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Electrification of Heat Demand: An Estimation of the Impact on the Future Italian Energy System

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ABSTRACT

The aim is to assess the impact of the civil sector's heat demand electrification on the entire energy system, in the Italian case study. The hourly heat demand profiles are estimated at census cells level using the BIN method or monitoring data. Profiles are used as input in the oemof-based NEMeSI model employed to optimize both the capacity expansion of power generation and the operation of the power system in 2030, with hourly temporal resolution and NUTS2 spatial detail, in three heat demand electrification scenarios. The model considers the availability of sources, the import and export profiles, and the limit on renewable sources. The results show that no additional capacity of renewable energy is driven by the increasing electrification in fact the installed capacity remains the same in the three scenarios (97GW of photovoltaic and 33GW of wind turbines). The increase of power demand results in a reduction of overgeneration (48.6TWh to 38.3TWh), an increase in installed batteries (40.6GWh to 115.3GWh) and in CHP (+10%) and CCPP systems (+16%). The results show a slight increase of natural gas in electricity generation (+5.2TWh) respect to a high reduction in its use in civil sector's heat demand (-68.5TWh).

1. INTRODUCTION

In recent years, the electrification of the final consumption in the civil sector has increasingly drawn the attention as a key strategy to the energy transition decarbonization reducing the greenhouse gas emissions and promoting more sustainable thermal system. In particular, the electrification of heating demand plays a crucial role in this context, as heating represents a significant portion of the total energy consumption in many countries of Europe, including Italy. In Italy the main energy carriers used in thermal systems are fossil fuels (i.e. natural gas) [1] which should be replaced with other alternatives, as electric heat pumps. Terna shows that the electricity demand of the civil sector increases in the years [2] and it must be met by the electrical grid which could require a significant investment in its infrastructure. In electrifications scenarios, to reduce the role of civil sector on the carbon emissions, the generation mix of electricity must be analyzed, because it is currently composed prevalently by natural gas (about 45%) [3]. In order to comply with current directive, the electrification must go hand in hand with the decarbonization of electricity generation.

The REPowerEU [4] package proposes to achieve a target of 45% of renewable energy in final consumption by 2030, revised by the Fit For 55 package [5] moving the target to 65%. Considering the current goals, an evaluation of the electrification impact from the energy system point of view is necessary.

Other studies have evaluated the impact of electrification on the energy system: Trabucchi et al. [6] discuss the impact of electrification for the Italian residential sector with a focus on the hypothesis formulation of the needed intervention on the electric system in the period 2020-2030. Veldman et al. [7] evaluated the impact of micro-CHP (Combined Heat and Power) and heat pumps systems in residential sector on the distribution and transmission grid. Blonsky et al. [8] underline that a network investment is necessary to meet the growth of electric demand.

The aim of this paper is to assess the impact of the entire civil sector's heat demand electrification on the energy system, in the Italian case study without focusing on one or the other. The model analyzes three different electrification scenarios and evaluates the new installed capacity or the change in the generation mix needed to meet demand. The strength of this model is the possibility to apply it individually to several specific sector or to the entire energy system, considering all the energy sectors simultaneously. This model can also be applied to different time frames, short or long term.

1.1 Structure of the paper

The paper is divided into three parts. Section 2 describes the methodology followed to evaluate the impact of heat demand electrification on the national energy system. The results are described in Section 3. At the end, the main conclusions are reported in Section 4.

2. METHODOLOGY

The followed methodology can be divided into two main steps: (i) hourly heat demand profiles definition and (ii) power demand optimization.

2.1 Hourly heat demand

The hourly heat demand profiles depend on four main parameters: (i) climate conditions, (ii) thermal systems typology, (iii) terminal units and (iv) use of buildings.

The methods used to profile the heat demand aim to consider all the four variables through building simulations or monitoring data.

The followed method is different according to the type of terminal units, i.e. radiant panels, or radiators, due to the different set of thermal systems and the availability of monitoring data. Heating systems with radiant panels are always switched on at low supply temperature with a sort of attenuation during the nights, instead heating systems with radiators and air heating systems follow an on-off trend during the day.

