Electrify Italy

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PREFACE

Francesco Profumo
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Energy is crucial for modern societies but a set of different issues are on the table and have to be addressed promptly.

Energy consumption is unevenly distributed around the world; total Final Energy Consumption (TFC) per capita ranges in the ration 1 to 145 for the population worldwide. A relatively small share of world population and areas consumes a large share of the world energy resources. This situation suggests that the idea of providing the same level of energy access to all the world population with the present prevalent paradigm is probably not viable. The allocation of a scarce resource is usually market-based, sharing the commodity based on the willingness (and ability) to pay, and eventually causes social tensions and energy poverty concerns. In 2016, 13% of the world population did not have access to electricity and 15% of the entire population in developed countries suffered from an energy poverty condition.

Fossil fuels also rise issues in terms of geopolitical security of energy, being large part of fossil fuels production concentrated in politically unstable and low developed countries while some developed ones, include the EU, show a significant level of energy dependency.

Furthermore, fossil fuels are very impacting from the point of view of GHG and air pollutant emissions – with drawbacks in terms of climate change and air/soil pollution and negative consequences on the life of biological systems (plants, animals and humans) – and will be exhausted in the mid/long term at this consumption rate. The potential further increase in energy consumption due to the expected additional contribution of the fast developing countries and of the less fast developing countries that need to recover the gap could lead to even more severe effects if a radical shift in paradigm is not undertaken in time.

All those issues prompt for an energy transition from the present fossil-based energy system to a new one based on renewables and efficient use of energy. The traditional fossil energy commodities are supposed to be integrated and, maybe in the long run, progressively substituted by other commodities both as energy vectors and in the final energy uses, and electricity may play a major role.

In particular, electricity generated from renewable sources looks a good candidate as alternative to fossil fuels, possibly in conjunction with hydrogen and biogas. Electricity can be directly generated from renewable energy sources (RES) and easily transferred over long distances while controlled with high efficiency. Most of the final energy uses based on electricity have higher efficiency than those based on fossil fuels.

The implementation of electricity as a mean for energy transition implies the so-called "electricity triangle": power generation from renewables, electricity as the main energy vector and electrification of final uses in all the sectors (buildings, industry and mobility). The electricity triangle is a general concept, and it applies to both main paradigms, i.e. centralised power generation and large-scale transmission systems (super grid) and distributed electricity production with small-scale distribution systems (smart grid).

The process of electrification of the energy sector may play a major role with cheap, self-produced electricity from distributed renewable sources that might cope with the energy needs of individuals and communities at more affordable prices. The general trend of the industrial countries toward "de-commoditization", in which the supply of an energy commodity is more and more substituted by the supply of a service (in which the amount and type of commodity is not anymore an issue for the final customers), provides an additional reason for selecting electricity as the energy commodity due to its flexibility in use and control. The exploitation of RES, locally available, can free or at least release the burden of energy dependency for many countries.

The implementation of an electricity-based energy transition is strictly intertwined with the extensive deployment of digital technologies to assure reliability, economic and operational energy efficiency. Digitalisation is a key aspect in the management of transmission and distribution networks and in the production section of the energy chain, under a perspective of a fast transition towards renewables. Digitalisation and electrification can lead to positive impacts from the point of view of an easier management of the energy systems and of their optimisation. The "internet-of-things" (IoT) will make it possible to connect the physical world (people, machines, materials, buildings, environment, etc.) to the information world (e.g. big data analytics), thus allowing to process data, providing analyses and foresights. Moreover, digitalisation could support energy demand response measures, like the shifting of heating and cooling loads and the optimal charging strategies for electric vehicles. Digitalisation could also impact on the social dimensions, nudging the habits of people and improving the quality of life in urban areas: this will allow the transformation of citizens from consumers to prosumers, enabling the so-called "energy communities".

The investigation of the possible pathway for an energy transition based on electrification in Italy up to 2050 and the joint effort undertaken by Politecnico di Torino, Massachusetts Institute of Technology and Enel Foundation is surely timely and able to set the stage for further analyses and discussions about the institutional, technological and regulatory framework needed for bringing our country in this new dimension.

In a forward-looking vision up to 2050 for the national energy scenario, we can trace, based on the PoliTo/MIT/Enel Foundation study, some possible trajectories, in terms of the electrification of the country, considering a multi-focus perspective that integrates the penetration of renewables with the electrification potential of the residential, industrial and mobility sectors.

In a forward-looking vision up to 2050 for the national energy scenario, we can trace, based on the PoliTo/MIT/Enel Foundation study, some possible trajectories, in terms of the electrification of the country, considering a multi-focus perspective that integrates the penetration of renewables with the electrification potential of the residential, industrial and mobility sectors. A 46% electrification of the three considered end-use sectors by 2050 is forecasted, coupled with an 86% penetration of renewable sources in the electricity generation mix, with solar playing a key role. Potential benefits can arise from the further electrification of the Italian energy system on energy, economic, environmental and social aspects. Indeed, the strong reduction of total final energy consumption (more than 40%), enabled by the higher efficiency of the electric technologies, allows reducing of almost 2/3 the CO_2 emissions by 2050, as well as greatly reducing the air pollutant emissions (approximately 70% reduction for both PM and NO_x). Italian economy can benefit from this electrification, which can help reducing of 70% the energy intensity. In parallel, from a social standpoint, electrification can unlock relevant savings in the healthcare (almost 800 Billion € cumulated savings by 2050) and can boost the energy affordability for Italian families.

FOREWORD

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The energy transition is a crucial challenge for humanity. The present energy paradigm is not sustainable, and we need to find new ways to satisfy the global energy needs in an equal, fair, and environmentally friendly way. The transition towards a sustainable energy system implies shifting from fossil fuels to renewable energy sources. This is already happening in electricity generation, and, through electrification of final energy uses, in transport, heating, cooking, as well as in industrial uses. This transition is environment-friendly, protecting our planet from pollution and climate change, and has significant benefits to the economy and the society.

This study, carried out jointly by Politecnico di Torino, Massachusetts Institute of Technology and Enel Foundation, aims to discuss possible pathways for an energy transition for Italy based on the electrification of the whole energy sector.

For this purpose, on the supply side we have considered the transition towards a massive exploitation of renewable energy sources for electricity production. On the demand side, we have studied the final energy uses and electrification potential of three crucial sectors: residential, industry, and transport. The analysis is carried out up to 2050, with two intermediate steps in 2022 and 2030. In particular, the sectorial electrification potential was investigated by means of developing and implementing ad hoc modelling techniques, able to consider the technical and economic characteristics of the currently available and the possible future development of electricity-based end use technologies. Consequently, the research developed multiple scenarios detailed in this document.

The outcome of our analysis shows that an energy transition based on electrification will bring Italy numerous benefits, which have been quantitatively assessed with an integrated multi-dimensional approach through a set of around 40 Key Performance Indicators, related to four different domains: energy, environmental, economic and societal.

The quantitative results have been compared with other national and international analyses and contrasted with the opinions of a set of key stakeholders about future energy scenarios and electrification. Altogether, we are confident to conclude that there is a general consensus and largely accepted evidences of a positive trend towards an electrified future for Italy, which will bring sizeable benefits to the environment, the economy, and the society.

We wish to thank the scientific advisory board, the research team of the project, and the experts who openly shared their views on this crucial topic for their valuable contributions.

IS COVID-19 CHANGING THE PICTURE?

COVID-19 is having significant impacts on Italian society and economy. These impacts are reflected in energy and electricity demand and prices.

Although this is an unquestionable fact, the nature and magnitude of the impacts are still uncertain even in the short term. Forecasts about how the Italian economy will perform in 2020 vary across experts and among national and international institutions, as well as over time. The most recent economic estimates at the time of publishing this book envisage a reduction of GDP in 2020 just below 10% with respect to 2019.

This shock will probably have the most significant impacts in the short term, while recovery is expected to take place in the longer term coinciding with the period considered by this study. The shape of the recovery is however very difficult to predict, also because econometric models capable of extrapolating behavioural patterns from the past do not apply in a totally new situation, as the one we are in. Yet, we asked ourselves if the electrification case made in this study would still apply in light of COVID-19 impacts, and concluded that it fundamentally will.

The Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) reported[1] a 7% reduction of primary energy consumption in the first quarter of 2020 and a projection of more than a 10%

1. *https://www.enea.it/it/seguici/pubblicazioni/pdf-sistema-energetico-italiano/01-analisi-trimestrale-2020.pdf*

reduction in the first two quarters, since the effects of the lockdown started to bite in the second half of March. These reductions are primarily for oil and gas resources, while renewables are estimated at the same level as 2019 and electricity imports have slightly increased.

In terms of final energy consumption, ENEA reports a reduction of 8% in gas and oil products and only 4.5% in electricity in the first quarter of 2020. There are serveral reasons for these trends. On the one hand, the lockdown strongly affected the private transport sector, which is still dominated by oil products. On the other hand, while electricity demand has gone down in the industrial sector, it has gone up in the residential sector. Moreover, it is important to remember that electricity enables a number of services, which proved fundamental in mitigating the effects of this emergency. These services include digital communication, which in turn enabled smart working and remote education, and entertainment technologies. Electricity, notwithstanding a significant demand reduction, emerges as being more resilient in situations like the COVID-19 emergency.

The reduction of electricity demand has, however, had an immediate effect on electricity markets. Higher marginal costs of thermal power generation have often pushed the latter out of the merit order, thus reducing its share in favour of renewables. This caused a reduction of day-ahead electricity prices by about 10 €/MWh (-24%) on average in the third week of March 2020 with respect to the third week of February 2020. This confirms that higher penetration of renewables tends to reduce generation cost, although it requires additional investments to adopt suitable measures to guarantee system stability, including not only an adequate amount of flexible generation capacity, but also smart grids, energy storage and demand response resources. A forward-looking regulation is fundamental to assure timely and cost-effective implementation of these measures.

Notably, the increased share of renewables in final energy consumption so far this year, supported by electricity, pushed CO_2 emissions down in a percentage that is higher than the reduction of energy consumption, since the corresponding reduction in generation was concentrated on fossil fuels.

The outcome of our analysis shows that an energy transition based on electrification will bring Italy numerous benefits, which have been quantitatively assessed with an integrated multi-dimensional approach through a set of around 40 Key Performance Indicators, related to four different domains: energy, environmental, economic and social.

All of the above suggest that the case for electrification made in this study therefore remains fundamentally valid. Of course, much will depend on what measures will be implemented to rescue the economy first, and then to support its rebound. As pointed out by a recent working paper by the Oxford University[2], stimulus policies directing resources towards investments in renewables and clean energy infrastructure are attractive both in the short and in the long-term. Such policies generate more jobs in the short run, boosting spending and increasing short-run GDP multipliers (which are derived from expanding demand). In the longer run, they require less effort for operation and maintenance, freeing up resources as the economy returns to full capacity thereby offering higher long-run multipliers (which are derived from expanding supply). Put simply, green investment policies have the potential to both support quick, short-term recovery and to sustain prosperity in the years to come. Therefore, there seems to be a way to turn this terrible emergency into a valuable opportunity for the economy, the environment, and the society at large. The process of electrification envisaged by this study is perfectly in line with this vision.

We humbly hope that this work might provide a positive scientific contribution to the debate about the energy transition and the approaches to implement it in an effective and beneficial way in Italy. We also hope that this study can serve as a basis for a fruitful discussion with all the stakeholders, including academics, industry and policy makers, aimed at tackling these important challenges and to identify actionable solutions for the implementation of future electrification scenarios.

2. Hepburn, O'Callaghan, Stern, Stiglitz and Zenghelis, "Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change?" Oxford Smith School of Enterprise and the Environment | Working Paper No. 20-02.

EXECUTIVE SUMMARY

This study explores a possible pathway to implement a new energy paradigm in Italy based on electrification.
The objectives are:

- **To build** a forward-looking vision of possible scenarios at 2022, 2030 and 2050 by integrating a multi-focus perspective on the penetration of renewables and the electrification potential of the residential, industrial and transport sectors.
- **To estimate** the potential benefits of further electrification through the calculation of Key Performance Indicators in four different areas: energy, economy, environment and society.

The study shows how the electricity triangle, a paradigm based on clean generation by renewable sources, electrification of final uses, and electricity exchange through efficient smart grids, closes the loop of clean energy and efficient consumption. This leads to improvements in energy, environment, economy and social performances, and boosts the share of renewables in final consumption.

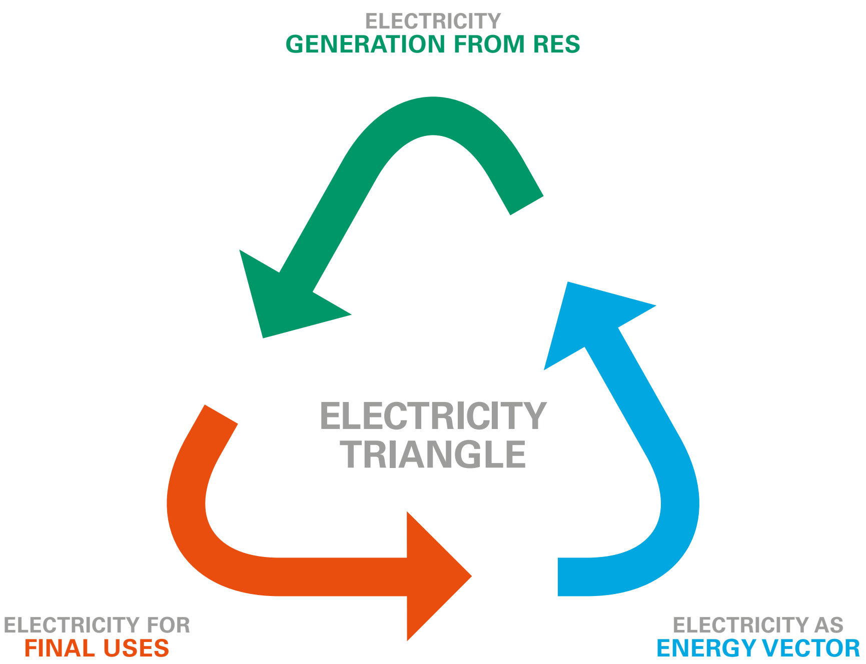

Figure 1
Electricity triangle.

Three key findings of the research are:

1. Electrification can effectively contribute to decarbonization

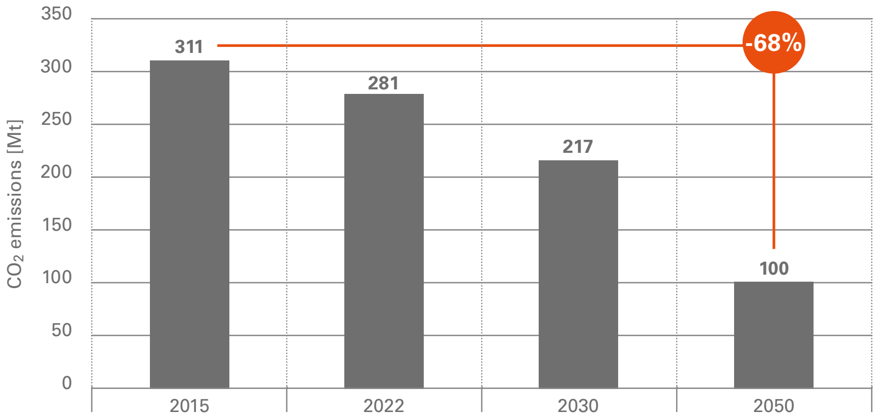

Figure 2
Total reduction of CO_2 emissions from residential, industrial and transport sectors.

2. Electrification can unlock relevant savings in the healthcare

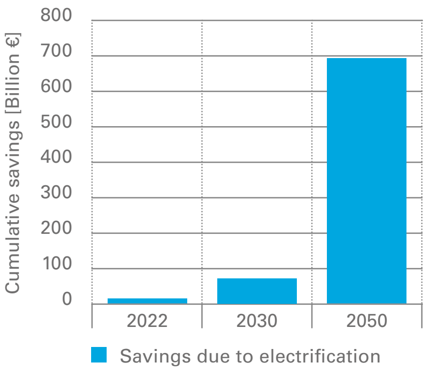

Figure 3
Cumulated cost savings (healthcare, productivity, life).

3. Electrification can increase the affordability of energy for Italian families

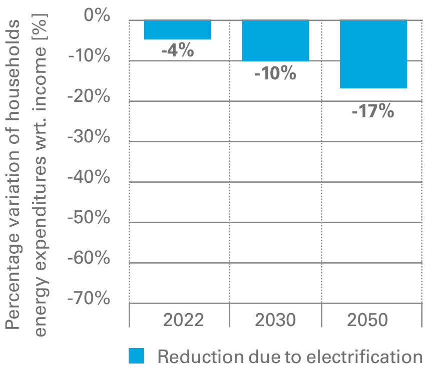

Figure 4
Households energy expenditures with respect to the income.

This study will serve as a basis to discuss the challenges related to the implementation of electrification scenarios with academics and other stakeholders.

1. MAIN HIGHLIGHTS OF THE STUDY

In a relatively prudent scenario, ***electrification in Italy will reach 46% of final energy uses in residential buildings, industry and transport in 2050.*** This further electrification of the Italian economy, accompanied by a consolidation of renewables, can represent a viable, effective solution to creating a more sustainable energy system:

- Strong reduction of total final energy consumption (-42%).
- Reduction of CO_2 emissions by 68%.
- Reduction of 76% of PM10 emissions and of 69% of NO_x emissions, generating cumulated savings of 692 Billion € by 2050, due to the reduction of healthcare expenditure, recovery of lost productivity and avoidance of premature deaths.
- Boosting energy affordability for Italian families, as the share of income that a family will need to devote to energy expenditures will decrease by up to 17% in 2050.

RES can economically achieve a penetration in excess of 85% in the generation mix, even with relatively low CO_2 prices:

- Solar will play a key role, reaching a penetration in excess of 60%.
- Storage will play an increasingly important role over time, with a projected installed capacity of about 112 GW, out of which 106 GW will be captured by electrochemical batteries.

The residential building and transport sectors have the largest electrification growth potentials, whilst the industrial sector can improve efficiency through electrification:

- The residential building sector has the potential to become the most electrified sector in Italy (up to 53%, from an initial 15%).
- Transport has the potential to grow from 3% to 41%.
- The industrial sector, already highly electrified, can further increase electrification from 39% to 42%.

