traditional combustion.

[e]The Italian average thermal efficiency of decentralised heating oil boilers was 77% in 2015 [2].

[f]The calculation of the capacity factor for solar thermal in Italy is related to the evaluations made by [1] for the Swiss case.

[g]Assumption in line with other decarbonisation studies for the Italian energy system [26, 14].

[h]The Italian average thermal efficiency of electric heaters was 89% in 2015 [2].

Table 16: Industrial and decentralised cooling technologies in the regionalised EnergyScope model. Input values are adapted from Limpens et al. [1], unless otherwise indicated. The indicated values for 2015 are used for model demonstration in Appendix B.1 (main article).

	f_{ref} [MW]	c_{inv} [€$_{2015}$/kW$_{\text{th}}$]	c_{maint} [€$_{2015}$/kW$_{\text{th}}$/y]	**Lifetime** [y]	c_p [%]	η_e [%]	η_{th} [%]	$f_{min,\%}$ [%]	$f_{max,\%}$ [%]
HP[a]	0.1	1000	16.85	25	0.95	0	285[b]	0	100
HP[c]	0.01	492	21	18	28.5	0	400[d]	0	100
Thermal HP[c]	0.01	315.7	9.5	20	28.5	0	150	0	100

[a]1 MW electrical HP for cooling processes, From Table 14 in [34]. From [2], 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 [2, 4], the Italian average Coefficient of Performance (COP) of industrial heat pumps for process cooling was 200 in 2015.

[c]Same HP considered in Table 15.

[d]According to [2, 4], the Italian average Coefficient of Performance (COP) of decentralised heat pumps for space cooling was 2.50 in 2015.

Table 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. [1]. 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.

be 2 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 [11]).

The efficiency of farming machines is instead calculated considering the average fuel consumption per hectare for the principal Italian cultivations reported in Allegato 1 in [35], and is equal to 1844 $\text{GWh}_{\text{fuel}}/\text{M-hectare}_{\text{cultivated}}$.

The technologies available in EnergyScope for freight transport are trains and trucks. Trains are considered to be only electric. Their efficiency for 2015 and 2050 is 0.088 and 0.068 kWh/tkm, respectively, from Limpens et al. [1]. The efficiency for freight transport by truck in 2050 is 0.423 kWh/tkm (0.686 kWh/tkm in 2015) based on the weighted average of the efficiencies for the vehicle mix (see Table 6 in [36]).

1.3 Resources

With respect to previous formulations of EnergyScope, the regionalised framework includes the following two new resources: biogas and bioliquid (which includes also the so-called other liquid/solid biomass in [38, 4]).

The availability of all the resources – except for wood, waste, biogas and bioliquid, which are considered local and/or limited – is set to a value high enough to allow unlimited import in each region of the modelled Italian energy system (uranium is set to zero due to national policies regarding nuclear energy). No import of hydrogen or biofuels is accounted for and fossils are assumed to be entirely imported. National availability of woody biomass is calculated in 90633 GWh/y from "Italy Sustainable Scenario" in [39] (forest wood, round-wood, forestry residues, industrial wood residues, landscape care wood), while Municipal Solid Waste (MSW) is limited to 53829 GWh/y. 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 [40]) is recycled and the average LHV is assumed to be equal to 12.35 MJ/kg (from [31]). 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 GNm^3 (see Table 1 in [41]) and the average LHV is 36.1 MJ/Nm^3 from [42]. Considering that the average efficiency of PSA technology upgrading biogas to biomethane is 85.5% [43], the resulting national availability of biogas is 99726 GWh/y, assuming the same potential of 2030 for 2050. National availability of bioliquid is considered to remain the same as in 2015, estimated to be 11012 TWh [4]. These national values are then further processed in order to be regionally defined (Table 19): wood is scaled proportionally to its regional forest availability (see Table 2.20 in [44]), while waste, biogas and bioliquid are scaled according to their regional distribution of production in 2015, from Table 2.16 in [40] and from [4], respectively. Finally, national availability of biodiesel is calculated to be 23690 GWh according to [4, 24], regionally subdivided according to the regional population in 2015.

Table 20 details the import price of each resource (c_{op}) and its CO_2 emission factor (gwp_{op}) from combustion according to [46]. c_{op} for imported biofuels is assumed to be equal to the price

Table 18: Fuel and electricity consumption for transport technologies in 2050, and minimum/maximum shares allowed in the regionalised EnergyScope model formulation. All values from Colbertaldo et al. [20] unless otherwise indicated.