The heat demand satisfied with radiators or air-to-air heat pump is profiled at hourly level using a linear correlation between external temperature and monitoring data. This correlation is obtained considering the day in which the average external temperature in heating period is lower than 15°C. The intercept and the angular coefficient are obtained in each hour of the day and assumed the same in each day during the heating period. The following equation describes the obtained correlation.

$$H_t = m_t \cdot T_{ext,d,t} + q_t \tag{1}$$

where, H_t is the heating consumption at hour t [kW], $T_{ext,t}$ is the external temperature of the day d and hour t [°C], m_t and q_t are respectively the angular coefficient and the intercept obtained by the linear regression.

The heat demand satisfied with radiant panels is profiled using the BIN-method [9]. This method allows to profile the heat demand relating the external temperature, the parameter that identify the set of the system and the peak power demand for this technology. The temperatures are considered through a coefficient, the part load ratio (PLR), calculated as follow:

$$PLR_t = \frac{(T_{ext,bal} - T_{ext,t})}{(T_{ext,bal} - T_{ext,min})} \cdot b \tag{2}$$

where, t is the hour, $T_{ext,bal}$ indicates the balance external temperature equal to 16°C (The balance external temperature is the air temperature at which it is assumed that the need of heating and cooling in buildings is equal to zero.), $T_{ext,min}$ represents the minimum external temperature during the considered year [°C], $T_{ext,t}$ is the external temperature at hour t [°C] and b is a factor that indicates the set of the thermal system between 0 and 1 (off, attenuated or on) based on the use of buildings and the current law.

The use of thermal system is different from a sector to another, for example the tertiary buildings have the thermal systems switched on during the working day and hours instead residential buildings only when people are at home. For tertiary sector the day of holiday are also considered as day in which the systems are always switched off. The set of thermal systems is also regulated by current law, which determines the period and the total hours of the day in which they can be switched on.

The peak of power demand is calculated as the ratio between the total heat demand and the sum of the PLR during the reference year.

Multiplying the peak of power demand for the PLR in each hour of the year, the hourly heat demand profiles are obtained.

For the next step the hourly consumptions are needed so, the hourly heat demand profiles are multiplied by the COP (Coefficient of Performance) value hour per hour. To considers that the COP depends on the external temperature, the Staffell equation is used [10].

$$\mathrm{COP} = 6.81 - 0.121 \cdot \Delta T + 0.00063 \cdot \Delta T^2 \tag{3}$$

where, ΔT is the difference between the supply temperature and the external temperature. The equation allows to understand that the COP increases when the difference between the temperature decreases.

2.2 Power demand optimization

The second step aims to optimize the capacity expansion of power generation and the operation of the power system. To achieve this goal, an OEMOF-based model [11], called NEMeSI (National Energy model for Sustainable Italy [12], is used. OEMOF (Open Energy Modelling Framework) is a model based on a linear programming problem that considers objective function (i.e. the minimum cost of the system), constraints (e.g. emissions or consumption constraints, heat and mass balances etc.) and decision variables (e.g. flow and capacity of technologies and processes). To simulate the energy system five main elements are considered: transformers (i.e. technologies or process), energy carriers (i.e. input and output of the transformers, e.g. heat, electricity, etc.), sources (e.g. availability of biomass, etc.), energy carrier flows (i.e. connection between the other elements) and sinks (e.g. heating or cooling demand) [13]. To correctly model the energy system, the elements have to be replicated and combined in different ways based on the availability of data and on the goal of the application.

Figure 1 shows the relation between the main elements of the OEMOF framework those can be replicated n-times to represent the entire energy system.

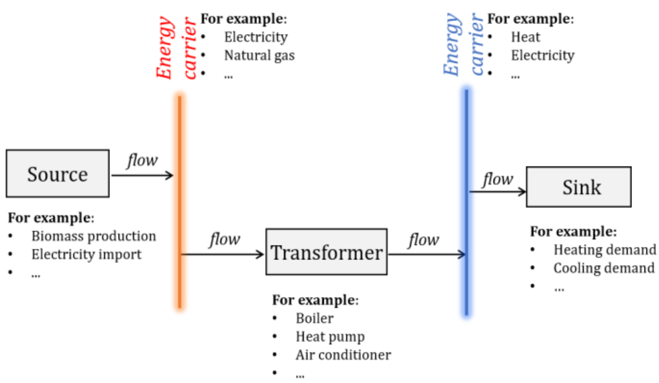

Figure 1. Representation of the relation between the elements of OEMOF framework [13]

The model optimizes the total cost of the system, calculated as follows:

$$C_{\text{system}} = \sum_h \left[\sum_c \left(f_{c,h} \cdot vc_c \right) + \sum_t \left(c_t \cdot i_t \right) \right] \tag{4}$$

where, the subscript h identifies the time, the subscript c represents the commodity, the subscript t indicates the technology and the variable C identifies the total cost of the system, f represents the flow, c indicates the new installed capacity, i is the investment cost.