Consumers making environmentally-friendly choices can be incentivized by appropriate policy measures, which can lower the barriers hindering a large-scale adoption of electrical technologies, and thus help the electrification process. The economics, which, in some cases, still unduly favour traditional technologies, can be significantly rebalanced, for example by:

- Properly pricing PM and CO_2 emissions.
- Revising regulated price components which overburden electricity with taxes and levies, and extending the non-progressive electric tariff for heat pumps.

SECTOR HIGHLIGHTS

Residential buildings:

- The penetration of heat pumps for space and water heating in the residential sector can grow 27 and 7 times respectively, reaching about 21 million units each.
- Due to the combined effect of the increase in both AC installations and the number of hot days, the demand for air conditioning will grow by 81% in 2050, with an additional electricity demand of 21 TWh. The effect of hot days alone will increase the AC energy demand by more than 12%, equal to more than 5 TWh.

Industry:

- Further electrification potential can be captured by progressively introducing low and low-to-medium temperature heat pumps. This corresponds to 3.1 TWh additional yearly electricity demand, equivalent to 76% of the low and low-to-medium temperature heat demand in 2050. On the contrary, the penetration of medium- and high-temperature electrical appliances is unlikely to happen according to the current outlook.
- Demand response and flexibility markets could change the economics of electrical appliances not yet convenient at current electricity-to-gas price ratios and conversion efficiencies. Flexibility requirements in the power sector are among the factors that could support the penetration of low-to-medium and medium temperature electrical appliances.

Transport:

- The share of electric vehicles in Italy will rapidly increase in the coming decades, up to 83% of the total fleet in 2050. The two main factors driving this are the reduction in the total cost of ownership and the likely increase in the environmental restrictions in urban areas.
- Additional electrification opportunities will come from public transport, as some Italian public transport operators are already starting to increase the share of electric vehicles in their fleet. For example, Milan has already committed to transform its fleet by 2030, with 1,200 extra electric buses.
- Moreover, long-range coaches have the potential to further expand this market driven by new models with ranges up to 400 km as well as the reduction of the cost of batteries. The report considers a penetration of 20% of electric coaches in Italy by 2050.

ELECTRIFY ITALY / EXECUTIVE SUMMARY

2. RATIONALE AND OBJECTIVES

This study originates from the observation of the limits of the current fossil fuel based global energy paradigm, especially those hindering sustainable development.
Today's global energy system predominantly relies on fossil fuels, which account for 81% of total primary energy supply.
Consequently, the energy sector is responsible for almost two-thirds (61%) of total CO_2 emissions, making it a major factor of anthropogenic climate change[1].
Moreover, it is responsible for the majority of air pollutants at a global level (>99% for both sulphur dioxide and nitrogen oxides, and about 85% for particulate matter 2.5)[2]. The only exception is ammonia, for which agriculture, solvents, and waste are the largest emitters.
Air pollution has a strong impact on public health. It is estimated that 7.3 million deaths every year are attributable to indoor and outdoor air pollution, and that 91% of the world's population live in areas in which air pollution exceeds the WHO[3] (World Health Organization) recommended limits.
According to VIIAS study[4] in Italy in 2010, around 35,000 premature deaths may have been related to exposure to air pollutants (particulate matter, nitrogen oxides and ozone).
Even with huge advances in new technology for energy provision, our current global energy systems are not capable of providing enough energy at an affordable price. Today, about 1 billion people still do not have access to electricity, mainly due to a lack of infrastructure or affordability issues. Even in otherwise developed countries, 15% of the population (about 200 million) are suffering from energy poverty[5].
Moreover, Total Final Energy Consumption (TFC) is quite unevenly distributed. In 2016, the average per capita TFC was 53.9 GJ/person, ranging from 1.9 GJ/ person in South Sudan to 289.9 GJ/ person in Qatar. The Gini[6] index of per capita TFC at a global scale is at 0.534, showing significant inequality in energy consumption. As a comparison, the same indicator is 0.222 between the 28 countries of the European Union, showing a much more even distribution.
Another major issue facing global energy production is the availability of resources. Fossil resources are concentrated in a few countries, many of which suffer from high political instability and low overall development. At the same time, several world areas show a significant level of energy dependency. In 2016 it was equal to 53.6% for the European Union and to 77.5% for Italy[7].
It is clear that ***the current energy paradigm is not sustainable, and a transition to a new system capable of overcoming the limits of the current one is necessary.***
This study aims to explore a new energy paradigm in Italy, a possible pathway to implementation, and to estimate the potential benefits of this transition.
Electrification can be a key tool for the transition towards a sustainable energy system. Electrification closes the loop of clean energy and efficient consumption; improves energy, environment, economy and social performances; boosts the share of renewables in final consumption.
This study shows how the energy triangle, a paradigm based on clean generation by renewables sources, electrification of final uses, and electricity exchange through efficient smart grids, can bring remarkable benefits. The positive impacts of the energy triangle include decarbonization, reduction of pollution and an increase in electricity affordability, thus representing a viable solution to the above-mentioned issues.

The objectives of this study are:

- To discuss electrification as a major option for implementing energy transition in Italy, starting from the present status of electrification and building a forward-looking vision of possible scenarios at 2022, 2030 and 2050.
- To integrate a multi-focus perspective, with analysis of demand and supply, to study the potential electrification of three main sectors (residential, industrial and transport) and the possible renewable penetration for Italy up to 2050.
- To estimate the potential benefits of further electrification of the Italian energy system through the calculation of Key Performance Indicators in four different areas: energy, economy, environment and society.

3. METHODOLOGY AND STRUCTURE

This work is based on the following elements:

- Review of the ***perspectives on electrification*** of the main energy players through interviews with sector experts.
- Analysis of the ***penetration of renewable*** energy sources in the energy supply.
- Assessment of three key ***demand sectors:*** residential buildings, industry and transport.
- Creation of a ***multisector scenario*** (ITELEC2050) composing the above analyses to represent a possible evolution of the Italian energy system up to 2050.
- ***KPI calculation*** to evaluate the potential benefits of this transition in four dimensions: energy, environment, economy and society.

PERSPECTIVES ON ELECTRIFICATION

The objective of this element is to identify the current perceptions of key

1. IPCC - Climate Change 2014: Synthesis Report; IEA Statistics, 2016 data; UN Environment Emissions Gap Reports, 2016 data; IPCC – Global Warming of 1.5°C, 2018.

2. IEA, "Energy and Air Pollution. World Energy Outlook Special Report", IEA Publications, Paris, 2016.

3. WHO - www.who.int/airpollution/en/

4. VIIAS, valutazione integrata dell'impatto ambientale e sanitario 2018.

5. IEA energy access outlook 2017.

6. The Gini index measures the extent to which the distribution of a variable deviates from a perfectly equal distribution. A Gini index of zero represents perfectly equal distribution and 1, perfect unequal distribution.

7. Eurostat, "Energy Statistical Database".

players in the energy sector on the transition of the Italian energy system. The main areas of interest are their perceptions on the expected impacts, benefits, barriers and concerns regarding the electrification process.
For this purpose, a sample of 16 representatives of the major players of the Italian energy sector were interviewed. The sample included experts from manufacturing companies, distribution system operators (DSOs), utilities, regulatory bodies and research institutions.
The main insights drawn from these interviews are as follows.
Interviewed players agree that the energy transition has already started, and electrification is key to this transition. Residential heating, transport and industry were identified as the main sectors in which the electrification process might provide the greatest contributions in terms of emission reduction and an increase in renewable energy use.

Main perceived benefits of the energy transition are:

- Energy efficiency increase, thanks to electric-powered technologies.
- An increase in renewable penetration.
- Subsequent decarbonization and creation of a sustainable system.
- Creation of new jobs connected to the birth of new industrial value chains.

The main perceived barriers are:

- Need for new customer propositions and to overcome some negative perceptions.
- High initial investment cost for technology development and substitution;
- Current high electricity-gas price ratio.
- Inertia of existing infrastructure.
- Lack of adequate regulation to enhance the recovery of the investments required by the transition.

ANALYSIS OF THE PENETRATION OF RENEWABLES

The assessment of renewable penetration in power generation is performed with a total cost optimization model. The GenX tool[8] is used for generation expansion planning (GEP). Three scenarios have been developed based on increasing CO_2 price levels: constant zero price, CO_2 price equal to IEA Current Policies scenario, and CO_2 price equal to IEA Sustainable Development scenario.

Key assumptions:

- Retirement of coal-fired power plants by 2025.
- No constraint on the potential expansion for gas, oil and solar power plants.
- Installed capacity for hydropower and geothermal is constant over time.
- Expansion of onshore and offshore wind power generation up to 20 GW and 1 GW respectively in 2050.
- Two types of bioenergy modelled: cogeneration units assumed without expansion potential; electricity-only production units assumed to have expansion potential.

8. GenX tool is a generation expansion planning tool developed by the MIT.

ASSESSMENT OF THREE KEY DEMAND SECTORS: RESIDENTIAL BUILDINGS, INDUSTRY, AND TRANSPORT

Residential buildings

The detailed analysis is based on the minimization of the Global Cost for CO_{2eq} Avoided (GCCA) indicator[9]. GCCA allows for the identification of the optimal technology mix for carbon emissions reduction.
This model is applied to space heating and water heating of residential building stock. These uses represent 80% of total energy consumption from the residential sector. As non-residential buildings represent only 10% of Italian building stock[10] and they are already highly electrified (51%) due to high appliance density and high air conditioning demands, they are not included.
The evaluation of the electrification potential and of future possible technological trends is performed through the development of the "scenario FB[11]".
The analysis is performed based on reference buildings representative of the Italian building stock, according to different typologies (Single Family Houses, SFH, and Multi-Family Houses, MFH) and periods of construction ("before 1980", "1981-2000", "after 2001"). Reference buildings are articulated in 5 geographical zones.
Alongside the GCCA-based detailed study on space and water heating, also cooking, space cooling, electrical appliances, and lighting are accounted for.
All of the above analyses are combined to compute the overall residential sector consumptions in 2022, 2030 and 2050. The ODEX ("Energy efficiency index")[12] coefficient is then applied to adjust consumptions in accordance with the expected efficiency increase of the sector.

Key assumptions:

- 1% annual new construction rate.
- 1.8% annual renovation rate.
- For each household, a maximum of one technology substitution over the entire timespan of analysis.
- Oil dismission by 2030.
- No biomass use in urban environments, in accordance with existing environmental policy constraints[13].

9. Ratio between the global costs of the technological options and the related CO_{2eq} emissions avoided. The lower the indicator, the more convenient the technological option.

10. ISTAT statistics, Available at: http://dati.istat.it/

11. FB: Focus Building.

12. ENEA, Rapporto annuale efficienza energetica, 2017.

13. Some Italian regions (i.e. Piemonte, Lombardia, Emilia Romagna) have imposed constraints to the installation of biomass heating systems in urban areas, due to local air pollution issues.

- New buildings are assumed to be fully electric.
- Substitution of gas stoves with induction ones is concurrent with the electrification of space and water heating.
- Space cooling, electrical appliances, lighting: projections of historical consumptions trends.
- Incentive mechanisms fixed as in 2015 (Ecobonus and Conto Termico 2.0).
- Non-progressive concessional tariff for SFH with heat pumps as the sole space heating system.
- Energy price growth rates as per IEA projections[14].

With reference to scenario FB, another five scenarios have been developed to highlight some key barriers and drivers to the electrification of the residential sector, and to provide possible strategies to further foster electrification. With the exception of the assumption variation studied by each scenario, the other assumptions are the same as FB.

- ***Sensitivity analysis on renovation rate***
  Annual renovation rate[15] appears to be a key driver in the electrification of the building sector.
  Sensitivity 1: annual renovation rate equal to 1.2% (renovation rate for Italy).
  Sensitivity 2: annual renovation rate equal to 2.5% (maximum renovation rate for Europe).
- ***SCENARIO TRF***
  Extension of the non-progressive concessional tariff (already valid for SFH with heat pumps as the sole space heating system) also to heat pumps in MFH for space heating and to heat pumps in SFH and MFH for water heating.
- ***SCENARIO SP***
  Constant electricity and gas prices, fixed to 2015 values.
- ***SCENARIO TX_PM***
  Adoption of taxation on PM10 emissions[16] (0.87 €/gPM10, weighted for SFH and MFH proportionally to their relative consumptions) for space and water heating systems.
- ***SCENARIO TX_CO_2***
  Adoption of taxation on CO_{2eq} emissions (0.2 €/kgCO_{2eq}, weighted for SFH and MFH proportionally to their relative consumptions) for space and water heating systems.

Industry

The methodology used to assess the evolution of the industrial sector toward higher use of electrical appliances is based on the definition of a bottom-up simulation model based on the minimization of the levelized cost of heat - LCOH. For each time step (2022, 2030, 2050), for each industrial subsector, and for different temperature levels, the model computes the cost of heat production achieved by different technologies (electrical, gas, oil and coal) and updates the stock choosing least-cost solutions.

Key assumptions:

- Potential of electrification based on energy services (mechanical work, refrigeration, heating, lighting).
- The model investigates 9 electrical technologies and conventional gas, coal and oil technologies providing heat, at 5 different thermal levels.
- Key variables: capital cost, learning curves, conversion efficiency, technology improvement, inertial stock substitution, electricity/gas prices, carbon prices.
- Service and agriculture not included in the analysis.
- LCOH is calculated assuming a discount rate of 5%. An escalation in commodity prices, namely electricity-to-gas prices, is assumed based on data available from International Energy Agency[17].
- The model includes inertial stock substitution, estimated at 3% per year conventional technology stock substitution[18].
- The model neglects innovation in competitive gas technologies (e.g., biogas, biomethane, CCS, etc..). Only one indirect electrical technology, namely power-to-gas for hydrogen production, is considered.

The study considers the evaluation of electrification under two different scenarios according to the table below:

	DRIVERS			
	GDP and population	**Final energy consumption**	**Energy prices variation**	**CO_2 Prices**
High electrification	OECD projections	Trend Extrapolation[19]	ETP 2016	ETP 2016
Beyond high electrification	OECD projections	Trend Extrapolation	Cumulative advantage[20]	ETP 2016

The bottom-up simulation model estimates the stock accounting variation based on LCOH. For each time step, industrial subsector and temperature level, the model computes the cost of heat production achieved by

14. *IEA, Energy Technology Perspectives (ETP) 2016, 2016.*

15. *BPIE (Building Performance Institute Europe), Europe's buildings under the microscope, 2011.*

16. *European Commission, Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements, 2012.*

17. *IEA, Energy Technology Perspectives (ETP) 2016.*

18. *Comitato Italiano Gas - CIG Forum 2018.*

19. *IEA Statistics, https://www.iea.org/statistics/?country=ITALY&year=2016&category=Energy%20supply&indicator=TPESbySource&mode=table&dataTable=BALANCES*

20. *In this scenario, electricity experiences a progressive reduction of the competitive disadvantage of price. This is achieved by introducing a synthetic yearly growth rate of 0.9 in retail price for electricity, while setting the gas growth rate to 1.1 for the same period.*

ELECTRIFY ITALY / EXECUTIVE SUMMARY

different technologies and updates the stock accounting with least-cost solutions assuming an inertial stock substitution, estimated at 3% per year conventional technology stock substitution.
The model calculates the stock time variation of gas, electricity, coal and oil appliances for heat production and updates the total final energy consumption mix.

Transport

The transport sector analysis is based on the Fuelling Italy's Future study[21], complemented with an additional study of electricity penetration in urban and extra-urban public transport, and integrated with the projection of other transport modalities.
The analysis of road transport is based on modelling the consumption of different types of vehicles, taking into consideration the aerodynamic and internal friction efficiency, resistance proportional to mass, and inertial load. Based on the stock of vehicles and other constraints, the total consumption of different energy commodities is calculated.
Other transport systems (trains, aircraft and ships) are integrated on the basis of historical data provided by Eurostat, and projected considering an increase proportional to GDP growth rate. According to this model, the contribution of each transport mode to the consumption of each commodity is evaluated. The final values are added to consumption for road transport.
The resulting transport model integrates city and long-range buses, air and maritime transport, trains, light commercial vehicles and passenger cars.

Key assumptions:

- Cost of batteries and electric powertrain decreases by 60% and 25% respectively from 2015 to 2050.
- The efficiency of energy conversion and powertrain of electric vehicles increases 3 points from 2015 to 2050.
- City buses are 100% electric by 2050, assuming that Milan will have a fully electric fleet by 2030, while other cities are assumed to be slower in the substitution of ICE buses.
- Market and stock share of passenger cars is assumed by the Fuelling Italy's Future study–TECH Scenario.
- A slower uptake of EV (including PHEV) in LCV sector will bring EV penetration at passenger cars level in 2030.
- The electrification of long-distance heavy vehicles (coaches and trucks) reaches a penetration of 20% and 25% in 2050, starting to be relevant in 2030.

ITELEC2050 SCENARIO COMPOSITION

The outputs of sectoral studies are merged as inputs of a single scenario called ITELEC2050.

21. Fuelling Italy's Future study, https://www.enelfoundation.org/content/dam/enel-found/news-pdf/news-pdf-2018/Fuelling_Italys_Future.pdf

In order to build the ITELEC2050 scenario, the following sub-scenarios at supply and demand sides have been selected:

- ***RES:*** Current Policy scenario selected. It represents an intermediate among the ones elaborated with different assumptions on CO_2 prices. This choice is based on the consideration that the impact of higher CO_2 prices is relatively limited in terms of CO_2 emissions and electricity production mix.
- ***Residential buildings:*** FB scenario selected. This scenario better reflects the current market regulation and business model in terms of incentives, tariffs and energy prices in comparison with the alternative scenarios, which have been developed to assess the impacts of some key variables on the electrification of the sector. In particular, the incorporation of a CO_2 price approximates the implementation of policies for decarbonization and energy efficiency. The use of the GCCA indicator is consistent with this choice, thus representing compliance with current policy targets, which are mainly focused on GHG emission reduction.
- ***Industry:*** High electrification scenario selected. This reflects major international trends in commodity cost variation, learning curves, efficiency gains, and carbon pricing.
- ***Transport:*** The TECH scenario has been built based on the FIF study related to passenger cars by adding on analyses of public transportation (urban and long-range buses), air and water transport, trains, and light commercial vehicles.