Vehicle type	**Fuel** [kWh/pkm]	**Electricity** [kWh/pkm]	$f_{min,\%}$ [a] [%]	$f_{max,\%}$ [a] [%]
Gasoline car	0.324[b]		0	100
Diesel car	0.375[c]		0	100
NG car	0.72[d]		0	100
HEV[e]	0.250[f]		0	100
PHEV	0.180[g]	0.040	0	100
BEV		0.100[h]	0	100
FC car	0.125[i]		0	100
Motorcycle	0.352[j]		5	10
Tram and Trolley Bus		0.165	5	10
Diesel Bus and Coach	0.265		0	100
Diesel HEV Bus and Coach	0.183		0	100
NG Bus and Coach	0.306		0	100
FC Bus and Coach	0.225		0	100
Train		0.092	30	45

[a] In order to let the model to evolve towards a deep decarbonisation scenario, all private passenger technologies are set free to evolve between 0 and 100% while for public ones realistic values are assumed.

[b] For the 2015 validation, an efficiency of 0.3861 kWh/pkm is calculated as an average between the values proposed by Colbertaldo et al. [20] and Codina Gironès et al. [36].

[c] For the 2015 validation, an efficiency of 0.4032 kWh/pkm is considered, from [36].

[d] For the 2015 validation, an efficiency of 0.847 kWh/pkm is considered.

[e] Using gasoline as the only fuel.

[f] For the 2015 validation, an efficiency of 0.2325 kWh/pkm is considered.

[g] For the 2015 validation, an efficiency of 0.2588 kWh/pkm is considered.

[h] For the 2015 validation, an efficiency of 0.1412 kWh/pkm is considered.

[i] For the 2015 validation, an efficiency of 0.1706 kWh/pkm is considered.

[j] Motorcycle efficiency is calculated as an average between scooters and motorcycles fuel consumption (gasoline) provided by [37]. The same efficiency is assumed for the 2015 validation.

Table 19: Regional availability of local and limited resources considered in the regionalised EnergyScope model.

	avail [GWh]		
Resources	North	Centre	South
Wood	43436	24864	22333
Biogas	79781	9973	9973
Waste	25009	17934	10877
Biodiesel	10850	7628	5212
Electricity	31017[a]	0	0
Bioliquid	3823	1198	5991

[a] Maximum values of imported electricity in 2030 according to available forecasts (see Tab. 49 in [45]). Electricity imported in Italy in 2015 was equal to 63594 GWh according to model demonstration (Appendix B.1 in the main article).

of the respective fossil equivalent. No cost is associated to 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 additional cost nor emissions for lack of detailed data. The biomass fraction of MSW is deduced as the 50% of total energy content, as indicated in [4].

Table 20: Price and CO_2 emissions of principal resources considered in the regionalized EnergyScope model.

Resources	c_{op} [$€_{2015}$/MWh$_{\text{fuel}}$]	gwp_{op} [kgCO_2-eq./MWh$_{\text{fuel}}$]
Electricity Import	104.0[a]	0.0[b]
Gasoline	139.3[c]	249.0[b].
Diesel	125.1[d]	267.0[b]
LFO	101.3[e]	275.0[b]
NG	30.9[f]	202.0[b]
Wood	66.8[g]	0.0[b]
Waste[h]	0.0	125
Coal	27.3[i]	346.0[b]
Biogas	85.00[j]	0.0[b]
Bioliquid[k]	34.2[l]	0.0[b]

[a]Based on electricity traded price in Italy in the year 2015 (65 $€_{2015}$/MWh, from Figure 26 in [47]). Projected from 2010 to 2050 using a multiplication factor of 1.6 (assumption).

[b] From [46].

[c]Based on oil products price without VAT and taxes for Italy in 2015 (61.9 $€_{2015}$/MWh, from [48]). Projected from 2015 to 2050 using a multiplication factor of 2.25 (assumption)

[d]Based on oil products price without VAT and taxes for Italy in 2015 (55.6 $€_{2015}$/MWh, from [48]). Projected from 2015 to 2050 using a multiplication factor of 2.25 (assumption)

[e]Based on oil products price without VAT and taxes for Switzerland in 2010 (45.7 $€_{2015}$/MWh, from [31]). The Italian price is considered to be the same due to lack of data. Projected from 2015 to 2050 using a multiplication factor of 2.25 (assumption)

[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 [49]). Projected from 2015 to 2050 using a multiplication factor of 1.67 from Table 2 in [10].