NEMeSI uses the OEMOF framework to model the entire energy system in a target year, with the NUT2 spatial detail and hourly temporal resolution. The model considers different demand (i.e. the civil sector demand, electricity demand and industry demand), energy carriers and commodities (e.g. natural gas, biomass, district heating etc.) The spatial detail allows to consider the different peculiarities of each region (e.g. the availability of sources), the exchange between them and the need to invest in additional capacity.

The power generation includes different technologies for generation and cogeneration, aggregated by typology, fuel and geographical area. In particular, the model can invest in different systems provided by:

1) Non-dispatchable renewable sources (e.g. photovoltaic utility and distributed, on-shore and off-shore wind, geothermal, etc.);
2) Dispatchable renewable sources (e.g. solid, liquid and gas biomass, pumped and reservoir hydropower, etc);
3) Conventional sources (e.g. combined cycle and gas turbine thermoelectric power plants, gas and oil cogenerate\ion plants).

The model can install new capacity of PV and wind systems or battery energy storage systems (BESS). No changes are planned for the other sources, but the coal phase-out is planned as indicated in the PNIEC directive [14].

For each technologies the current installed capacity, the residual capacity at 2030 and the potential at 2030 is defined in order to give the possibility to invest in new and less emissive technologies.

The system is very complex, and it is very difficult and complicated to represent and analyzed in each part.

Starting from these inputs, the model optimizes the total cost of the system, assessing which types of technology meet demand on hourly basis.

2.2.1 Italian case study

The above-described methodology is applied to the electricity sector of the Italian case study. This section describes the input data used to implement the optimization model.

Residential demand is considered divided into single-family and multi-family houses, the latter divided by type of thermal system, autonomous or centralized. The tertiary sector is considered divided into autonomous or centralized thermal systems. The demand is estimated at census cell level but in the model is implemented at NUTS2 level. The regional heat demand for residential sector provided by GSE (Gestore dei Servizi Energetici) is equal to 236.1 TWh referred to 2013 [15]. This demand is divided into census cells considering the specific heat demand available from a report developed by RSE (Ricerca sul Sistema Energetico) [16], the buildings characteristics provided by ISTAT (Istituto nazionale di STATistica) [17] and climate variables. The heat demand for residential sector is obtained with the detail on the type of buildings (apartments block and single-family houses) and the construction ages. The heat demand for tertiary sector is distributed starting from the results of Hotmaps projects estimated equal to 84.2TWh for the 2012 [18]. The tertiary sector is composed by different subsector (i.e. schools, offices, commercial buildings, etc.) those have very different heat demand. The total heat demand is divided into the subsectors considering the demand for each subsector available in GSE report [15]. Then, the demand is evaluated in each census cells through the total number of employees available from ISTAT [19] divided into each considered subsector according to the ATECO code. The current demand is divided into the different energy carriers (e.g. natural gas, electricity etc.) considering the specific data available from ISTAT open data [1].

Figure 2 shows the current heat demand density in all the Italian census cells for the civil sector.

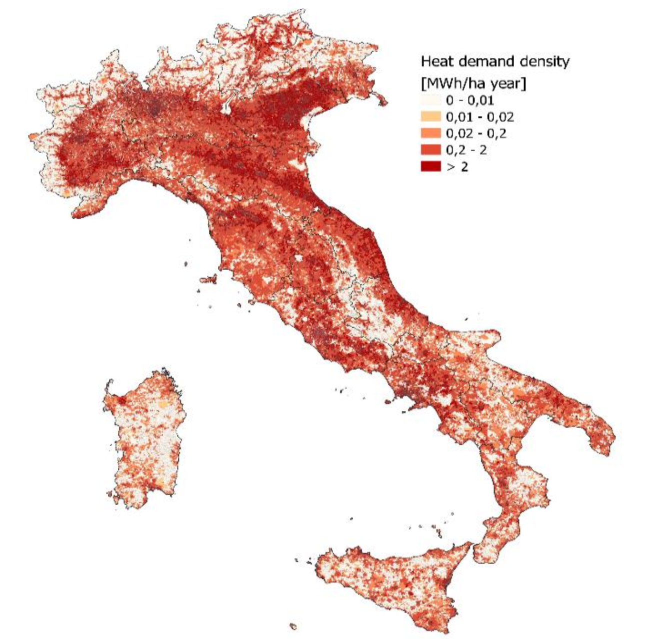

Figure 2. Heat demand density in the current year (2013) in each census cell [MWh/ha year]