KPIs

A set of KPIs has been defined and calculated for ITELEC2050. The KPIs aim to assess the benefits of electrification in four dimensions: energy, economy, environment, and society.
Energy KPIs aim to understand the overall impact of electrification on the energy system. KPIs include electrification rate, total primary energy supply, total final consumption, and contribution of electrification to the overall reduction of consumption.
Environmental KPIs aim to highlight the benefits of electrification for the environment at both global (CO_2) and local (pollutants) levels. KPIs include CO_2 and pollutant emission reductions, and the contribution of electrification to these.
Economic KPIs serve to evaluate the impact of electrification on national economics. Indicators include energy intensity and carbon intensity, giving an indication of how electrification can contribute to the creation of an economic system in which economic growth can coexist with decreasing energy consumption and emissions.
Social KPIs aim to deepen the direct benefit that electrification can have on peoples lives, both on economic and quality of life levels. Indicators include the reduction of family income share required for energy needs and the healthcare savings connected to air pollution reduction (mainly PM10 and NO_x).

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4. MAIN RESULTS

The ITELEC2050 scenario shows that the electricity triangle can represent a viable, effective solution to address the issues of the current energy paradigm.

- ***Environment:*** -68% CO_2 emissions in 2050, with an electrification contribution of 85%.
- ***Health:*** €692 billion cumulated savings thanks to reduced healthcare expenditures, productivity recovery, and human lives saved.
- ***Affordability***:-17% in energy expenditures for Italian families[22].

This is achieved:
- On the supply side, thanks to the high penetration of RES (85.6% in 2050), with solar playing a key role.
- On the demand side through the penetration of electricity for final uses, up to 46% in 2050.
- From a sectoral point of view, residential building and transport sectors have the largest electrification growth potentials from 2015 to 2050 (from 15% to 53% and from 3% to 41%, respectively), while the industrial sector, already highly electrified, can further improve (from 39% to 42%).

ENVIRONMENT

The energy transition can substantially contribute to decarbonization, with a progressive reduction of studied sector emissions up to 68% in 2050 compared to 2015.
Electrification will reach 46% in 2050, thus contributing to 85% of carbon emission reduction. The rest of the reduction is attributable to an overall increase of efficiency in the use of other energy sources.

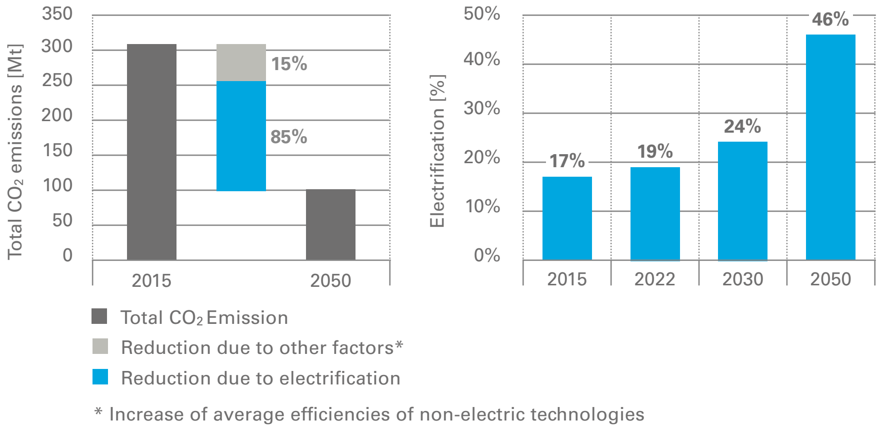


Figure 5
Contribution of electrification to carbon emission reduction and future electrification of demand sectors.

22. Including the effect of average income increase.

These results underline the ***importance of electrification*** in the context of the objectives of carbon emission reduction to ***tackle climate change.***

HEALTH

The energy transition can have a key role in reducing pollutants, with an emission reduction of 76% of PM10 and 69% of NO_x by 2050. The benefit on public health translates in a cumulated saving of €796 billion in 2050 due to the reduction of healthcare expenditures, recovery of lost productivity, and avoidance of premature deaths. Electrification will contribute up to 87% of this reduction, equal to €692 billion in 2050. The rest is due to commodity shift and increased efficiency of traditional tecnologies. Buildings will contribute the most to this benefit, followed by transport and industry, mainly due to the decrease of biomass (the highest PM10 and NO_x emitter) in the residential sector in 2050.

AFFORDABILITY

Electrification will boost energy affordability for Italian families. Ruling out the effect of an increase in average income, the share of income that a family will need to devote to energy expenditures will decrease by10% by 2050 (17% inlcuding the effects of average income increase). Even if the average income does not increase and wealth distribution does not improve in the years to come, electrification will improve the impact that energy expenditures have on a family budget. This will presumably also induce positive feedback supporting further penetration of electrical technologies. This effect is not taken into account in this study.

SUPPLY SIDE: RENEWABLES

Renewables will be a key factor in a sustainable energy system. Their penetration in power generation will steadily increase up to 85.6% in 2050 (45% in 2022, 59% in 2030), almost 120% more than the current level.
A strong penetration of renewables is possible even without considering the effect of environmental externalities. In fact, even considering a zero CO_2 price, renewable sources are projected to reach 84% by 2050 (48% in 2022, 56% in 2030).
Moreover, even a very high CO_2 price (e.g. up to 191 €/ton in 2050) would not result in dramatically higher RES penetration rates (90% in 2050).
Solar PV will play a key role, with a penetration of 62% by 2050 (24% in 2022, 34% in 2030). The growth of wind and hydro is indeed constrained by intrinsic resource limitations, while for solar power, the only theoretical limitation is the surface available for panel installation.
The level of penetration projected is reachable with an extension of about 1,400 km², just 1.1 times the area of Rome municipality. This measure is a conservative maximum upper value as it does not consider any improvement in the efficiency (kW/m²) of solar PV technology.
Energy storage can address the variability and uncertainty in RES. Italy's power system can already rely on pumped hydro storage, which is assumed

to stay at a constant level, although this study shows that additional battery capacity will be needed in the future.
According to this study's projections, storage will indeed play an increasingly important role over time, with a projected installed capacity of about 112 GW, out of which 106 GW will be represented by electrochemical batteries.
Interestingly, the economic optimum does not include battery storage until 2030 when some investment in battery storage occurs under the high emissions price scenario. However, in 2050 when the cost of battery storage is assumed to be substantially lower, the model finds it economically beneficial to install large amounts of battery storage, particularly in scenarios with non-zero CO_2 prices.

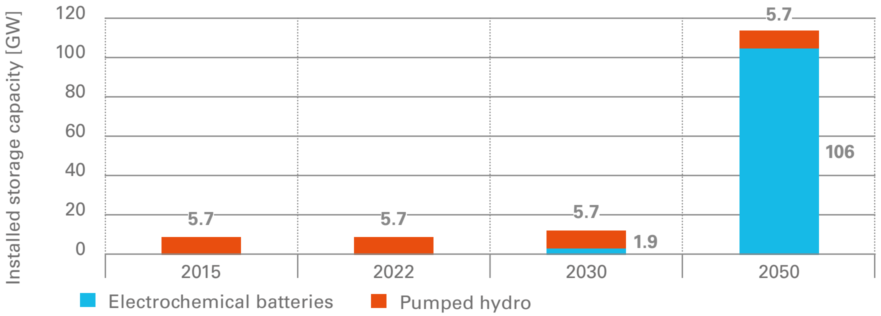


Figure 6
Installed energy storage capacity.

The growing role of renewables in the energy mix could be enhanced and consolidated by the adoption of long-duration energy storage. In a scenario with a growing share of renewables, it is necessary to guarantee system stability and overcome the barrier represented by the inherent exposure to the cannibalization effect: low short-term prices when resources are available, and low generation when prices are high, which substantially affects the revenue streams of these sources. Long-duration energy storage, on which promising research and development projects are ongoing[23,24,25], may represent one of the key innovative technology tools able to predictably control the output of renewable sources and to stabilize their market revenues, thus increasing their stability and economic viability while helping to provide enough flexibility in systems with close to 100% renewables.
Finally, it is worth noting how tools such as PPAs (Power Purchase Agreements) can be used to mitigate the above-mentioned risk and are expanding worldwide. This is due to an increasing number of commercial companies willing to improve their sustainability profile by using renewable energy, as well as advertising their products and services as "made with renewable energy". Such an increasing consumer demand for "green products and services" will further sustain the penetration of renewable energy sources.

23. *"Lowering the Bar on Battery Cost" Yet-Ming Chiang, Liang Su, Mengshuan Sam Pan, and Zheng Li; Joule 1, 212–219, October 11, 2017.*

24. *"Air-Breathing Aqueous Sulfur Flow Battery for Ultralow-Cost Long-Duration Electrical Storage", Zheng Li, Menghsuan Sam Pan, Liang Su, Ping-Chun Tsai, Andres F. Badel, Joseph M. Valle, Stephanie L. Eiler, Kai Xiang, Fikile R. Brushett, and Yet-Ming Chiang; Joule 1, 306–327, October 11, 2017.*

25. *"Long Duration Energy Storage, and the Future of Renewables Generation", Enel Foundation and Form Energy Inc. research ongoing at the time of writing.*

DEMAND SIDE

From a demand point of view, electrification (i.e. the electricity share in total final consumption), can increase up to 19% in 2022, 24% in 2030 and 46% in 2050.
Out of the 46% electrification rate in 2050, 20% is linked to the residential building sector, 13% to industry and 13% to transport.
The evolution of the energy system in this way will lead to a strong reduction in total final consumption (-42% in 2050). Electrification will contribute to more than 3/4 of this reduction, thanks to the higher efficiency of electric technologies compared to their traditional equivalent. The highest contribution to the reduction of TFC is the electrification of the transport sector, contributing 42% of TFC reduction, followed by buildings (31%) and industry (8%).

Demand side sectoral view: overview

Industry will conserve a high electrification rate, which will further grow from 39% to 42%.
The sector that has the largest growth potential is transport, which may grow by twelve times the current rate.
Also, the residential sector has a substantial threefold growth potential. Overall, the building sector has the potential to become the most electrified sector (53% in 2050) followed by industry and transport.

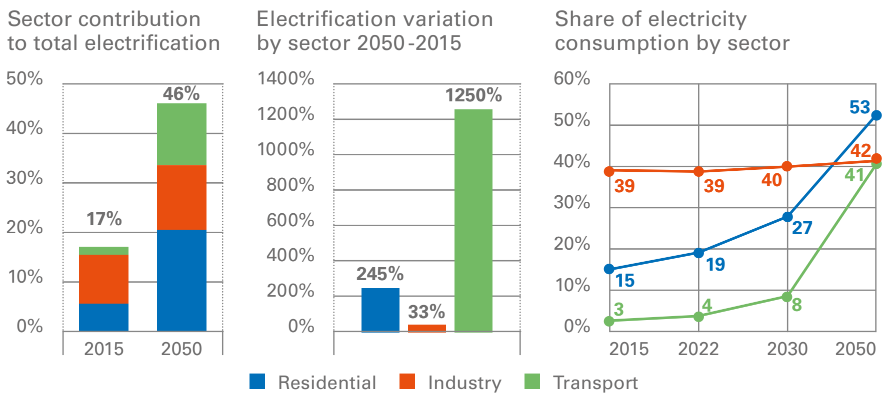


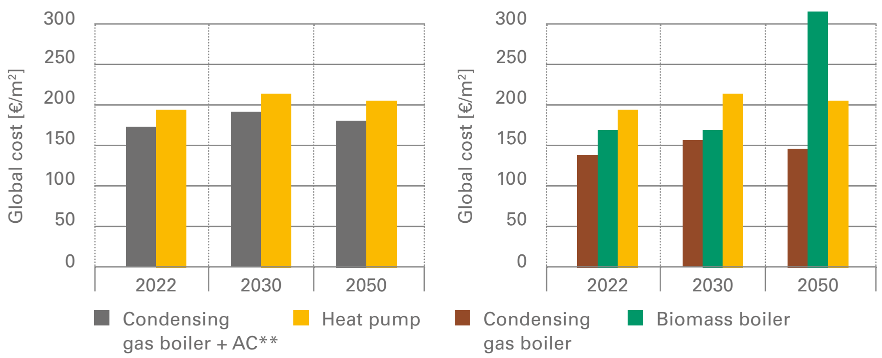
Figure 7
Electrification sectoral view.

Demand side sectoral view: residential buildings

Customer choices are a key factor in the process of electrification of the residential sector and are driven by a variety of factors. Economic convenience is one of the most important, and therefore traditional technologies are still favoured in some cases. Indeed, from a purely financial viewpoint, electrical technologies are already competitive in the market, but with a slight disadvantage. This is mainly due to higher investment costs for electrical technologies with respect to traditional ones, as well as higher energy prices for electricity. Under current conditions in urban areas, the extra global costs[26] of electrical technologies are always lower than 15% (Figure 8a), while extra-costs compared to biomass technologies are more variable depending on the context. In particular, in an extra-urban context (Figure 8b), biomass technologies will still be slightly more economically convenient in 2022 and 2030 (extra costs range between +10% and +25%), while energy commodity price projections[27] favour heat pumps in 2050. It is important to note that, in urban areas, the cost for a multi-split air conditioning system is computed as part of the global cost for gas technologies, representing an opportunity cost that permits a comparison of the services that these solutions can provide (heat pumps can provide both heating and cooling services at once).

a. Urban area*

b. Extra-urban area



* Some Italian regions (i.e. Piemonte, Lombardia, Emilia Romagna have imposed constraints to the installation of biomass technologies in urban areas, due to local air pollution issues.

** In urban area, the cost for a multi-split air conditioning system is added to the global cost for gas techs, representing an opportunity cost that permits to compare the services that the solutions can provide (heat pump can provide both heating and cooling services).

Figure 8
Annual global cost (€/m²) for different technological solutions, in urban (a) and extra-urban (b) areas. Case study: multi-family house, built before 1980, NW Italy, space heating, 20 years lifetime.

Electric technologies are the most environmentally sound, and represent, among the analyzed technological solutions, the best compromise between PM and CO_2 emissions. Conversely, gas technologies are the worst in terms of CO_{2eq} emissions, while biomass is the highest PM emitter.
For this reason, environmentally-friendly consumer choices can be incentivized by appropriate policy measures, which can impact costs, and thus help the electrification process. An analysis of the delta global cost between electrical and gas technologies for the urban area (in which biomass is excluded), and between electrical and biomass technologies in the extra-urban area (in which biomass can still be convenient), allows to evaluate the extent to which other technologies are still more economically convenient than electric ones. Moreover, different scenarios were built to be compared with the reference scenario (scenario FB), based on the current situation.
In an urban context (Figure 9a) in which gas and electrical technologies compete, a PM taxation (scenario TX_PM) has a marginal effect, whereas taxation on CO_2 (scenario TX_CO_2) can help to reduce the extra-cost of electrical technologies. However, in these situations, environmental costs are not enough to ensure the economic convenience of heat pumps in all contexts. Appropriate financial measures such as the extension of the non-progressive electric tariff for heat pumps (scenario TRF) and fixed prices growth rates for gas and electricity (scenario SP), can reverse results, clearly advantaging heat pumps over competing technologies.
In the extra-urban context (Figure 9b), consumer choices could move significantly toward electric technologies if the environmental cost is reflected in the final cost for the customer. Here, the additional financial burden borne by a consumer choosing an electric technology can be reduced by more than 20% if a tax on PM10 (scenario TX_PM) is associated with the environmental impacts of the solution. In this context, financial measures have a lower impact on the competition.

a. Urban area: delta-extra-cost between electric and gas technologies

b. Extra urban area: delta-extra-cost between electric and biomass technologies

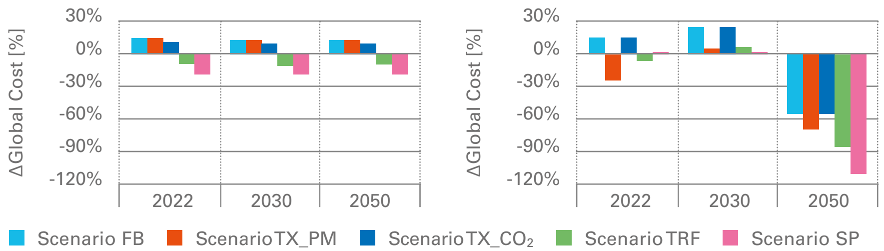


Figure 9
Delta global costs of heat pumps with respect to global costs of the competing technological option for MFH < 1980 North-West – space heating. a) left: gas-heat pump competition (urban area); b) right: biomass-heat pumps competition (extra-urban area).

Therefore, policies are needed to lower the barriers hindering massive adoption of technological options with the greatest environmental performance. In this framework, this study section assesses the effects of relative convenience incorporating the valorization of key environmental aspects (e.g. carbon and pollutant emissions) and investigates the potential for electric penetration in the residential sector based on optimal environmental choices.
To do so, a new indicator named ***Global Cost for CO_{2eq} Avoided (GCCA)*** is defined. This indicator is able to couple the global cost (considered as the main driver from a private point of view) and the potential for CO_{2eq} reduction (a key driver from the public perspective). GCCA is calculated as the ratio

26. Global cost is defined as the total cost of a system over its lifetime. The calculation accounts for the initial investment cost of the intervention and the annual costs (discounted at the present value with a constant rate), including maintenance and energy costs. In this study, incentives are added to the formula.

27. Energy costs for the base year are defined according to ARERA and Unione Petrolifera. Projections for all the energy commodities are derived from IEA growth rates for 2022, 2030 and 2050 (ETP 2016).

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between the global costs of technological options and the correspondent CO_{2eq} emissions avoided, and it allows the identification of the optimal technologies for carbon emission reduction. The lower the indicator, the more competitive the technology is when a retrofit occurs.