[g]Average price of wood in Italy considering the same price of Switzerland is 44.5 $€_{2015}$/MWh, from Moret [31]). Projected from 2015 to 2050 using a multiplication factor of 1.5 (assumption)

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

[i]Based on coal price without VAT and taxes for Italy in 2015 (13.0 $€_{2015}$/MWh, from [48]). Projected from 2015 to 2050 using a multiplication factor of 2.1 from Table 2 in [10].

[j]From [50].

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

[l]Considering average import price of palm oil in Italy in 2015 equal to 850 €/t [51]. Assuming a LHV$_{\text{palm oil}}$ = 36.6 MJ/kg, the price is estimated equal to 23.2 $€_{2015}$/MWh. For 2050 the import price is assumed equal to 1250 €/t.

1.4 Other parameters

1.4.1 Storage

Storage technologies available in the regionalized EnergyScope modelling framework are the same available in Limpens et al. [1].

1.4.2 Hydrogen production

In the EnergyScope 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. For further details refer to Limpens et al. [1].

1.4.3 Biomass and Biogas to synthetic fuels

In the EnergyScope model 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 NG. Table 21 reports the data characterising the aforementioned technologies. In the table, “fuel” corresponds to the main synthetic fuel given as product.

Furthermore, the regionalised EnergyScope model considers a new technology able to allow the injection of biomethane into the gas 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 upgrade 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 being Pressure Swing Adsorption (PSA) [43].

Table 21: Woody biomass to synthetic fuels plus PSA conversion technologies.

	c_{inv} [€$_{2015}$/kW$_{\text{fuel}}$]	c_{maint} [€$_{2015}$/kW$_{\text{fuel}}$/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]	474.5[a]	68.5[a]	20[a]	0.85	0.85[a]	-	-

[a] 41.5 MW Pressure Swing Adsorption (PSA) unit [43].

1.4.4 Additional cost for national improvements

The Italian energy system is set to significantly change in the near future due to the energy transition. These modifications of the energy system will require specific investments: in particular, the energy demand reduction cost associated with an overall increase of efficiency of energy conversion technologies and building renovation is estimated to be about 130 B€$_{2015}$ (see Table 4 in [52]). Since in the regionalised EnergyScope model an efficiency improvement by 2050 is expected, this is considered as a fixed cost in our 2050 scenarios.

1.4.5 Other

The real discount rate for the public investor i_{rate} is fixed to 3.215%, from [1].

Losses ($\%_{loss}$) in the electricity grid are 6% in 2050 [10] and 6.2% in 2015 [8]. 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 10% of the total centralised heat production in 2050 while for 2015 they represent 17.1% of the centralised heat production (see Table 9 in [33]).

The input and output efficiency of each storage technologies for electricity production ($\eta_{sto,in}$ and $\eta_{sto,out}$) are defined according to Limpens et al. [1].

2 Demonstration for the year 2015 (additional data)

This section details the data of the Italian energy system in the year 2015 used to demonstrate the LP model formulation adopted in EnergyScope described in Appendix B.1 of the main article.

The input data necessary to replicate the state of 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 ($\%_{\textbf{Public}}$), train in freight ($\%_{\textbf{Rail}}$) and centralised heat production ($\%_{\textbf{Dhn}}$); (iv) the fuel efficiency for mobility, heating and power generation technologies.

$\%_{\textbf{Public}}$, $\%_{\textbf{Rail}}$ and $\%_{\textbf{Dhn}}$ are reported in Table 22. In this context, $\%_{\textbf{Public}}$ and $\%_{\textbf{Rail}}$ are not regionally defined, while $\%_{\textbf{Dhn}}$ is set to be 8% in the North and 1% in the Centre (no DHN in the South) [33].

Table 22: $\%_{\textbf{Public}}$, $\%_{\textbf{Rail}}$ and $\%_{\textbf{Dhn}}$ for the Italian energy system in 2015.

	Share [%]
$\%_{\textbf{Public}}$	19.3 [13]
$\%_{\textbf{Rail}}$	14.0 [13]
$\%_{\textbf{Dhn}}$	2.3 [33]

The annual gross electricity production share for power technologies derives from data provided by Terna S.p.a [8] and GSE [4]. The yearly shares of mobility and heating&CHP technologies per type of EUD are reported in Tables 25, 26 and 27.