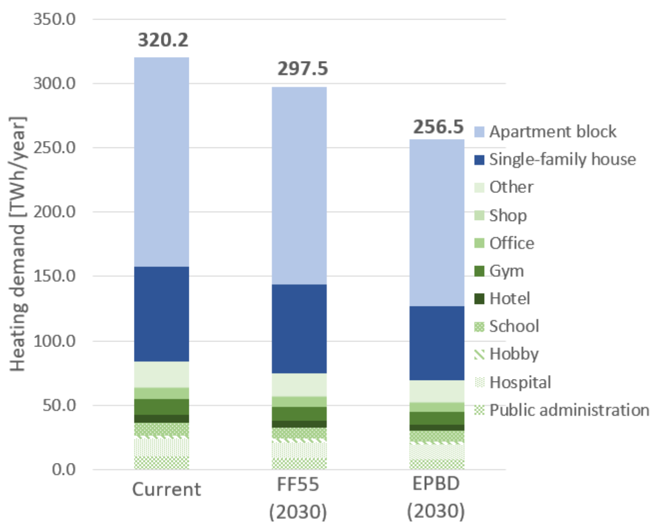

Figure 3. Heating demand in the current year and at 2030 according to FF55 and EPBD [TWh/year]

The single-family houses need a heating demand equal to 73.5TWh/y instead the demand of the apartment blocks is more than double, equal to 162.6TWh/y.

The future heat demand at 2030 is calculated starting from the distributed current demand and according to the annual retrofit rate of the FF55 package [5], equal to 2%/y for residential sector and 3%/y for tertiary sector, or the retrofit rate of the proposal of the Energy Performance of Buildings Directive (EPBD), equal to 4%/y for residential sector and 6%/y for tertiary sector. The refurbishment is applied starting from the buildings with the highest specific heat demand per area. Figure 3 shows the heating demand in the current year and the reduction with the FF55 package and the first proposal of the EPBD retrofit rate. The energy saving is about 20% with the EPBD retrofit and 7% with the FF55 retrofit, compared with the current heating demand of about 320.2TWh/year.

Three different electrification scenarios are considered (25%, 35% and 45% of the total heat demand), and the heat demand hourly profiles are calculated for each scenario.

The change of energy carriers into electricity is evaluated considering that the substitution of existing thermal systems takes place first for less efficient ones, i.e. oil and LPG boilers or biomass boilers. The electricity powers new heat pumps thermal systems with radiant panels in case of retrofitted buildings and radiators in the others.

Starting from the distributed heat demand in each census cells, the hourly heat demand profiles are calculated using the two descripted methods. The external temperature used to apply the methods are available from ERA5 [20] and the periods in which the thermal systems are switched-on are present in the Table A of the DPR 412/93 [21].

To calculate the hourly heat consumption necessary as input in the optimization model, the COP of heat pump is considered with supply temperature between 30-45°C for underfloor heating and 60-75°C for conventional radiators [10].

Not only the heat demand is given as input into the optimization model, but also the cooling and domestic hot water (DHW) consumption. The cooling consumption is estimated starting from Hotmaps project [18] and considering the air conditioning systems diffusion in the buildings, the cooling degree days (CDD) and the buildings surfaces. The DHW consumption is calculated through a linear correlation between the specific DHW demand pro capita and the heating degree days (HDD).

The model NEMeSI uses the demands data as input, together with other data about the sources for the generation mix. The latter are given from open data source available online. GSE and Terna through their annual statistical publication [22, 23] gives information about the installed thermoelectric and renewable (solar, wind and bioenergy systems) installed capacity with NUT2 spatial detail. From ENTSO-E [24] the European association of electric energy TSO cooperation, the hourly data are available for each region. The data are then divided into distributed and utility through the GSE AtlaImpianti [25], where the photovoltaic (PV) and wind systems are mapped.