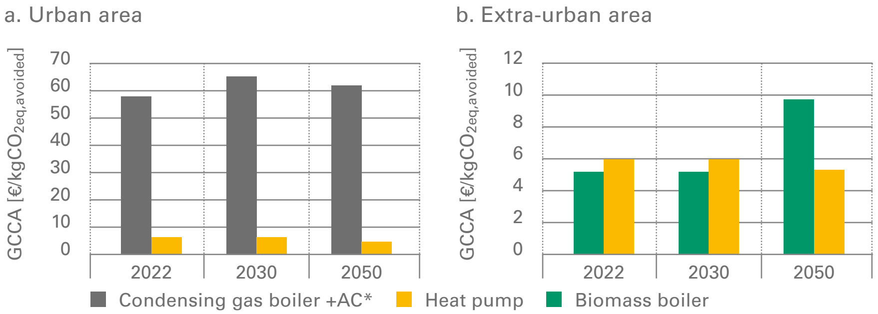

Figure 10
GCCA indicators in 2022, 2030 and 2050 for MFH < 1980 North-West – space heating. a) left: in urban area; b) right: in extra-urban area.

* In urban area, the cost for a multi-split air conditioning system (AC) is added to the global cost for gas techs, representing an opportunity cost that permits to compare the services that the solutions can provide in equal terms (heat pump can provide both heating and cooling services at once).

Based on the indicator, in urban areas, electrical technologies are preferred to gas ones. In extra-urban areas, there still is competition between biomass and electricity up until 2050, when electrical technologies are preferred.
Accordingly, scenario FB is built based on the minimization of the GCCA indicator for the overall residential stock, highlighting that the building sector has a high electrification potential that can be captured with currently existing technologies. According to this scenario, the penetration of heat pumps for space and water heating can grow 27 and 7 times respectively by 2050 compared to 2015, reaching about 21 million units each.

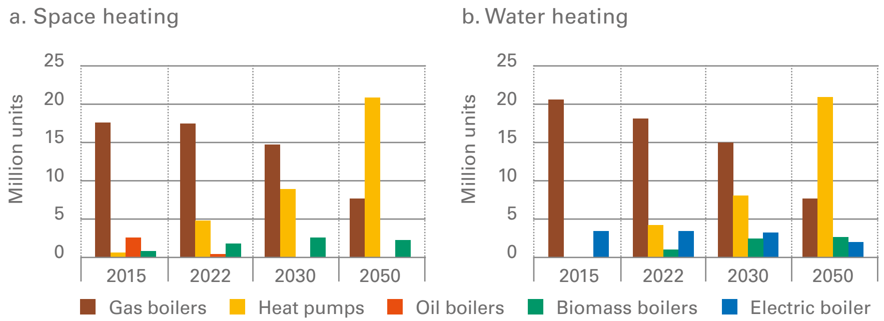

Figure 11
Technological mix in 2015, 2022, 2030 and 2050 for thermal uses (space heating and water heating) in residential buildings (both urban and extra-urban) in terms of number of units. a) left: space heating; b) right: water heating.

Considering the overall residential sector (i.e. including all other uses: space cooling, cooking, lighting, and appliances), the study found a forecasted electrification potential of 53% for the entire Italian residential sector (19% in 2022 and 27% in 2030), including both urban and extra-urban buildings. This means that the energy consumption of electricity up to 2050 is expected to represent more than half of total consumption for the whole sector, against the current 15% (with respect to the baseline of the study, namely 2015).

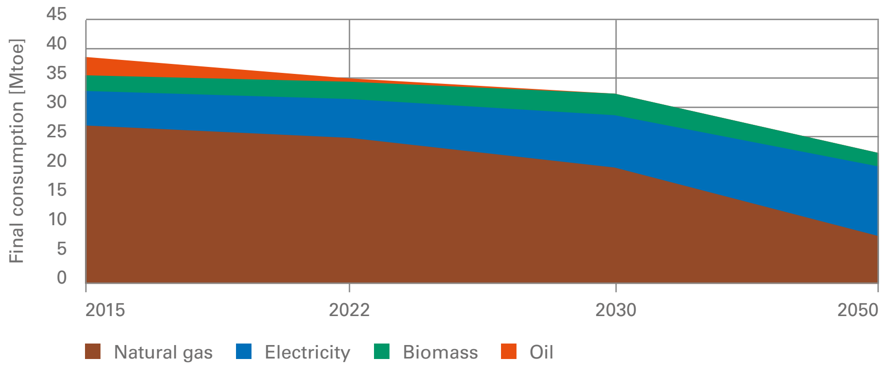

Figure 12
Final energy consumption [Mtoe] by fuels in 2015, 2022, 2030 and 2050 for the overall residential sector.

Penetration of new technologies is marginally affected by measures such as concessional electric tariffs and fixed prices for gas and electricity, whilst measures encouraging renovation rates have the potential to accelerate technology substitution (when varying the renovation rate from 1.2% to 2.5%, the electrification potential ranges from 43% to 66% in 2050). This confirms that, besides the upfront investment cost, one of the key barriers is the inertia of current traditional technologies. Moreover, to unlock the electrification potential that could be captured with existing technologies, a surge in renovation rates would be a key driver.
As for the direct impact of climate change, when considering buildings, it is necessary to take into account the impact of increasing summer temperatures on public health, as an increase in the number of hot days due to climate change will increase the mortality risk[28]. As an example, in 2003, an unexpected heatwave in France caused 15,000 deaths, 80% of which were over 75 years old. Subsequently, the French government requested that all retirement homes have at least one room air-conditioned to less than 25°C on each floor during extreme periods of heat.
If we consider that in Italy the percentage of people over 75 will steadily grow, reaching 21% in 2050, and that the number of hot days[28] will increase, it is clear that the situation in France in 2003 is unfortunately destined not to remain isolated, if adequate mitigating strategies are not undertaken.
Therefore, it is reasonable to expect that, to tackle this issue and to address the need to maintain an adequate comfort level in buildings, the demand for air conditioning will grow. The energy demand for air conditioning for both residential and non-residential buildings due to the simultaneous effect of a rise

28. The Imperative for Climate Action to Protect Health, Andy Haines, M.D., and Kristie Ebi, M.P.H., Ph.D., The new England Journal of Medicine, January 17, 2019.

in AC installations and increase of hot days[29] is expected to increase by 81% from 2015 to 2050, with an additional electricity demand of +21 TWh. The effect of hot days alone will increase the energy demand for air conditioning by 12.3%, equivalent to more than 5 TWh.

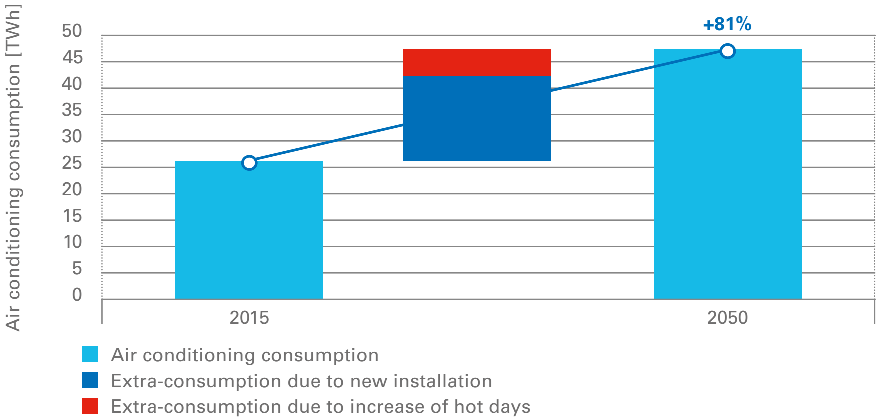

Figure 13
Air conditioning consumption in residential and tertiary sectors.

Demand side sectoral view: industry

The industrial sector is already highly electrified with a share of about 39% in 2016, with total electricity consumption at about 209 TWh.

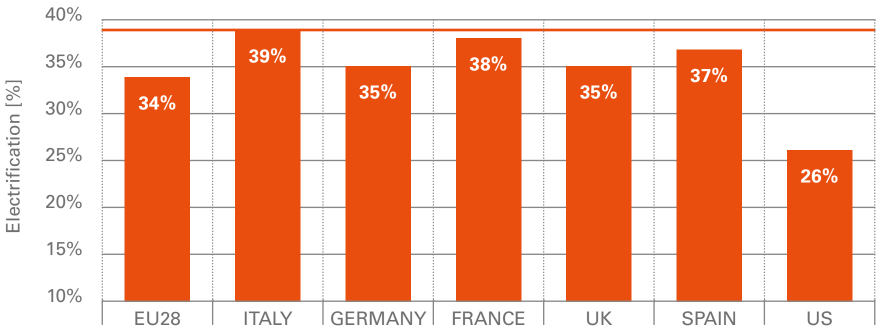

Figure 14
Industry electrification: an international comparison.

According to the "High electrification" scenario, the industrial sector can capture further electrification potential, reaching an electrification rate of about 42% by 2050 (approximately +3% compared to 2015) by progressively introducing low and low-to-medium temperature heat pumps. This corresponds to an additional 3.1 TWh annual electricity demand, equivalent to 76% of the low and low-to-medium temperature heat demand in 2050.

29 *According to ISTAT definition, hot days are those with external air temperature greater than 25°C*

From a purely technological perspective, that considers only availability and technology maturity, electrical appliances could potentially be introduced in all sectors at different temperature levels, with a theoretical potential of 88 TWh thermal energy by 2030 (Figure 15).
Nevertheless, by introducing economic constraints, it is possible to estimate what fraction of this theoretical potential can be captured, as shown in Figure 16 for low-temperature heating appliances.

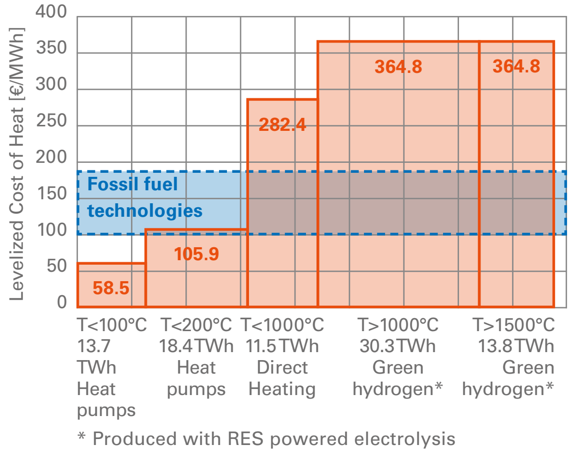

Figure 15
LCOH merit order, by potential and temperature range for the year 2030. Green hydrogen refers to power-to-gas technologies fed on renewable power sources.

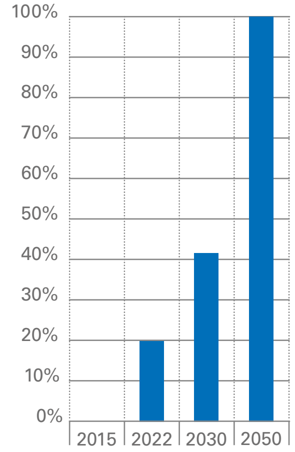

Figure 16
Share of low-temperature heat provided by electrical appliances.

Low temperature (<100°C)

Due to high conversion efficiency (COP range 3.5 - 5.5 for low-temperature heat pumps vs. 0.75-0.9 efficiency of a gas boiler), low-temperature heat pumps are already in competition with gas appliances. Their 13.7 TWh thermal energy potential in 2030 can be captured at 43% due to the inertial stock substitution.

Low-to-medium temperature (100°C - 200°C)

Due to high conversion efficiency (COP range 2 - 3 for low-to-medium temperature heat pumps vs. 0.7- 0.8 efficiency of a gas boiler), low-to-medium temperature heat pumps will become competitive technologies with gas appliances after 2030, when the electricity-to-gas price ratio is below 3.5. They capture 40% of heat production potential in 2050.

Medium temperature (200°C - 1000°C)

It appears that electrical appliances for medium temperature applications are not competitive as the efficiency advantage compared to gas technologies is not enough to counterbalance the comparatively high cost of electricity. In 2050 the breakeven would be at a ratio of 1.5 (57% lower than IEA estimates), compared to the present 3.9. The value of providing flexibility services to the power grid and low-cost on-site generation from renewables could improve the competitiveness of these electrical appliances.

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High-temperature (1000°C - 1500°C)

High-temperature solutions (e.g. hydrogen production), characterized by efficiencies slightly lower than their traditional equivalent, are not competitive due to the high capital cost and comparatively high cost of electricity. To be competitive with gas, industrial hydrogen use for high and ultra-high temperature applications would require electricity-to-gas price ratios of 0.7 at 2030 and 1.1 at 2050 (meaning 80% and 70% lower than IEA estimates).

Sector coupling, on-site renewable power sources and/or market designs that reward flexibility and storage could provide those conditions. Sector coupling, i.e. the integration of power and gas infrastructure, could promote high-temperature solutions. Power-to-gas technologies may produce low-cost "green" hydrogen (i.e. produced with electrolyzers using mostly renewable energy), as well as provide ancillary services by avoiding power grid congestions and mitigating temporal and geographical mismatches between electricity generation and consumption.

Ultra-high temperature (>1500°C)

Ultra-high temperature electrical technologies (e.g., electric arc furnaces, not represented in Figure 15) are mature and competitive with conventional gas or coal blast furnaces. However, their introduction in the technology mix requires a major change in basic metal processing; therefore, coal-based blast furnaces are assumed to provide ultra-high temperature heat.

Based on the above considerations, the findings of this study suggest that it is possible to increase electrification in the industrial sector, especially providing high efficiency low and low-to-medium temperature heat as indicated in Figure 16.

In particular, low-temperature heat pumps can add 1.3% of electrification in 2030, equivalent to 1.4 TWh of additional yearly electricity demand, corresponding to 43% of the low temperature heat demand. Low and low-to-medium temperature heat pumps can add 3.4% of electrification in 2050, equivalent to 3.1TWh additional electricity demand annually, and corresponding to 76% of the low and low-to-medium temperature heat demand.

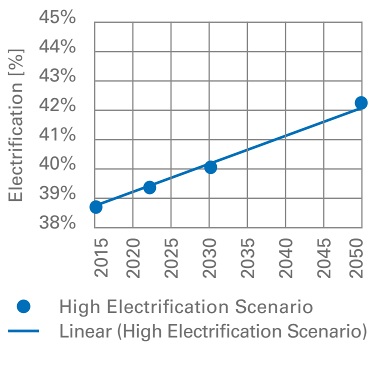


Figure 17
Electrification potential in Italian Industry.

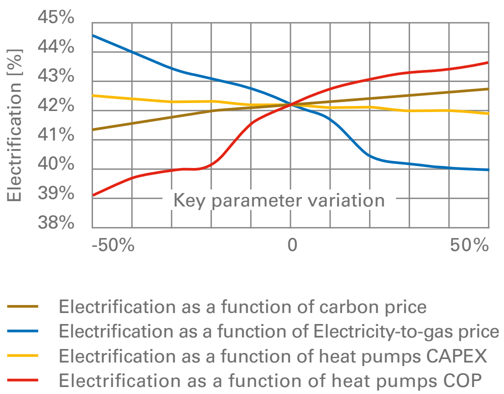


Figure 18
Sensitivity analysis: electrification of industry in 2050 as a function of key parameters variation vs. High Electrification Scenario assumptions.

In Figure 18, sensitivities show how variations of key assumptions can affect electrical technology penetration.

Electricity-to-gas price ratios, conversion efficiencies, carbon price, and CAPEX are the main parameters affecting electrification in the industrial sector, with electricity-to-gas price ratios, carbon pricing and conversion efficiencies giving the highest sensitivity.

Reducing the electricity-to-gas price ratio by 50% with respect to International Energy Agency estimates for 2050 could add up to 3% more electrification. Almost 2% of higher electrification can be achieved with 50% higher COPs of low and low-to-medium temperature heat pumps.

On the contrary, the sensitivities confirm that the penetration of medium- and high-temperature electrical appliances is unlikely to happen according to the current outlook. In 2050, the electricity-to-gas breakeven price ratio that enables the penetration of induction ovens is about 1.4, or 60% below IEA baseline estimates. Industrial hydrogen utilization can be profitable with electricity-to-gas price ratios lower than 1.1, 70% below IEA baseline estimates.

The effect of key parameters on the share of electrification in the industrial sector has been further analysed, and results are shown in Figure 19 and Figure 20.

Figure 19 shows the share of electrification in the industrial sector as a function of electricity-to-gas price ratios. Sensitivity to electricity-to-gas price ratios is considered with -50% to +50% variation with respect to the baseline value of 3.4 at 2050. Electricity-to-gas price ratio variations have the potential to change from -2% to +3% electrification at 2050. Variations affect the year in which low and low-to-medium temperature electrical heating appliances become less/more profitable with respect to gas technologies, thus promoting a delayed/early adoption by industrial users.

Figure 20 shows the share of electrification in the industrial sector as a function of carbon prices. Sensitivity to CO_2 prices are calculated with -50% to +50% variation with respect to the High Electrification Scenario assumption of 140.9 €/t_{CO2} by 2050. Carbon prices have the potential to vary the electrification rate by -1% to +1% in 2050 due to the change in the cost of heat production from fossil-fed heating appliances.

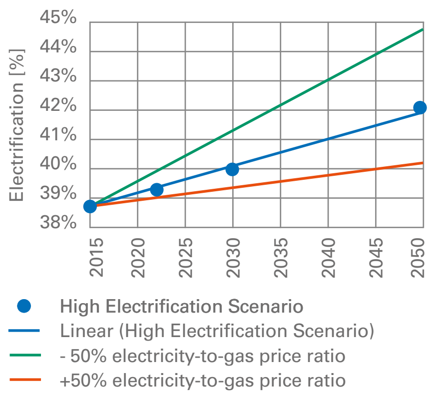


Figure 19
Sensitivity analysis: electrification of industry as a function of electricity-to-gas price ratios vs. High Electrification Scenario assumption.

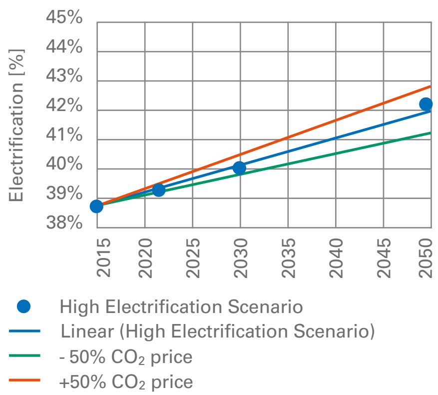


Figure 20
Sensitivity analysis: electrification of industry as a function of carbon prices vs. High Electrification Scenario assumption.