For private passenger mobility (Table 23), the repartition among the different types of vehicles available in the EnergyScope model is estimated based on the actual pkms in 2015.

Table 23: Yearly shares of private vehicles technologies for the Italian energy system in 2015 [53].

	Share Mpkm [%]
Gasoline car	30.16
Diesel car	56.07
NG car	6.98
HEV	0.94
PHEV	0.00
BEV	0.09
FC car	0.00
Motorcycle	5.76

For public mobility (Table 24), the reported values are obtained considering the modal split of passenger transport on land among buses&coaches in [13].

Regarding low and high temperature heat/cold production, the yearly shares have been calculated based on a report of the Heat Roadmap Europe Website called “D 3.1: Profile of heating and cooling demand in 2015” [2]. efficiencies of energy conversion technologies in 2015 reported in Tables 25, 26 and 27 are used.

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

Table 24: Yearly shares of public mobility technologies for the Italian energy system in 2015 [13].

	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 25: Yearly shares of decentralised low temperature heat & CHP technologies for the Italian energy system in 2015 [2].

	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 26: Yearly shares of DHN low temperature heat & CHP technologies for the Italian energy system in 2015 [33].

	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 27: Yearly shares of services and industrial high temperature process heat & CHP technologies for the Italian energy system in 2015 [2].

	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.	7.4

for heating, hot water and for industrial/services processes. Furthermore, in 2015 oil and coal are still present as energy sources for heat production: in particular, coal still accounts for a relevant role in the production 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. HPs and DHN), the reported data suggests that their role is not relevant in 2015.

References

[1] Gauthier Limpens, Stefano Moret, Hervé Jeanmart, and Francois Maréchal. EnergyScope TD: A novel open-source model for regional energy systems. *Applied Energy*, 255:113729, December 2019. ISSN 0306-2619. doi: 10.1016/j.apenergy.2019.113729. URL `http://www.sciencedirect.com/science/article/pii/S0306261919314163`.

[2] Baseline scenario of the heating and cooling demand in buildings and industry in the 14 MSs until 2050, 2017. URL `https://heatroadmap.eu/wp-content/uploads/2018/11/HRE4_D3.3andD3.4.pdf`. European Project n. 695989, D3.3 and D3.4, "Heat Roadmap Europe 4 (HRE4): Building the knowledge, skills, and capacity required to enable new policies and encourage new investments in the heating and cooling sector".

[3] Eurostat. Energy consumption in households, 2015. URL `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households#Context`.

[4] Rapporto Statistico. Energia da fonti rinnovabili in Italia. Technical report, Gestore dei Servizi Energetici (GSE), 2015. URL `https://www.gse.it/documenti_site/Documenti%20GSE/Rapporti%20statistici/Rapporto%20statistico%20GSE%20-%202015.pdf`.

[5] ISPRA. Consumi energetici e heating degree days (hdd) a confronto. proiezioni al 2050 degli hdd in differenti scenari climatici., 2017. URL `http://www.isprambiente.gov.it/it/pubblicazioni/rapporti/consumi-energetici-e-heating-degree-days-hdd-a-confronto.-proiezioni-al-2050-degli-hdd-in-differenti-scenari-climatici`. Report.

[6] Decarbonizzazione dell'economia italiana. scenari di sviluppo del sistema energetico nazionale. Technical report, 2017. URL `http://www.dsctm.cnr.it/images/Eventi_img/de_carbonizzazione_3_ottobre_2017/RSE%20Decarbonizzazione_WEB.PDF`.

[7] Piano d'Azione Italiano per l'Efficienza Energetica (PAEE). Technical report, Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA), 2017. URL `http://enerweb.casaccia.enea.it/enearegioni/UserFiles/PAEE-2017.pdf`.

[8] Terna - Dati statistici, 2019. URL `http://www.terna.it/it-it/sistemaelettrico/statisticheeprevisioni/datistatistici`.

[9] Illuminazione intelligente negli edifici non residenziali. Technical report, Associazione Nazionele Produttori Illuminazione (ASSIL), 2015.

[10] Terna - Documento di descrizione degli scenari, 2019. URL `https://www.terna.it/it/sistema-elettrico/rete/piano-sviluppo-rete/scenari`.

[11] Bagni Umberto, Bonafé Nadia, Bortoni Girolamo, and Bracaglia Massimo. Conto nazionale delle infrastrutture e dei trasporti. anni 2014-2015. Technical report, Ministero delle Infrastrutture e dei Trasporti (MISE), 2017.