The areas suitable for the installation of new photovoltaic systems are evaluated through radiation hourly data available from Copernicus Climate Change Service website [26]. Instead, the new wind systems are evaluated considering the wind velocity always available from Copernicus website.

The potential of wind and photovoltaic systems at 2030 are available from TERNA and SNAM evaluation [27] according to FF55 package and reported in Table 1.

Table 1. Potential capacity at 2030 of PV and wind systems in the FF55 scenario [GW] [27]

[GW]	Distributed PV	Utility PV	Onshore Wind	Offshore Wind
North	12.0	10.0	0.3	0.6
Centre-Nord	1.9	2.8	0.4	0.4
Centre-South	3.8	11.1	3.1	0.9
South	1.6	14.5	8.0	3.8
Calabria	0.5	1.1	1.8	0.0
Sicily	1.2	7.9	3.0	1.4
Sardinia	0.5	5.6	1.9	1.4

Table 2. Investment cost of PV and wind systems [€/MW]

Technology	Investment cost [€/MW]
Utility PV	656
Onshore Wind	831
Offshore Wind	2304

Table 3. Italian installed capacity for each power plant technology at 2030 [GW]

Power Plant Technology	Installed Capacity [GW]
Natural Gas Combined cycle	24.00
Turbogas	2.48
Solid biomass	0.26
Biogas	0.40
Biofuel	0.43
Waste-to-Energy	0.40

The considered investment costs for PV and wind systems are reported in the following Table 2.

The input data about current electric generation by programmable sources are provided by:

- Terna [23]: regional installed capacity for each technology;
- Ensto-e transparency [28]: installed power of each plant with information about sources and region of installation;
- ISPRA [29]: waste-to-energy installed capacity.

Table 3 reported the Italian installed capacity for each power plant technology at 2030, distributed then in each region.

A particular attention is given to the district heating (DH) network and to the cogeneration plants. The current installed capacity for each technology is available for the AIRU Yearbook [30].

Table 4 reported the current installed capacity of cogeneration plant connected to DH network.

Terna [23] provides the current installed capacity of cogeneration plants not connected to DH network. Table 5 reported the current installed capacity of cogeneration plant not connected to DH network.

Table 4. Cogeneration installed capacity connected to DH network [MW] (source [30])

Power Plant Technology	Installed Capacity [MW]
Natural gas CHP	814.5
Heat recovery	3881.5
Waste-to-energy	426.6
Biomass CHP	20
Industrial heat recovery	194.8

Table 5. Cogeneration installed capacity not connected to DH network [GW] [23]

Power Plant Technology	Installed Capacity [GW]
Combined cycle	18.46
Internal combustion	3.65
Condensation and spillover	1.92
Backpressure	0.53
Gas turbines	1.02

Table 6. Cogeneration plants electric power at 2030 [GW] [23]

Natural Gas CHP Technology	Installed Electric Power [GW]
High efficiency industrial CHP	7.42
Standard industrial CHP	11.14
Civil CHP	1.24

Table 7. Hydroelectric current installed power [GW] [23, 28]

Hydroelectric Technology	Installed Power [GW]
Pumped storage	7.28
Reservoir	4.46
Flowing water	10.44

The potential at 2030 is estimated according to some hypothesis:

- Industrial cogeneration natural gas plants are set to 97% of the total generation (as reported in GSE report [15]);
- Industrial cogeneration plants with high efficiency are set to 60% of the total generation;
- No potential of new capacity is possible, so the capacity at 2030 is equal to the current capacity.

Table 6 shows the electric power installed at 2030 for natural gas CHP technologies.

Ensto-e transparency [28] and Terna [23] provide data about the hydroelectric power plants.

Table 7 shows the current power installed hydroelectric technologies.

The descripted input data rule the modelled energy system by defining the availability of sources, the import and export profiles, and the limit on renewable sources. Electricity generation by renewable sources is constrained to a minimum of 65% of the total demand according to the FF55 package.

3. RESULTS

In this section the main results are shown.

The model NEMeSI is applied considering only the retrofit scenario according to the FF55 package, due to the review of the new EPBD of April 2024.

Different electricity penetration in the heating systems is considered, calculated as about 25%, 35% or 45% of the total heat demand, i.e. a total electric consumption in heating demand of about 30.5TWh, 42.5TWh and 55.3TWh.