A high share of RES in the power sector would create an emission factor of electricity generation lower than 51 kg_{CO2}/MWh_e, thus including a low contribution from environmental externalities to electricity prices. Therefore, high carbon prices would sustain the introduction of electrical appliances in sectors with high emissions such as industry.
Besides the price of CO_2, gas and electricity, other factors can enhance the penetration of electrical technologies. Efficiency and emission targets, demand response, on-site generation, low electricity cost for power-to-gas applications, and sector coupling could promote these technologies and spread hydrogen use in industry. In particular, demand response to participate in flexibility markets could change the economics of electrical appliances not yet convenient at current electricity-to-gas price ratios and conversion efficiencies. Thus, flexibility requirements in the power sector could support the penetration of low-to-medium and medium temperature electrical appliances. On the other hand, sector coupling of power and gas sectors through power-to-gas technologies could support the indirect electrification of the industrial sector, producing low-cost hydrogen as an energy carrier for high and ultra-high temperature applications. Some of these factors depend on the specific regulation and market design adopted, thus confirming the key role of regulation in the electrification process.
Energy efficiency targets that promote the adoption of technologies enabling the reduction of primary energy consumption per unit of physical output can enhance the penetration of electrical technologies, typically characterized by higher efficiencies. Environmental regulations[30] aimed at reducing both CO_2 and pollutant emissions may also change the pace of industrial electrification, bolstering the adoption of electrical appliances that will avoid environmental costs.

Electrification may be an enabler for the entry of industrial stakeholders into the energy market who can combine both capacity and flexibility opportunities from new electricity market designs that appropriately value these services.
Demand Response (DR) is an alternative and less costly way to balance the grid by adjusting the load according to generation capacity. It has multiple sources of value:

- By avoiding investments in peak generation - capacity value.
- By providing reserves for TSOs - flexibility value.
- By balancing supply and demand locally and avoiding congestions - network value.

Commercial and industrial consumers can respond to market variations by increasing or reducing their energy consumption with the aim of responding to peaks in electricity supply and demand, resulting in greater grid flexibility and stability as well as more efficient use of energy infrastructures and resources.
If electrified, certain industrial processes can be stopped on demand, in response to a price signal or a communication (remotely controlled devices, etc.) that usually correspond to specific grid emergencies (e.g. extreme events, price spikes, unexpected system issues).
Aggregation may provide further potential for flexibility and capacity, enabling the participation of industries to new electricity markets as virtual aggregated units. Thanks to digitalization, DR aggregators are able to create values both for the customers and for the utilities/TSOs: their role is to connect energy users to market opportunities in order to balance supply and demand.
Practical examples of energy reduction strategies to implement DR include:

- For cement manufacturing: stop primary and secondary crushers or stop proportioning and grinding mill.
- For industrial gas production: shut down air separation units and associated pumps.

Participation in capacity markets may be further enhanced by adopting dispatchable on-site generation solutions such as CHP systems or RES + Storage configurations. Moreover, low LCOEs of local generation solutions may increase the profitability of electrification of industrial final uses.

Demand side sectoral view: transport

The passenger car sector has a large electrification potential, with further benefits from public transportation and long range buses.
The share of electric vehicles is going to increase strongly in the coming decades due to two main factors: the reduction in the total cost of ownership and the likely increase in environmental restrictions in urban areas. According to the FIF[31] study, the number of electric passenger cars may increase up to 83% of the total fleet in 2050.

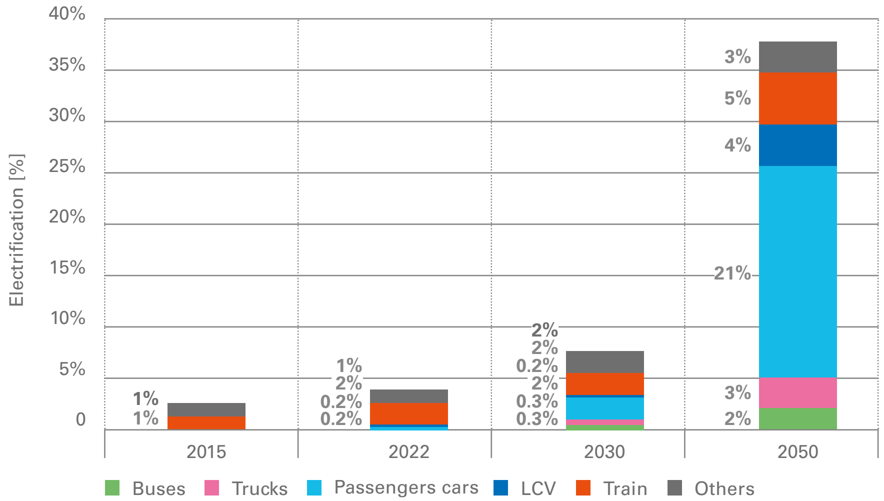


Figure 21
Penetration of electrification in transport sector.

30 As an example, the Italian National Energy Strategy claims for a reduction of greenhouse gas emissions to be two third of the value of 2005 in 2030, being even more ambitious for the sectors that are under the Emission Trading Scheme foreseeing a reduction of 57% on the same baseline. Concerning air pollutants, the new European Directive 2016/2284 imposes new limits on most relevant emissions including the SO_2 reduction of 71% by 2030, NO_x reduction of 65% by 2030, COVNM reduction of 46% by 2030, NH_3 reduction of 16% by 2030, PM2.5 reduction of 40% by 2030.

31 Low-carbon cars in Italy: A socioeconomic assessment, Cambridge Econometrics, 2018" (link: https://www.camecon.com/wp-content/uploads/2018/09/FIF-Technical-Report.pdf).

Electrification leads to a strong increase in the efficiency of passenger cars. Although the total amount of km remains roughly constant, total energy consumption decreases by 92% in 2050 with respect to 2015.

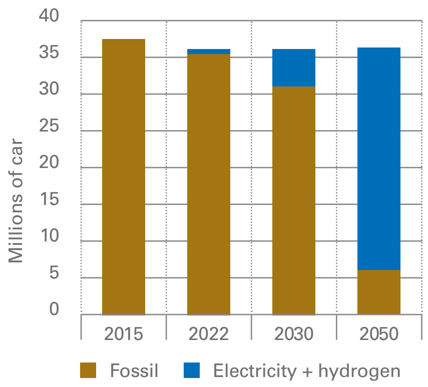


Figure 22
Evolution of electrification in passenger cars.

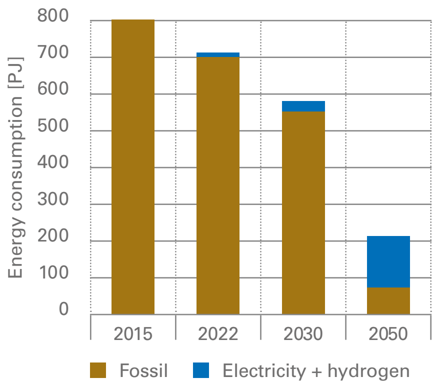


Figure 23
Energy consumption of passenger cars.

Additional electrification opportunities will come from public transport. EU regulations are encouraging the penetration of electric buses.

- The directive 2009/33/EC (Clean Vehicles Directive) on the promotion of clean and energy-efficient road transport vehicles sets the regulatory requirement of energy efficiency, CO_2 and pollutant emissions as an evaluation criterion in all the tenders related to the procurement of road vehicles. The directive is currently under revision. When in force, the updated directive will set minimum targets for the public procurement of clean vehicles, differentiated by Member State and by vehicle category. For Italy, the objectives for the procurement of a fleet of clean buses are 45% from 24 months following the date at which the Directive comes into force, to 31st December 2025, and 65% from 1st January 2026 to 31st December 2030.
- Initiatives like the European Clean Buses Initiative[31] aim to promote the penetration of clean buses by setting a 30% target penetration of alternatively fueled buses by 2025.

Public transport operators are responding by increasing the share of electric vehicles in their fleet.

ATM (Milan's municipal public transport agency) has already committed to transforming its fleet by 2030, with 1,200 extra electric buses. Dutch provinces will purchase only zero-emission vehicles starting in 2025. Several cities and regions have announced plans to stop purchasing conventionally fueled buses, including Copenhagen (in place since 2014), London (2018), Berlin (announced for 2020) and Oslo (announced for 2020)[32].

32. https://ec.europa.eu/transport/themes/urban/cleanbus_en

In Italy, considering the leading effect of Milan, it is reasonable to believe that the national fleet of local public transport buses could be 100% electric by 2050.

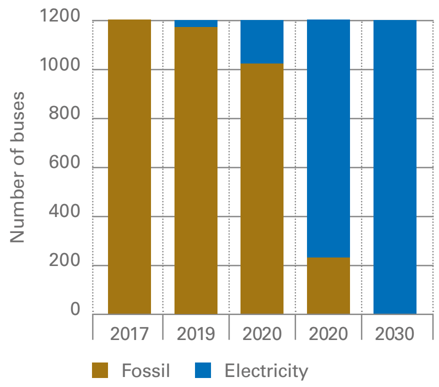


Figure 24
Penetration of electric urban buses, plan of Comune di Milano.

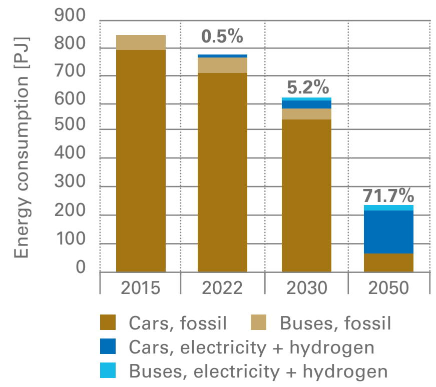


Figure 25
Total consumption of public transport systems.

Moreover, long-range coaches have the potential to further expand this market. Electric buses with a range up to 400 km are already available on the market. In 2017 a prototype built by Proterra set a world record of 1,102 miles (1,763 km) on a single charge.

It is therefore not unreasonable to expect an additional electricity penetration in the long-range bus division. The reduction in the cost of batteries, which is expected to drop from 237 €/kWh in 2016 to 70 €/kWh in 2050[33] enables a penetration rate of 20% for electric coaches in 2050. This would bring the reduction of consumption for long-range coaches up to 22 PJ, 21% of the 2015 value.

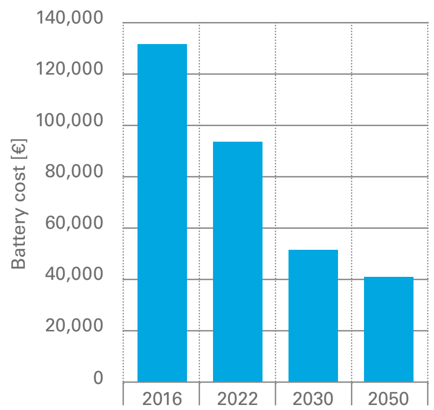


Figure 26
Cost of a 500 km battery for a heavy vehicle.

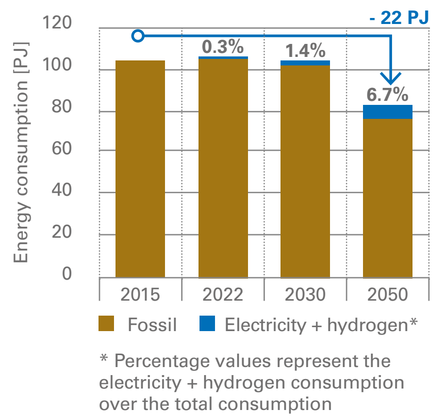


Figure 27
Total consumption of long-range transport systems.

33 Low-carbon cars in Italy: A socioeconomic assessment, Cambridge Econometrics, 2018" (link: https://www.camecon.com/wp-content/uploads/2018/09/FIF-Technical-Report.pdf).

Electrify Italy

Possible electrification pathways in Italy up to 2050 and related benefits

BASELINE 2015

20.8%
ELECTRIFICATION
share of electricity in total final consumption

Research Partners
enel Foundation
POLITECNICO DI TORINO
ENERGY CENTER
EST ENERGY SECURITY TRANSITION
MIT

INDUSTRY
2015: **39%**
2050: **42%**

TRANSPORT
2015: **3%**
2050: **41%**

RESIDENTIAL
2015: **15%**
2050: **53%**

DECARBONIZATION
CO_2 emissions will be slashed by more than half

CO_2 emissions
% variation vs. 2015

2022	281 mt	-10%
2030	217 mt	-30%
2050	100 mt	-68%

ELECTRIFICATION
Electrification will increase up to almost half of final consumption

2015: **17%**
2022: **19%**
2030: **24%**
2050: **46%**

Share of electricity in total final energy consumption of the three sectors studied

RENEWABLE PENETRATION
Renewable share in electricity supply will overcome 85%

2022	2030	2050
48%	59%	85.6%

Share of total electricity supply produced by renewable

PUBLIC HEALTH SAVINGS
Total costs saved due to better air quality reach 692 bn€

2022	2030	2050
16 bn€	72 bn€	692 bn€

Cumulated savings due to reduction of healthcare expenditures, recovery of productivity, avoidance of premature deaths (billion €)

AFFORDABILITY FOR FAMILIES
Weight of energy bill for families will be reduced by 17%

2022	2030	2050
-4%	-10%	-17%

Household energy expenditures over the income (% reduction due to electrification only)

Source: Electrify Italy, ITELEC 2050 scenario

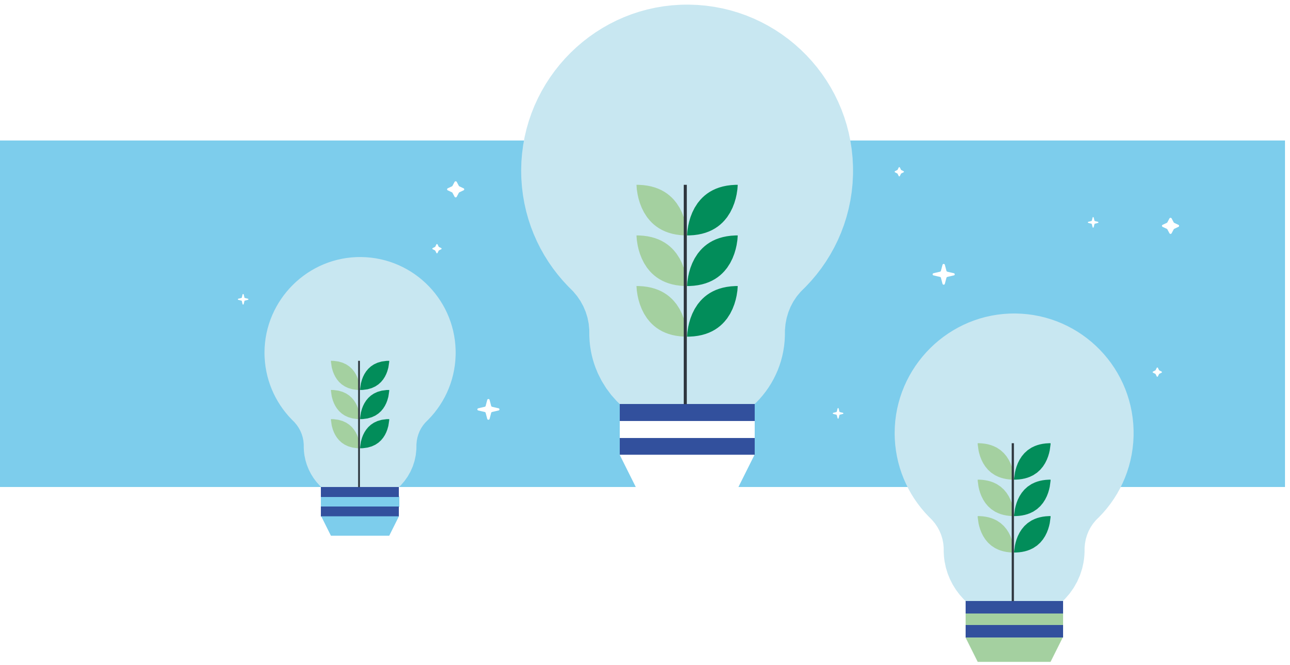
ENERGY EFFICIENCY
Primary energy consumption will steadily decrease

2022	2030	2050
-10.2%	-18.9%	-42%

Primary energy consumption % variation vs. 2015

Chapter 1

RATIONALE, CONTEXT AND OBJECTIVES



1.1 RATIONALE AND OBJECTIVES OF THE STUDY

This study originates from the observation of the limits of the current fossil fuel based global energy paradigm, especially those hindering sustainable development.

Today's global energy system predominantly relies on fossil fuels, which account for 81% of total primary energy supply. Consequently, the energy sector is responsible for about two-thirds (62%) of total CO_2 emissions, making it a major factor of anthropogenic climate change [1], [2], [3].

Moreover, it is responsible for the majority of air pollutants at a global level (>99% for both sulphur dioxide and nitrogen oxides, and about 85% for particulate matter 2.5) [4]. The only exception is ammonia, for which agriculture, solvents, and waste are the largest emitters. Air pollution has a strong impact on public health. It is estimated that 7.3 million deaths every year are attributable to indoor and outdoor air pollution, and that 91% of the world's population live in areas in which air pollution exceeds the WHO recommended limits [5]. According to VIIAS study [6] in Italy in 2010, around 35,000 premature deaths may have been related to exposure to air pollutants (particulate matter, nitrogen oxides and ozone).

Even with huge advances in new technology for energy supply, our current global energy systems are not capable of providing enough energy at an affordable price. Today, about 1 billion people still do not have access to electricity, mainly due to a lack of infrastructure or affordability issues. Even in otherwise developed countries, 15% of the population (about 200 million) are suffering from energy poverty [7].

Moreover, Total Final Energy Consumption (TFC) is quite unevenly distributed. In 2016, the average per capita TFC was 53.6 GJ/person, showing significant discrepancy among the different countries. The Gini[1] index of per capita TFC at a global scale is at 0.534, showing significant inequality in energy consumption. As a comparison, the same indicator is 0.222 between the 28 countries of the European Union, showing a much more even distribution.

Another major issue facing global energy production is the availability of resources. Fossil resources are concentrated in a few countries, many of which suffer from high political instability and low overall development. At the same time, several world areas show a significant level of energy dependency. In 2017 it was equal to 55.1% for the European Union and to 77% for Italy [8].

It is clear that the current energy paradigm is not sustainable, and a transition to a new system capable of overcoming the limits of the current one is necessary.

1. The Gini index measures the extent to which the distribution of a variable deviates from a perfectly equal distribution. A Gini index of zero represents perfectly equal distribution and 1, perfect unequal distribution.