[12] Annuario statistico 2016. Technical report, Automobile Club d'Italia (ACI), 2016. URL `http://www.aci.it/laci/studi-e-ricerche/dati-e-statistiche/annuario-statistico/annuario-statistico-2016.html`.

[13] EU transport in figures: statistical pocketbook. Technical report, Commission of the European Communities and Statistical Office of the European Communities, Luxembourg, 2015. OCLC: 930773071.

[14] P. Capros, A. De Vita, N. Tasios, P. Siskos, and M. Kannavou. EU reference scenario 2016. Energy, transport and GHG emissions : trends to 2050, 2016. URL https://op.europa.eu/en/publication-detail/-/publication/aed45f8e-63e3-47fb-9440-a0a14370f243/language-en/format-PDF/source-106883045.

[15] Il trasporto delle merci su rotaia nell'ue non è ancora sul giusto binario. Technical report, Corte dei Conti Europea, 2016. URL https://www.eca.europa.eu/Lists/ECADocuments/SR16_08/SR_RAIL_FREIGHT_IT.pdf.

[16] ISTAT. Popolazione residente al 1° gennaio, 2015. URL http://dati.istat.it/Index.aspx?DataSetCode=DCIS_POPRES1.

[17] DeA. Industria 2015, 2015. URL http://www.deagostinigeografia.it/wing/schedapaese.jsp?idpaese=001#sez10.

[18] ISTAT. Atlante dell'agricoltura italiana 2013. Technical report, 2013.

[19] EnergyPLAN |Cost Database, 2018. URL https://www.energyplan.eu/useful_resources/costdatabase/.

[20] Paolo Colbertaldo, Giulio Guandalini, and Stefano Campanari. Modelling the integrated power and transport energy system: The role of power-to-gas and hydrogen in long-term scenarios for Italy. *Energy*, 154:592–601, July 2018. ISSN 0360-5442. doi: 10.1016/j.energy.2018.04.089. URL http://www.sciencedirect.com/science/article/pii/S0360544218306960.

[21] Wind potentials for eu and neighbouring countries. Technical report, Joint Research Center (JRC), 2018. Tech. Report.

[22] Entso-e, Transparecy Report. Actual Generation per Production Type., 2019. URL https://transparency.entsoe.eu/generation/r2/actualGenerationPerProductionType/show.

[23] G. Buonasorte, R. Cataldi, T. Franci, W. Grassi, A. Manzella, M. Meccheri, and G. Passalev. Previsioni di crescita della geotermia in italia fino al 2030, 2011. URL https://www.unionegeotermica.it/stime-crescita-geotermia-italia.asp.

[24] Strategia Energetica Nazionale (SEN), 2017. URL https://www.mise.gov.it/images/stories/documenti/Testo-integrale-SEN-2017.pdf. Mise, Italian Government.

[25] A. Bordoni, E. Romagnoli, G. Toscano, G. Rossini, and D. Duca. La filiera olio-energia. aspetti salienti dello stato dell'arte e prospettive. Technical report, 2010. URL www.assam.marche.it.

[26] Maria Rosa Virdis. Pathways to deep decarbonization in Italy. Technical report, 2015.

[27] RSE G.A Zanetta. Cicli combinati, 2014. URL http://www.pdc.minambiente.it/it/catalogo-della-decarbonizzazione.

[28] Christian Bauer, Thomas Heck, Roberto Dones, O. Mayer-Spohn, and M Blesl. *Final report on technical data, costs, and life cycle inventories of advanced fossil power generation systems*. 01 2008.

[29] O. Senneca and G.A Zanetta. Impianti usc a carbone, 2014. URL `http://www.pdc.minambiente.it/it/catalogo-della-decarbonizzazione`.

[30] Combined heat and power. Technical report, Energy Technology System Analysis Programme (ETSAP), 2010.

[31] Stefano Moret. *Strategic energy planning under uncertainty*. Doctoral Thesis, EPFL, 2017. URL `https://www.research-collection.ethz.ch/handle/20.500.11850/71958`.

[32] Constantine Karytsas, Dimitrios Mendrinos, and Johann Goldbrunner. Low enthalpy geothermal energy utilisation schemes for greenhouse and district heating at traianoupolis evros, greece. *Geothermics*, 32:69–78, 2003.

[33] Il riscaldamento urbano. ANNUARIO 2016. Technical report, Associazione Italiana Riscaldamento Urbano (AIRU), 2016.