The result of a higher electrification of the sector is the increase of the peak power demand during the winter period while the profile of power demand remains always the same. In the implemented scenarios, the peak increases of about 30-40% between the scenarios in the northern and southern bidding zones (North, North-Centre, South, South-Centre), and of about 5-10% for the other bidding zones (Sicily, Sardinia and Calabria). An example of the results obtained by NEMeSI is shown in Figure 4 for the bidding zone North in the first scenario (25% of electrification) during the day of winter peak of the electric demand. The hourly profile of the civil sector demand is represented in the figure by the dotted orange line.

The constraints to a minimum of 65% of renewable sources in the total demand results in a total installed capacity of 96.9GW of photovoltaics panels and 32.6GW of wind turbines. The expectation is an increase of the installed capacity of photovoltaics panels and wind turbines following the increase of heat demand electrification, instead the installed capacity of these two technologies is the same in the three electrification scenarios. This means that the increasing electrification from a scenario to another does not require additional installed capacity of renewables and the added electric demand is satisfied by other systems.

Figure 5 shows the power supply in the three scenarios. The power demand is prevalently met by solar energy (about 28% in the three scenarios), followed by industrial combined heat and power plants (CHP, about 23%) and then wind energy (about 19%). Hydroelectric systems satisfy about 29% of the total power supply, instead of power plants, driven by oil, natural gas and biomass those satisfy only the 7% of the total power supply.

Between the scenario 25% and 35% of electrification, a slight increase in the use of natural gas in CHP systems (+10%) and combined cycle power plant (+16%) are noticed, due to the network stability imposed by the model. The increase of natural gas in electricity generation is about 5.2TWh between 25% and 45% scenario respect to the reduction in the use of natural gas for the civil sector's heat demand of about 68.5TWh.

The variation in the use of other technologies is lower than the +/-5%.

No relevant increase in the power supply is noticed between the scenario 35% and the scenario 45%.

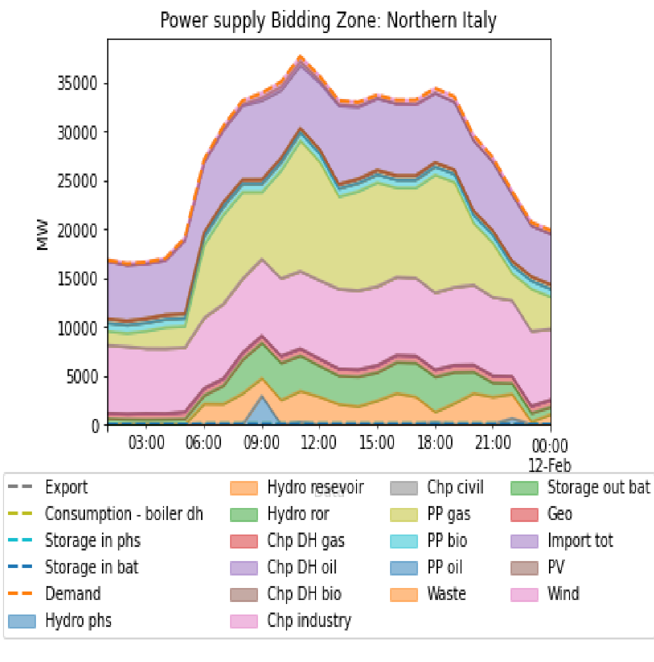

Figure 4. Power supply in bidding zone Northern Italy for the scenario 25% of electrification, for the peak day [MW]

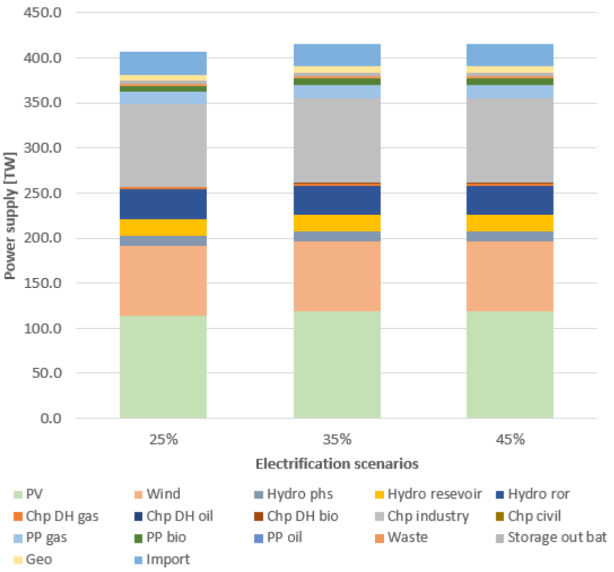

Figure 5. Power supply for the three electrification scenarios for the entire Italy [TW]