This study aims to explore a possible pathway to implement a new energy paradigm in Italy and to estimate the potential benefits of this transition. Electrification can be a key tool for the transition towards a sustainable energy system. Electrification closes the loop of clean energy and efficient consumption; improves energy, environment, economy and social performances; boosts the share of renewables in final consumption.

This study shows how the energy triangle, a paradigm based on clean generation by renewables sources, electrification of final uses, and electricity exchange through efficient smart grids, can bring remarkable benefits. The positive impacts of the energy triangle include decarbonization, reduction of pollution and an increase in energy affordability, thus representing a viable solution to the above-mentioned issues.

The objectives of this study are:

- To discuss electrification as a major option for implementing energy transition in Italy, starting from the present status of electrification and building a forward-looking vision of possible scenarios at 2022, 2030 and 2050.
- To integrate a multi-focus perspective, with analysis of demand and supply, to study the potential electrification of three main sectors (residential, industrial and transport) and the possible renewable penetration for Italy up to 2050. The sectoral analyses, jointly developed by Politecnico di Torino (PoliTO), Massachusetts Institute of Technology (MIT) and Enel Foundation, are merged to build an integrated scenario, the so-called ITELEC2050 scenario, aimed to depict the future Italian electrification potential.
- To estimate the potential benefits of further electrification of the Italian energy system through the calculation of Key Performance Indicators in four different areas: energy, economy, environment and society. The results of the ITELEC2050 scenario are then compared to the main national and international scenarios available in scientific literature to understand how the developed scenario stands in the international framework.

1.2 THE ENERGY TRANSITION: CONTEXT AND CHALLENGES

1.2.1 Energy and economy

The energy cruciality for humanity is a well-settled concept, knowing that energy availability has impact at different levels, from sheer survival to the welfare of nations and social communities. According to the United Nations Environment Assembly, "people need clean air to breathe, safe water to drink, healthy food to eat, energy to produce and transport goods, and natural resources that provide the raw materials for all these services" [9]. In the ranking of basic goods needed by mankind to survive, energy comes immediately after air, shelter, water and food. According to the WEHAB Working Group[2], "although energy itself is not a basic human need, it is critical for the fulfilment of all needs. Lack of access to diverse and affordable energy services means that the basic needs of many people are not being met" [10].

The welfare of a nation or a society has been strictly related to the exploitation of energy resources and the economic development has been accompanied by an increase in the need for energy commodities. In 2016 the world Gross Domestic Product (GDP) was 3.9 times the value in 1971; over the same time horizon, the Total Primary Energy Supply (TPES)[3] grew 2.5 times larger. In the United States, the GDP in 2016 was 3.4 times the 1971 value, while the TPES 1.4 times. In Italy, the 2016 GDP was 2.2 times the 1971 value, while the TPES 1.4 times [1], [11]. The socio-economic growth showed a synchronous increase with respect to the energy consumption. At global level, analysing the historical time series, a significant coupling between energy demand and economic growth can be observed. If the annual growth rates of TPES and GDP are compared, a very close evolution is noticed [1]. Focusing on the last decades, the relevant and rapid simultaneous decreases of both TPES and GDP corresponding to the two global energy crises (1973 and 1979) and to the economic crisis (2008) are clearly identifiable. While in 1973 the global TPES and GDP were respectively 5.4% and 6.6% higher than in 1972, in 1974 their growth reduced to +0.6% and +2.0% with respect to the 1973 values. The same trends can be observed in 1980 (-0.4% for TPES and + 1.9% for GDP with respect to +3.1% and +4.2% of the previous year) and in 2009 (-0.9% for TPES and -1.7% for GDP with respect to +1.2% and +1.8 of 2008). It can be further noticed that the reduction of GDP registered in 2009 was the only annual decrease in the global GDP in the whole 1961-2016 time series, while reductions in TPES occurred in 1980, 1981 and 2009 [1], [11]. However, during recent years, energy and economy are being progressively decoupled, mainly thanks to the technological advancement and the improvements in energy efficiency, in turn driven by more and more urgent decarbonization needs. At global level, from 2012 to 2017 the GDP increased by 11.3%, but the TPES growth has been equal to only 3.7%. Similarly, in the European Union, over the same period, the GDP increased by 6.4%, while the TPES decreased by 3.1%. Italy followed a pathway analogue to the European one, even if characterised by a smaller GDP growth (+0.2%) and a stronger reduction in the TPES (-6.4%) [1], [11].

2. TWEHAB (Water, Energy, Health, Agriculture and Biodiversity) initiative was proposed by former UN Secretary General Kofi Annan as a contribution to the preparations for the World Summit on Sustainable Development (WSSD).

3. The Total Primary Energy Supply (TPES) corresponds to the overall energy needs of a country and, based on the definition provided by Eurostat [8], can be calculated as: TPES = local production of energy commodities + recovered products + net imports + variations of stocks – bunkers.

ELECTRIFY ITALY / 1. RATIONALE, CONTEXT AND OBJECTIVES

FOCUS BOX: ENERGY IN THE HISTORY OF HUMANITY

The history of humanity is accompanied by the evolution and development of energy technologies, from wood fire to renewables, to fossil fuels, to nuclear, back to renewables again. Energy evolution passed through several transactions in terms of energy sources, technologies and ways in which energy is exploited by societies. The use and control of fire since Palaeolithic firstly allowed to increase the human welfare, improving the nutrition (by supporting the penetration of protein-rich food) and introducing the possibility of producing light and heat, and it led to a progressive transition towards an economy based on agriculture and cattle breeding. During history and up to the Industrial Revolution, the technological evolution relied on the exploitation of four main energy sources: human and animal power, water and wind (especially through watermills and windmills). The industrial revolution, started in Britain at the end of the 18th Century, determined instead the transition towards the so-called "fossil fuel economy", characterised by the introduction of steam engines and a wide use of coal as key energy commodity. This led to a rapid and relevant technological development, especially in the industrial and transport sectors, with significant cascading effects on the society. Later, in the 19th Century, the penetration of electricity as energy commodity started. In 1882, the first coal-fired power station was built in London; in the same year the Pearl Street Station, the first coal-fired power station in the US, aiming at providing electric lighting to a part of the Manhattan Island area, went into operation. In 1883, the Santa Radegonda station in Milan (one of the first power plants in Europe) began to produce electricity; in 1884, during the Italian General Expo, Galileo Ferraris carried out the first electricity transmission experiment, connecting Torino and Lanzo through a 42 km long, 3000 V single-phase line. The 20th Century saw a dramatic increase in the role played by fossil fuels (mainly, petroleum products and natural gas), but also the appearance of a new energy source, the nuclear energy (in 1954 the Obninsk Nuclear Power Plant, in former Soviet Union was the first world grid-connected nuclear plant).

1.2.2 Energy and society

Energy consumption is unevenly distributed around the world. A relatively small share of world population and areas consumes a large share of global energy resources and can rely on substantial installed electric generation capacity. Besides a clear fairness issue, this situation suggests that the idea of providing the same level of energy access to the entire world population with the present paradigm (based on fossil fuels, large scale power plants and extended energy networks), is probably not the most viable one. This is true not only from a pure resource allocation standpoint, but also from the geopolitical and environmental ones. The allocation of a scarce resource is usually market-based, sharing the commodity based on the willingness (and ability) to pay, eventually causing social tensions and energy poverty concerns. Moreover, on one hand, a large part of fossil fuels production is concentrated in countries characterised by high levels of political instability and low levels of development; on the other hand, several world areas show a significant level of energy dependence (in 2017 it was equal to 55.1% for the European Union and to 77% for Italy [8]). These two facts clearly affect the geopolitical dynamics and are among the root causes of many international tensions and conflicts. The extension of the present prevalent energy paradigm would inevitably lead to an increase of such tensions and to relevant changes in the international geopolitical equilibrium. In this framework, the access to raw materials like rare-earth metals, fundamental to produce high-efficiency electrical appliances will play a relevant role.

In 2017, the average global Total Final Energy Consumption (TFC)[4] per capita was 53.6 GJ/person. In the same year, at country level, the same indicator showed large differences, ranging from 1.8 GJ/person for South Sudan to 430 GJ/person for Qatar. African countries, in general, were characterised by very low level of energy consumptions, and the average for the whole continent was 19.8 GJ/person. In 2017, in China the TFC per capita was equal to 60.1 GJ/person, in India to 18.3 GJ/person, in the EU to 94.2 GJ/person, in Russia to 141.4 GJ/person and in the U.S. to 194.5 GJ/person. Italy showed a slightly lower value with respect to the European average, with a per capita TFC of 82.4 GJ/person [1], [11], [12].

In order to quantitatively express the world energy inequality, the Gini index [13], which measures the extent to which the distribution of a variable deviates from a perfectly equal distribution, can be used. In particular, a zero Gini index represents a condition of perfect equal distribution, while a unitary value stands for a condition of perfect unequal distribution. As it is possible to note from Figure 1, the Gini index of per capita TFC at world level is equal to 0.534, showing a quite uneven distribution; as a comparison, the EU value is 0.222, indicating a more even distribution.

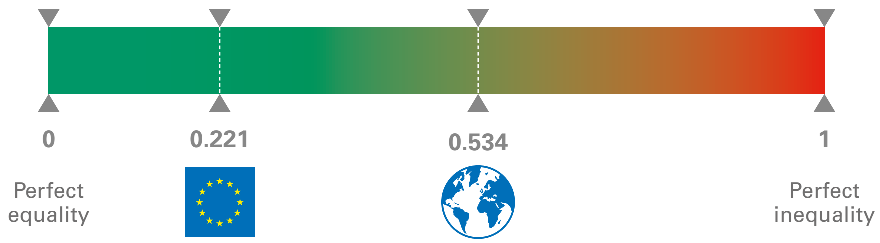


Figure 1
Per capita final consumption Gini index.

Another critical aspect is represented by the fact that, inside areas and countries, a large share of world population has no full energy access either because of a technology/infrastructure gap or due to problems with its affordability, giving rise to the so-called "energy poverty". According to IEA [14], in 2017, 13.2%

4. TFC is the amount of energy consumed for fulfilling the so-called "services demand" (space heating and cooling, lighting, industrial production, mobility of passengers and goods, etc.) in the different end-use sectors (agriculture, industry, residential, commerce and services and transport).

of the world population (around 992 million people) did not have access to electricity and this percentage grows when considering solely the developing countries (17%). The rate of electricity access shows large inequalities among the different areas of the planet. In fact, while countries like China and North Africa are able to almost ensure the full electricity access to their citizens, other developing countries like India still do not have a complete access (only 87.5% of the population in 2017). Sub-Saharan Africa shows a very low electricity penetration level, equal to an average of about 43% of population in 2017, even though the situation has improved since 2010 (23% of electricity access); in particular, there are countries in the Sub-Saharan region characterized by 1% electricity access rate in 2017 (i.e. Chad, Djibouti, South Sudan, Burkina Faso, etc.) [15]. Another indicator of energy poverty is the access to clean cooking; according to [15], the global share of people without access to clean cooking is 36%, representing 2677 million of people in the world. The highest percentages, again, are reached in Sub-Saharan Africa (84%) [15].

The "energy poverty" is not only due to the physical unavailability of energy infrastructures to produce, transport and distribute energy commodities, but also to the impossibility to afford the energy services, even if these are available. In this sense, the energy poverty can affect also developed countries, where modern and reliable energy infrastructures and services are available, but where a part of population can have difficulties in accessing them, basically for economic reasons (high energy costs with respect to households' incomes and spending capabilities). It has been roughly estimated that more than 15% of the entire population in developed countries (namely those belonging to the Organization for Economic Cooperation and Development, OECD), corresponding to about 200 million people, suffer from an energy poverty condition [7].

1.2.3 Energy and climate

The current energy system predominantly relies on fossil fuels, since 81% of total primary energy supply in the world is still produced using fossil sources, as depicted in Figure 2.

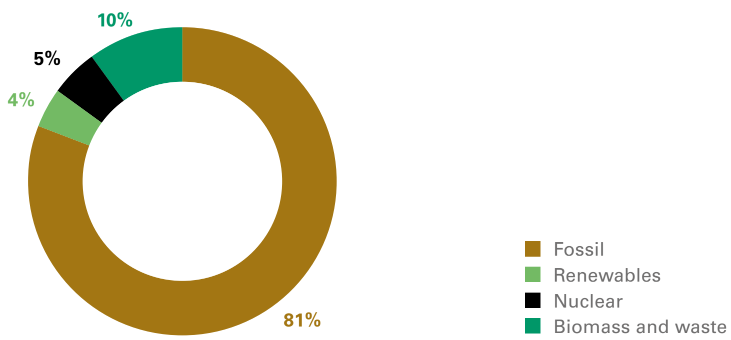


Figure 2
World total primary energy supply by fuel in 2017 [1].

Besides any considerations on their future availability[5], fossil fuels are very impacting from the point of view of GHG and air pollutant emissions, with drawbacks in terms of climate change, air/soil pollution and negative consequences on the life of biological systems.

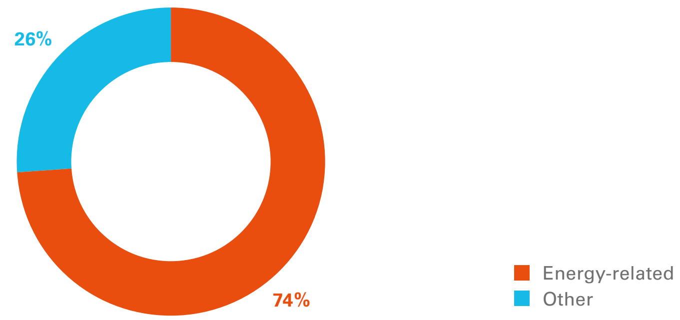


Figure 3
World total greenhouse gas (GHG) emissions in 2015 [18].

The energy sector alone accounts for two-thirds of total GHG emissions[6] (see Figure 3) and for 80% of CO_2 ones [16]. The sole operations (production, processing and transportation) in the oil and gas sector are responsible for a huge amount of emissions: it was estimated that in 2015 there were, globally, 76 Mt of methane emissions from oil and gas operations, roughly equally divided between the two commodities and due to several reasons, like process vent and leaks (from valves, seals, etc.) [17]. Moreover, other processes like the gas flaring and the combustion of a part of the produced/transported natural gas for plants operation (e.g. for compressor stations) lead to CO_2 emissions. More importantly, the transformation of fossil commodities into electricity and heat causes relevant greenhouse gas (GHG) emissions: in 2017 the electricity and heat production sector was responsible for 13.6 Gt of CO_2 emitted at global level, corresponding to 41.4% of the overall amount of CO_2 emissions [18]. Other less intuitive issues related to the exploitation of fossil fuels can be also pointed out, like the earthquakes (due to soil subsidence) originated by the extraction of natural gas, that lead to effects on the built environment and, consequently, to monetary

5. The current estimations for the reserves/production ratio at global level are 50.2 years for oil, 52.6 years for natural gas and 134 years for coal [15].

6 The most abundant greenhouse gases are: water vapour, carbon dioxide, methane, nitrous oxide, ozone, chlorofluorocarbons (CFCs), hydrofluorocarbons (HCFCs and HFCs). Totally, the gases are transformed in equivalent CO_2 emissions, through the computation of the global warming potential (GWP) index, which depends on both the efficiency of the molecule as a greenhouse gas and its atmospheric lifetime. GWP for CO_2 is assumed equal to 1.

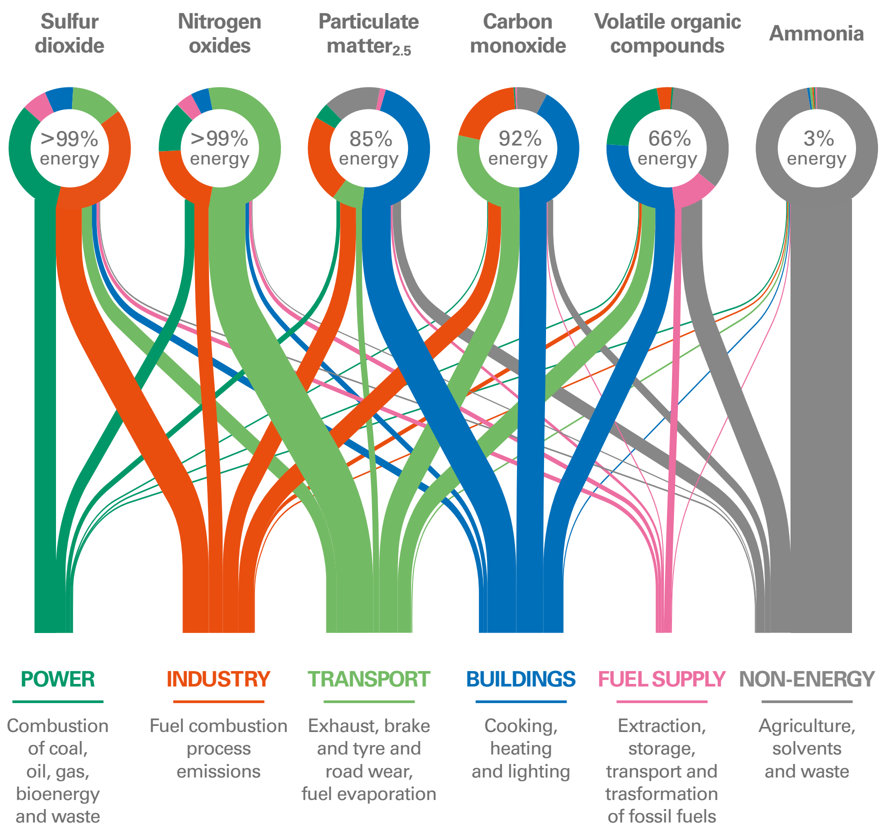


Figure 4
Air pollutant emissions from different energy and non-energy sectors in 2015 [4].

(damages to properties) and non-monetary (related to social aspects like a decrease in the living comfort and in life quality) costs. Regarding this aspect, Koster et al. estimated an overall non-monetary cost correlated to earthquakes induced by the activity in the gas fields located in Groningen (the Netherlands) equal to 170 million euros (corresponding to around 600 euros per household affected) [19].