[34] Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the eu. Technical report, European Commission (EC). JRC Science Hub., 2017.

[35] Serie generale n° 67 - allegato i, 2014. URL `https://www.gazzettaufficiale.it/do/atto/serie_generale/caricaPdf?cdimg=02A0307600100010110001&dgu=2002-03-20&art.dataPubblicazioneGazzetta=2002-03-20&art.codiceRedazionale=02A03076&art.num=1&art.tiposerie=SG`.

[36] Victor Codina Gironès, Stefano Moret, François Maréchal, and Daniel Favrat. Strategic energy planning for large-scale energy systems: A modelling framework to aid decision-making. *Energy*, 90:173–186, October 2015. ISSN 0360-5442. doi: 10.1016/j.energy.2015.06.008. URL `http://www.sciencedirect.com/science/article/pii/S0360544215007136`.

[37] Energy4Travel. Data sources reference guide - fuel consumption, 2015. Presentation.

[38] Bilancio Energetico Nazionale (BEN). Technical report, Ministero dello Sviluppo Economico (MISE), 2015. URL `https://dgsaie.mise.gov.it/ben.php`.

[39] Elbersen Berien, I. Startisky, G. Hengeveld, M.J. Schelhaas, and H. Naeff. Atlas of eu biomass potentials. spatially detailed and quantified overview of eu biomass potential taking into account the main criteria determining biomass availability from different sources. Technical report, Biomass Futures, 2012.

[40] Rapporto rifiuti urbani. Technical Report 251, ISPRA, 2015.

[41] Stefano Bozzetto, Marco Pezzaglia, Lorella Rossi, and Biagio Pecorino. Considerazioni sul potenziale del "biogas fatto bene" italiano ottenuto dalla digestione anaerobica di matrici agricole, 2016. URL `http://www.consorziobiogas.it/pubblicazioni-in-evidenza.htm`.

[42] Ali Jalalzadeh-Azar, Genevieve Saur, and Anthony Lopez. Biogas Resources Characterization, 06 2010. 2010 Hydrogen Program Annual Merit Review. Presentation.

[43] A.D. Wiheeb, Z. Helwani, J. Kim, and M.R. Othman. Pressure swing absorption technlogies for carbon dioxide capture. *Separation and Purification Reviews*, 45, 2016. doi: https://doi.org/10.1080/15422119.2015.1047958.

[44] M. Mancini, M. Berton, L. D'Apote, D. Rotundo, and R. Papili. Biomasse ed energia. Technical report, ENAMA, 2011. URL https://www.enama.it/userfiles/PaginaSezione/files/p1c2.pdf.

[45] Piano Nazionale Integrato Energia e Clima (PNIEC), 2019. URL https://www.mise.gov.it/images/stories/documenti/PNIEC_finale_17012020.pdf. Mise, Italian Government.

[46] B. Koffi, A. Cerutti, M. Duerr, A. Iancu, A. Kona, and G. Janssens-Maenhout. CoM Default Emission Factors for the Member States of the European Union, 2017.

[47] Quarterly Report on European Electricity Market. Technical report, European Commission (EC), 2015. URL https://ec.europa.eu/energy/data-analysis/market-analysis_en?redir=1.

[48] Energy prices and costs in Europe. Technical report, European Commission (EC), 2016. URL https://ec.europa.eu/energy/sites/ener/files/documents/swd2.pdf.

[49] Quarterly Report on European Gas Markets. *DG Energy*, 9, 2015. URL https://ec.europa.eu/energy/data-analysis/market-analysis_en?redir=1.

[50] Alessandro Ragazzoni. Analisi della redditività degli impianti per la produzione di biogas alla luce delle nuove tariffe incentivanti, 2013. Presentation.

[51] Clal.it. Olio di palma, malesia, 2019. URL https://www.clal.it/?section=palma_m.

[52] LIBRO BIANCO. Per un Sviluppo Efficiente delle Fonti Rinnovabili al 2030. Technical report, Confindustria. Centro Studi., 2018. URL https://anierinnovabili.anie.it/libro-bianco-per-uno-sviluppo-efficiente-delle-fonti-rinnovabili-al-2030-confindustria/?contesto-articolo=/pubblicazioni/#.XUvhQC1aauU.

[53] Domenico Gaudioso, Antonella Bernetti, and Riccardo Lauretis. Il contributo del traffico all'inquinamento atmosferico. *Qualità Ambiente Urbano*, 12:25–33, 2016.