The increase of power demand is not met by new installed capacity because it has been satisfied by a reduction of the overgeneration (as shown in Figure 6) and an increased use of batteries (as shown Figure 7). The overgeneration goes from 48.6 TWh in the 25% scenario to 40.8 TWh in 35% scenario (-16%) and to 38.3 TWh in the 45% scenario (additional -6%). The installed capacity of battery storage increases from 40.6 GWh in the 25% scenario to 10GWh in 35% scenario (+160%) and to 115.3GWh in the 45% scenario (additional +9%).

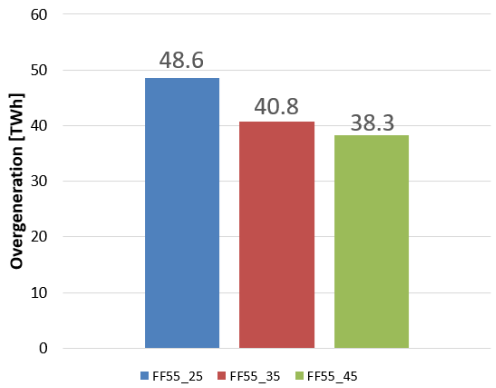

Figure 6. Overgeneration in the three scenarios at 2030 [TWh]

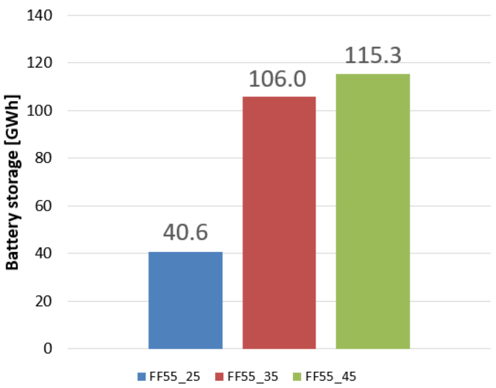

Figure 7. Battery storage in the three scenarios at 2030 [GWh]

4. CONCLUSIONS

This work aimed to evaluate the impact of the civil sector electrification from the entire energy systems point of view starting from an evaluation of heat demand with high detail in space and in time. The used model defines the optimal mix of power generation those minimized the total cost form the system point of view. The evaluation has been done under three different electrification scenarios of civil sector heat demand, in order to consider the possible penetration of heat pumps in heating systems.

The increase in the electricity required by heating systems results in an increase of power peak higher in the north and south area than in the islands.

The results show that the electricity penetration does not have a very heavy effect on the sources used to produce the needed electricity, in particular between the two scenarios with the highest level of electrification. But the increase of electricity demand has been met by a new installed capacity of batteries and by a reduction in overgeneration. The waste of renewable energy could be further reduced by buildings thermal inertia that provides flexibility to the power system.

The imposed constraint on a minimum percentage of power supply by renewable sources results in a total installed capacity that remains the same in each analyzed scenario.

A slight increase in the use of natural gas to produce the required electricity has been noticed, but it remains much lower than the natural gas saved through refurbishment and the use of electricity in heating systems.

This methodology can be applied considering different retrofit and electrification scenarios of civil or other sector to analyze the effect of both on the entire national energy system. An example of a new application could be the new EPBD approved in April 2024. If other sector were considered instead of just the civil sector, a global view of the entire energy system would be obtained.

This work could be a starting point for policy makers to evaluate if electrification of final consumption was sustainable from the system's point of view.

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NOMENCLATURE

BESS	Battery Energy Storage System
CDD	Cooling Degree Days
CHP	Combined Heat and Power
COP	Coefficient Of Performance
DH	District Heating
DHW	Domestic Hot Water
FF55	Fit For 55
GSE	Gestore dei Servizi Energetici
HDD	Heating Degree Days
ISTAT	Istituto nationale di STATistica
MITE	Ministero Italiano della Transizione Ecologica
NEMeSI	National Energy Model for Sustainable Italy
OEMOF	Open Energy MOdelling Framework
PLR	Part Load Ratio
PV	Photovoltaic
RSE	Ricerca sul Sistema Energetico