In addition to global impacts, mainly connected to GHG emissions, local air pollution deserves major attention. The energy sector is responsible for most of the air pollutants at global level (>99% for both sulphur dioxide and nitrogen oxides, and about 85% for particulate matter 2.5) [4]. Figure 4 shows the main sources of GHG and air pollutant emissions at world levels, linking them with the major sectors (both demand and supply side). From the picture, it is possible to notice how, with the sole exception of ammonia (whose main sources are agriculture, solvents and waste), most pollutant emissions from human activities are energy-related.

Air pollution, whose impacts are more visible and problematic in urban areas, due to pollutant emissions from cars and heating systems in buildings, has a strong impact on public health. It was estimated that globally 7.3 million deaths every year are attributable to indoor (heating and cooking with biomass systems and lighting with kerosene) and outdoor (power generation and transport sector) air pollution (see Figure 5), and that 91% of world population lives in places where air pollution exceeds the World Health Organization (WHO) guidelines limits [5].

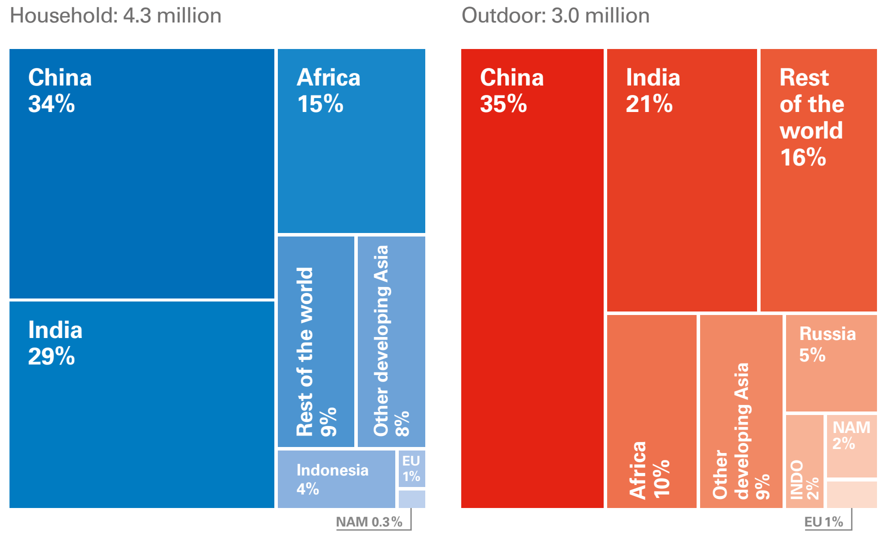


Figure 5
Deaths attributable to air pollution in 2012 [5].

1.2.4 Energy transition: the electricity triangle as a new paradigm

It is therefore clear that the current energy model is not sustainable, and that there is an urgent need for a transition towards a new system paradigm able to overcome the above-mentioned limits. Indeed, considering the historical energy trends, the increase in energy consumption worldwide (mainly from fossil sources) during the last century caused incremental negative effects. Its potential further increase, due to the expected additional contribution of the fast-developing countries that need to recover the gap, could lead to even more severe effects if a radical energy transition is not undertaken in time. The energy transition towards decarbonization implies the choice of alternatives to fossil fuels. Electricity generated from renewable sources is a good candidate, possibly in conjunction with hydrogen and biogas. Electricity, indeed, can be directly generated by the most relevant renewable energy sources (RES), like wind and sun, easily transferred over long distances and controlled with high efficiency. Furthermore, also most of the final uses based on electricity are characterised by high efficiency, especially compared to those that use fossil fuels.

ELECTRIFY ITALY / 1. RATIONALE, CONTEXT AND OBJECTIVES

The ***electricity triangle***, shown in Figure 6, concisely represents the concept of an energy system transition revolving around electricity as main vector.

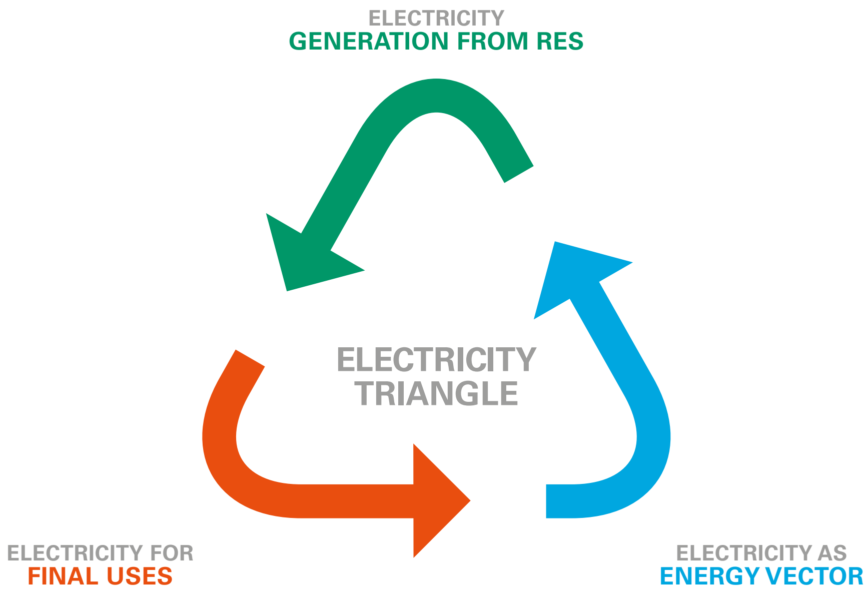


Figure 6
Graphical scheme of the electricity triangle as the basis of the electrification strategies.

The triangle is characterised by the following elements:

- ***Power generation*** from ***renewable*** energy sources (mainly wind and solar), avoiding thermoelectric generation.
- ***Transmission and distribution*** of energy through the ***electricity vector***, making power lines the key energy transmission infrastructures, and overcoming the role played by other energy transport alternatives like gas and oil pipelines and marine routes, railways and roads.
- Relevant growth of the ***electrification*** of energy ***end-uses***.

When dealing with electricity-based energy transition, at the opposite ends of a continuum of possible models, two possible reference paradigms for energy generation, transmission/distribution and utilization can be outlined. The first one is based on a small number of large RES generation facilities, concentrated in a limited number of production areas, connected with long-distance electricity transmission infrastructures to consumption areas ("super grids"); the second is based on the exploitation of locally available, small rated power RES resources, with the development of smart electricity systems ("smart grids"). The electricity triangle is a general concept, and it applies to any paradigm between – and including – these two extreme paradigms.

Nevertheless, the implementation of an electricity-based energy transition, is, in any case, strictly intertwined with the extensive deployment of digital technologies to improve reliability, economic and operational energy efficiency, in addition to the improvement in the efficiency of the end-use technologies. Digitalisation is a key aspect in the management of transmission and distribution networks and in the production section of the energy chain, under the perspective of a fast transition towards renewables. Digitalisation and electrification can lead to positive impacts from the point of view of an easier management of the energy systems and of their optimisation. The "internet-of-things" (IoT) will make it possible to connect the physical world (e.g. people, machines, materials, buildings, environment, etc.) to the information world (e.g. big data analytics), thus allowing to process data, providing analyses and foresights. In final energy uses, digitalisation will be relevant especially at urban scale, namely on mobility and building sectors. In the mobility sector, digitalisation could support, in the long term, the penetration of autonomous, shared and electric vehicles, thus allowing to decrease the demand for oil products. In the building sector, at global scale, it has been estimated that digitalisation could lead by 2040 to a cumulative reduction of energy consumption of 65 PWh[7] [20], which represents about two times the energy consumed in 2017 by the whole building sector (residential and commercial buildings together). Moreover, digitalisation could support demand response measures, like the shifting of heating and cooling loads and the optimal charging strategies for electric vehicles. Digitalisation could also impact on the social dimensions, nudging the habits of people and improving the quality of life in urban areas; this will allow the transformation of citizens from consumers to prosumers, enabling the so-called "energy communities". Even if attention should be paid to the new threats related to this configuration of energy systems (as cyber-attacks directed against the electrical networks and the digital control of power systems), the coupling between the maturity of the power sector and the innovation provided by digitalisation and ICT technologies could represent the winning option for effectively and positively facing the challenges of the energy transition through electrification.

1.3 ITALIAN ENERGY SCENARIO

Focusing on Italy, the current configuration of the national energy system still widely relies on fossil fuels. In particular, focusing on the Total Primary Energy Supply (TPES) composition, analysing the data provided by IEA [12] with reference to 2015[8], it can be noticed that coal, oil and natural gas accounted for 79.4% of the TPES (equal to 152.6 Mtoe). If the historical evolution is considered (Figure 6), however, some specific

7. 1 PWh = 10^{15} Wh.

8 IEA Headline statistics [12] recently provided data also for 2016; 2015 has been assumed as reference year for the project due to the limited differences in the energy mix, in terms of supply and consumption composition, among the two years.

aspects can be pointed out. First, after a peak in 2005, the overall TPES shows a decreasing trend. This can be related to the combination of two concurrent effects:

- The economic downturn that affected Italy, started from the 2008/2009 global crisis and whose effects spread over several years. This economic downturn led to a reduction in the national final consumptions and in the industrial production.
- A progressive increase in the overall efficiency of the energy system, also considering the need for meeting tight environmental targets of reduction of GHG and pollutant emissions arising from fossil fuel combustion. This is also reflected by the evolution of the energy intensity, which can be roughly considered an indicator of the "efficiency status" of a country, and that reduced from 0.079 toe/2015 $ PPP[9] in 2005 to 0.068 toe/2015 $ PPP in 2015 [21].

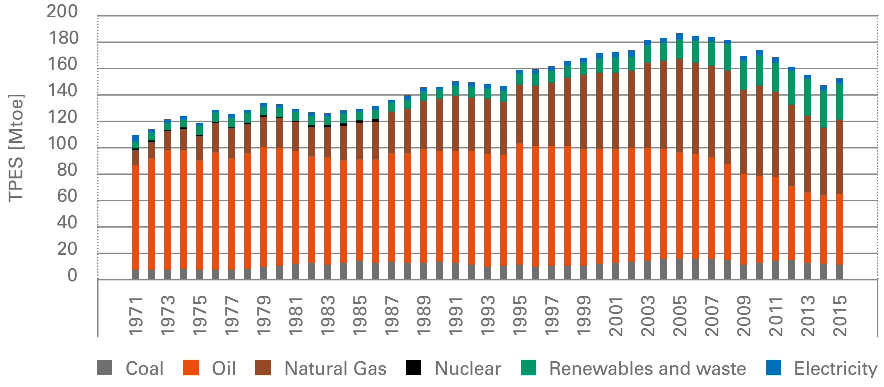


Figure 7
Historical trend of TPES by commodity type in Italy [8].

Furthermore, taking into account the composition of TPES by commodity [8], the relevant reduction in the role played by oil can be noticed: its contribution decreased by 75.1% in 1971 to 35.1% in 2015, in favour of natural gas, which comparatively is less impacting in terms of CO_2 emissions. Besides this shift from oil to natural gas, during the last decade a significant growth of renewables can be observed: in 2015 their percentage contribution to TPES reached a value of 18%. Coal and, more in general, solid fuels remain instead quite negligible (8.1%) and their role, due to the above-mentioned environmental constraints, is expected

9 This refers to the Gross Domestic Product (GDP) based on Purchasing Power Parity (PPP), which represents the "rate of currency conversion that try to equalise the purchasing power of different currencies, by eliminating the differences in price levels between countries" [22].

to further decrease during next years. Finally, it must be observed that the electricity taken into consideration in the TPES is related only to the net import from abroad, which remained quite stable over the last years [8].

The wide reliance on fossil commodities is strictly related to the high level of Italy's import dependence, which exposes the country to possible geopolitical risks associated to the energy supply. In 2015 the overall energy import dependence of Italy was equal to 77.1% [8]; higher values are related to the supply of the main commodities, in particular natural gas (90.4%, mainly from Russia) and oil (89.5%, with a more relevant diversification with respect to gas). This aspect allows to underline the effectiveness that the exploitation of locally available renewable sources can have not only from the environmental point of view, but also from the energy security perspective, by reducing the dependency on fossil commodities import.

Focusing on final energy consumption (equal to 118.9 Mtoe in 2015), it can be observed that transport sector provides the most relevant contribution, accounting for 30.6% of the total (Figure 8). Referring to this sector, it must be underlined that, unlike the others, it is almost fully dependent on a single commodity: oil products represent in fact the 91.2% of its TFC.

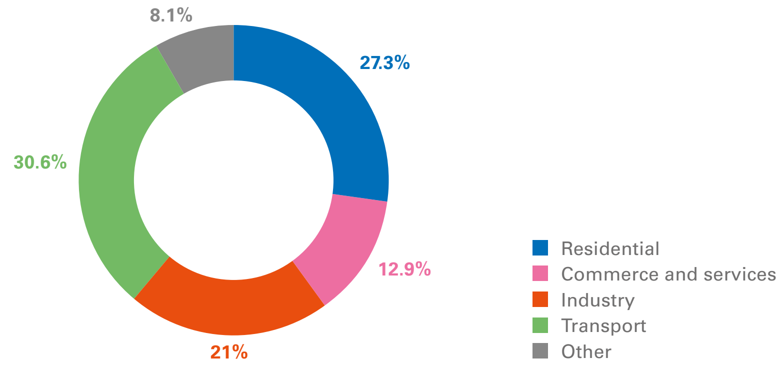


Figure 8
Final energy consumption by end-use sector in Italy in 2015 [8].

Considering the composition by commodity reported in Figure 9, a major role of oil products – due to their above-mentioned wide use in transport sector – can be observed. The shares of natural gas and electricity in final energy comsumption come respectively in the second and third place. In particular, referring to natural gas, 50.6% of the amount available for final consumption (equal to 33.6 Mtoe) is used in the residential sector (for space heating and water heating), 24.7% in the industrial sector and 19.4% in the commerce and services sector. 39.2% of the total electricity available (24.7 Mtoe) is instead consumed in the industrial sector, 32.0% in commerce and services sector and 23.0% in the residential sector.

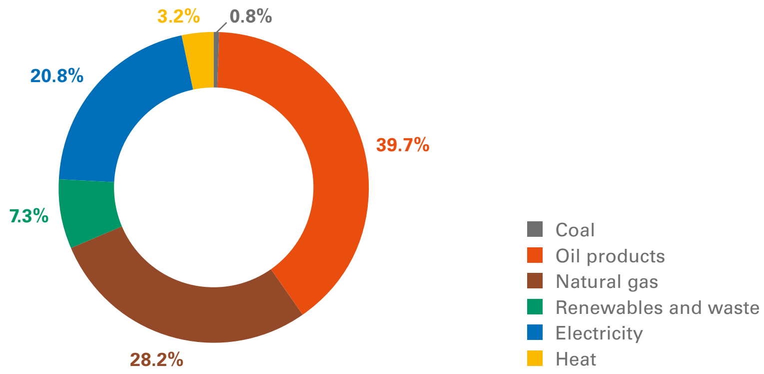


Figure 9
Final energy consumption by commodity in Italy in 2015 [8].

Linking energy and environmental aspects, Figure 10 shows the contribution of the different end-use sectors in total Italian GHG emissions in 2015. From the graph, it clearly appears that the highest contributions come from transport (32%) and industry (27%) sectors, due to the high reliance on fossil sources; the role of the civil sector (both residential and non-residential buildings) is particularly strong, while agriculture just contributes to 3% of overall emissions.

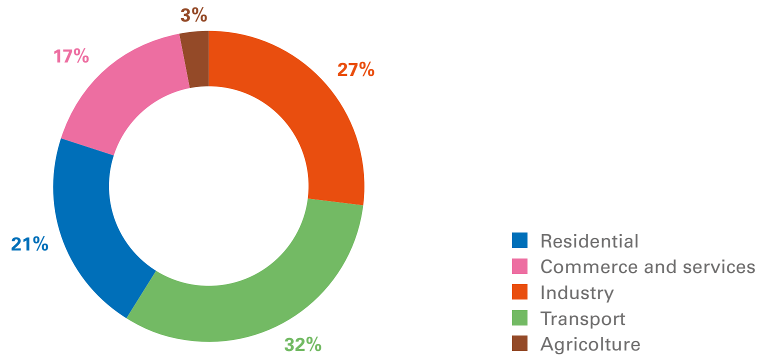
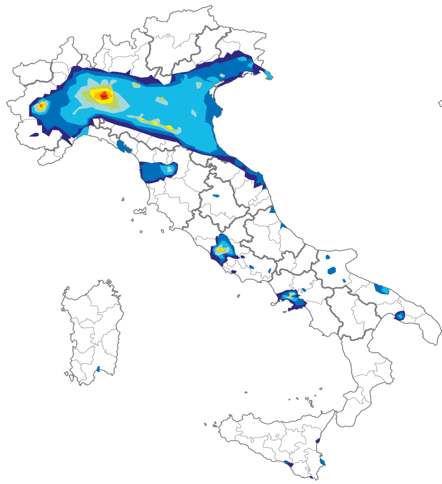
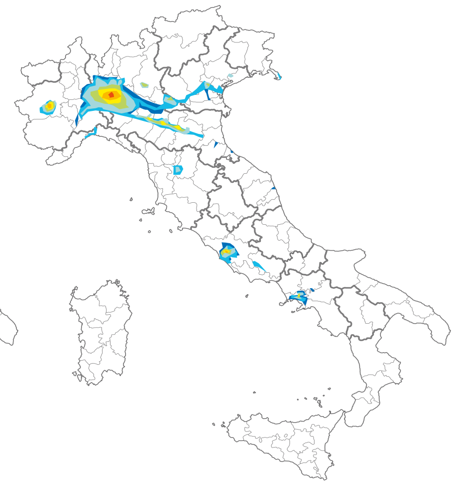


Figure 10
Share of GHG emissions by sector in Italy in 2015 [23].

As pointed out before, however, also the problem of air pollution is particularly strong in the Italian context. Indeed, according to the VIIAS study [6], in Italy in 2010, around 35,000 premature deaths may be related to air pollution (particulate matter, nitrogen oxides and ozone) exposure, as reported in Figure 11 and Figure 12.





Deaths/100,000 inhabitants

< = 10	21 - 50	81 - 100	121 - 150	201 - 250
11 - 20	51 - 80	101 - 120	151 - 200	> 250

Figure 11
Deaths due to PM 2.5 in 2010 [6].

Figure 12
Deaths due to NO2 in 2010 [6].

1.3.1 The role of electricity in Italy

Focusing on the end-use sectors and on the role of electricity, the comparison among the current electrification rates at global, European (also with reference to some of the most relevant Member States of European Union) and Italian level is shown in Table 1 [12].

	WORLD	EU	FRANCE	GERMAN	SPAIN	UK	ITALY
INDUSTRY	26.9	33.7	36.2	35.0	36.2	35.2	38.2
TRANSPORT	1.3	1.7	2.0	1.7	1.8	1.0	2.6
RESIDENTIAL	22.9	24.9	34.8	20.8	40.5	25.5	17.5
COMMERCE AND SERVICES	51.1	48.9	55.8	37.2	61.7	49.5	51.5
TOTAL	**18.5**	**21.2**	**24.7**	**20.1**	**20.7**	**20.8**	**20.7**

Table 1
Penetration rates of electricity by end-use sector at global, European and Italian level in 2015.

It can be noticed that the electrification status in Italy is almost aligned with the European average, in turn higher with respect to the global one. Considering the single end uses, as expected, transport sector is characterized by the lowest penetration, while half of the final uses in the commerce and services sectors are already electricity-fuelled.

In Italy, the residential sector shows the lowest electrification rate compared to the EU and world averages, making it a sector with wide potential for further electrification. Referring to the main services (space heating and cooling, water heating, cooking, lighting and use of electrical appliances), it can be noticed that some of them – lighting, space cooling and electric appliances – are fully satisfied by electric technologies. The highest electrification potentials lie in the heating (both space and water heating) and cooking services, which can shift towards electricity-based technologies that are already competitive on the market (i.e. electrical heat pumps, electric boilers, induction stoves). For this reason, sectoral policies aiming at supporting the penetration of these technologies coupled to a decrease in the electricity costs for final users could lead to a relevant increase of electrification in the residential sector, even in a short-time period. Moreover, the electrification of the residential sector can be coupled with measures able to further reduce energy demands and increase energy efficiency (by implementing appropriate retrofitting actions on envelopes).

The commerce and service sector, characterised by the same services of the residential one (space heating and cooling, water heating, cooking, lighting, use of electrical appliances), is already highly electrified, mainly due to the higher density of electrical appliances and the wider use of air conditioning systems compared to residential buildings. For this reason, despite an expected increase of the consumptions in future years, the sector has lower potential for further electrification with respect to the residential one.

As for industry and transport sectors, their electrification rates in 2015 are comparable to the ones of the other EU countries. In the industrial sector, a wider electrification of the productive processes, both direct (including the use of electricity for generating heat for industrial processes) and indirect (i.e. by using electricity for producing hydrogen or synthetic gases to be used in industrial processes), could be technically feasible during next decades, according to the studies available in the scientific literature, among which Lechtenböhmer et al. work [24] can be cited. By means of "what if" scenarios the authors assessed the applicability and the effects of electrification in energy intensive industries devoted to the production of basic materials up to 2050 [24]. In particular, the authors referred to the EU and took into consideration some of the most consuming industrial subsectors, like the iron and steel, the non-metallic mineral (which includes the production of cement, lime and glass) and the chemical (including the production of petrochemical products, ammonia and chlorine) ones. For each of them, they assumed a full electrification, implemented through ad hoc productive processes and technologies, as the adoption of electrowinning in the steel production, high temperature electro-thermal processes for non-minerals production, the use of synthetic gases obtained by means of electricity from renewables in petrochemicals production and the Haber-Bosch process (with hydrogen from water electrolysis) for the ammonia production.

In the transport sector, three main drivers will render electrification crucial: reduction in the emission of air pollutants and greenhouse gases, reduction in total transport cost, increase in reliability and system availability [25]. Indeed, the substitution of internal combustion engines (ICE) with electric motors can deal with all these elements. Electric drives typically show high reliability due to their structure, which is much simpler than that of ICE [26], and the efficiency in conversion of electric power into mechanical one is much higher than in the case of conversion of chemical energy stored in fuel into mechanical power [27]. Finally, electric solutions have clear environmental advantages, with respect to ICEs, decoupling the location where energy is used and those where combustion gases are released to produce electric power. Moreover, the option of producing electric power from renewable sources makes possible the design of transport systems where no combustion gas is emitted at any level. The actual possibility of increasing the electrification of transport systems is related with technological advances both in the field of batteries, and energy storage in general, and in that of electric motors construction and control [28].

Globally in 2017 the sole power sector was responsible for 41% of the overall emissions, thus resulting the major contributor with respect to transport (25%), industry (24%) and residential (6%) [17]. It is interesting to notice that if the electricity and heat production emissions are reallocated to the final sectors (proportionally to their consumptions), the percentage distribution among the sectors will change, resulting in a higher contribution from the industrial sector (almost half of the emissions), while building and transport counts for one quarter each. These data underline the need for modifying the power generation mix, going towards a wider deployment of renewables and a higher penetration of new electricity-based technologies in the end-use sectors, in order to reach an effective decarbonization.

To face the needs for energy systems transition, national and international (i.e. European) policy framework should bring more regulatory certainty and better encourage investments in the energy sector. Regarding this matter, the "Clean Energy for all Europeans" package was designed to push consumers to have an active role in the overall energy transition, fixing two main targets for 2030: 32% of renewable energy generation and 32.5% of energy efficiency [29]. This package goes hand in hand with the "Roadmap for moving to a competitive low-carbon economy in 2050", which targets an overall 80% GHG emissions reduction by 2050 (and 90% for the building sector). Recently, the EU increased its ambitions by launching the so called New Green Deal, a roadmap aiming to European carbon neutrality by 2050.

Focusing on Italy, the Italian National Energy Strategy (SEN 2017 [30]) plans to achieve a target of 28% of renewables in the total energy consumption at 2030, which corresponds to:

- 55% renewables in the power generation by 2030 with respect to 33.5% in 2015.
- 30% thermal renewables by 2030 with respect to 19.2% in 2015.
- 21% renewables in transport sector by 2030 with respect to 6.4% in 2015.

SEN targets have been updated with the "Piano Nazionale Integrato per l'Energia e il Clima" (PNIEC) [31], which has been recently published in its final form, after approval from European Commission. The plan envisages a 43% reduction of primary energy consumption by 2030 and a 33% reduction of greenhouse gas emissions (from energy sectors). This should be coupled to a share of 30% of renewables in the total energy consumption at 2030, which should be covered by 55.4% in the power generation, by 33% in the thermal sector and by 21.6% in the transport one (values slightly higher with respect to the previous SEN) [31].
In order to reach these goals, the current technological and energy mix of the end-use sectors and their potential evolution towards electrification should be investigated, assessing the impacts, costs, benefits and issues related to this transition. Different national and international long-term scenarios were designed in order to forecast the transition of the national energy system towards its decarbonization. Among them, ENEA [32] foresees a contribution of wind and solar PV to the Italian power generation by 2050 equal to 33% and 54%, respectively. The EU Reference Scenario 2016 [33] foresees instead an electricity penetration in the national final uses equal to 23% in 2030, 27% in 2040 and 29% in 2050.

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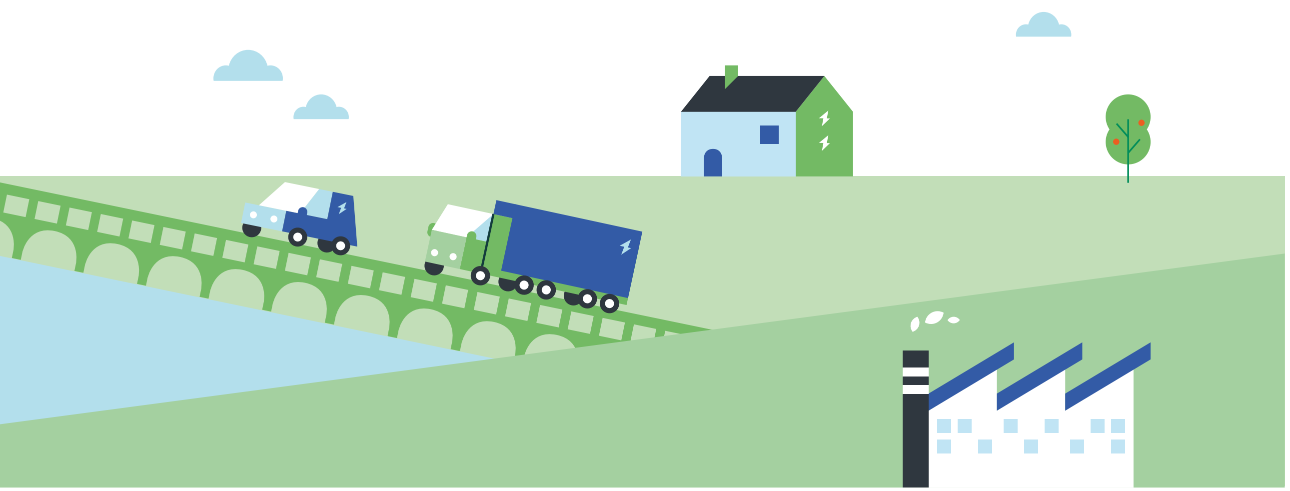
ELECTRIFY ITALY / 1. RATIONALE, CONTEXT AND OBJECTIVES

Chapter 2

METHODOLOGY AND STRUCTURE OF THE STUDY



2.1 METHODOLOGY AND STRUCTURE

As outlined in Figure 1, this work is based on the following elements:

- ***Players' perspective.*** Review of the perspectives on electrification of the main energy players through interviews with sector experts.
- ***Sectoral analyses.*** Analysis of the penetration of renewable energy sources in the energy supply and assessment of three key demand sectors: residential buildings, industry and transport.
- ***Scenario composition.*** Creation of a multi-sector scenario (ITELEC2050) composing the above analyses to represent a possible evolution of the Italian energy system up to 2050.
- ***Benefits evaluation.*** Key Performance Indicators (KPIs) calculation to evaluate the potential benefits of this transition in the energy, environment, economy and society dimensions, and comparative analysis with national and international scenarios.

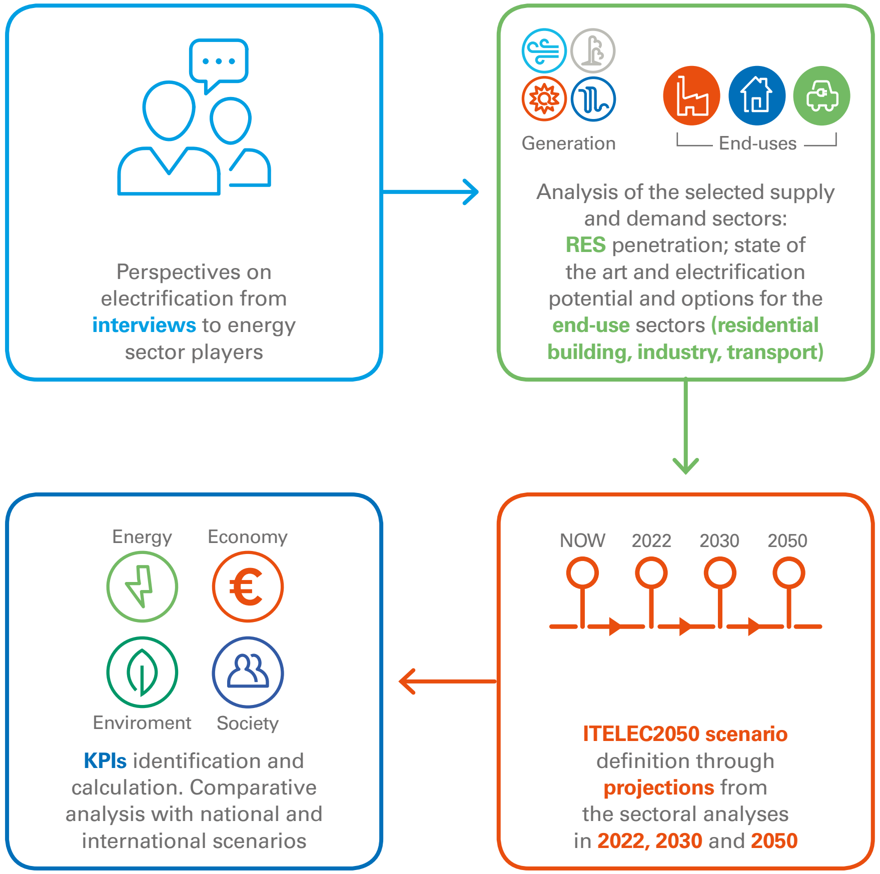


Figure 1
Structure of the study.

2.2 PLAYERS' PERSPECTIVES

The objective of this element is to identify the current perceptions of key players in the energy sector on the transition of the Italian energy system. The main areas of interest are their perceptions on the expected impacts, benefits, barriers and concerns regarding the electrification process. For this purpose, a sample of 16 representatives of the major players of the Italian energy sector were interviewed. The sample included experts from manufacturing companies, distribution system operators (DSOs), utilities, regulatory bodies. Chapter 3 explores this part of the study, reporting the main perceptions from the interviewed players in the framework of the project.

2.3 SECTORAL ANALYSES

The objective of this step is to analyze the supply side by assessing the penetration of renewables in the generation mix and to assess three key demand sectors: residential buildings, industry and transport. For each sector, the quantitative evaluation was carried out by means of specific methodological approaches, tailored on the peculiarities of each sector. The methods adopted are based on techno-economic analyses, aiming to take into consideration the most relevant aspects that can represent the key drivers and the enabling factors for supporting electricity penetration in the sectors. For each sector, the analysis started from the characterization of its current structure (assuming 2015 as reference year) in terms of adopted technologies to meet the services demand and of energy mix composition, highlighting the role that electricity currently plays and paying special attention to the environmental impacts (GHG and air pollutant emissions) that arise from current fuel mix. Each sectoral study defined a set of possible electrification scenarios and sensitivity analyses to assess the electrification levels according to different assumptions.

2.3.1 Analysis of renewable penetration

The assessment of renewable penetration in power generation is performed with a total cost optimization model. The GenX tool[1] is used for generation expansion planning (GEP). The study includes the main generation technologies available in the Italian power system, considering their evolution in the electricity mix by 2050. Three scenarios have been developed based on increasing CO_2 price levels: constant zero price, CO_2 price equal to IEA Current Policies scenario, and CO_2 price equal to IEA Sustainable Development scenario. This part is detailed in Chapter 4.

The key assumptions are:

- Retirement of coal-fired power plants by 2025.
- No constraint on the potential expansion for gas, oil and solar power plants.
- Installed capacity for hydropower and geothermal is constant over time.
- Expansion of onshore and offshore wind power generation up to 20 GW and 1 GW respectively in 2050.
- Two types of bioenergy modelled: cogeneration units assumed without expansion potential; electricity-only production units assumed to have expansion potential.

2.3.2 Assessment of key demand sectors: residential buildings

The detailed analysis is based on the minimization of the Global Cost for CO_{2eq} Avoided (GCCA) indicator[2]. GCCA allows for the identification of the optimal technology mix for carbon emissions reduction. This model is applied to thermal uses only (space and water heating) of the residential building stock evaluating their electrification potential in Italy, considering available technologies. Non-thermal uses (space cooling, cooking, lighting and electrical appliances) are then added to the model through projections based on historical data, to broadly explore the future electrification of the entire sector. As non-residential buildings represent only 10% of Italian building stock [1] and are already highly electrified (51%) due to high appliance density and high air conditioning demands, they are not included.

The evaluation of the electrification potential and of future possible technological trends is performed through the development of the "scenario FB[3]". The analysis is performed based on reference buildings representative of the Italian building stock, according to different typologies (Single Family Houses, SFH, and Multi-Family Houses, MFH) and periods of construction ("before 1980", "1981-2000", "after 2001"). Reference buildings are articulated in 5 geographical zones. Alongside the GCCA-based detailed study on space and water heating, also cooking, space cooling, electrical appliances, and lighting are accounted for.

All of the above analyses are combined to compute the overall residential sector consumptions in 2022, 2030 and 2050. The ODEX ("Energy efficiency index") [2] coefficient is then applied to adjust consumptions in accordance with the expected efficiency increase of the sector.

The key assumptions are:

- 1% annual new construction rate.
- 1.8% annual renovation rate.
- For each household, a maximum of one technology substitution over the entire timespan of analysis.

1. GenX tool is a generation expansion planning tool developed by the MIT.

2. Ratio between the global costs of the technological options and the related CO_{2eq} emissions avoided. The lower the indicator, the more convenient the technological option.

3. FB stands for "Focus Building".

- Oil dismission by 2030.
- No biomass usage in urban environments, in accordance with existing environmental policy constraints[4].
- New buildings are assumed to be fully electric.
- Substitution of gas stoves with induction ones is concurrent with the electrification of space and water heating.
- Incentive mechanisms fixed as in 2015 (Ecobonus and Conto Termico 2.0);
- Non-progressive concessional tariff for SFH with heat pumps as the sole space heating system.
- Energy price growth rates as per IEA projections [3].

With reference to scenario FB, other five scenarios are developed to highlight some key barriers and drivers to the electrification of the residential sector, and to provide possible strategies to further foster electrification. This part is detailed in Chapter 5.

2.3.3 Assessment of key demand sectors: industry

The methodology used to assess the evolution of the industrial sector toward higher use of electrical appliances is based on the definition of a bottom-up simulation model based on the minimization of the Levelized Cost of Heat (LCOH). For each time step (2022, 2030, 2050), for each industrial sub-sector, and for different temperature levels, the model computes the cost of heat production achieved by different technologies (electrical, gas, oil and coal) and updates the stock accounting with least-cost solutions.

The key assumptions are:

- Potential of electrification based on energy services (mechanical work, refrigeration, heating, lighting).
- The model investigates 9 electrical technologies and conventional gas, coal and oil technologies providing heat, at 5 different thermal levels.
- Key variables: capital cost, learning curves, conversion efficiency, technology improvement, inertial stock substitution, electricity/gas prices, carbon prices.
- Service and agriculture not included in the analysis.
- LCOH is calculated assuming a discount rate of 5%. An escalation in commodity prices, namely electricity-to-gas prices, is assumed based on data available from International Energy Agency.
- The model includes inertial stock substitution, estimated at 3% per year conventional technology stock substitution [4].

4. Some Italian regions (i.e. Piemonte, Lombardia, Emilia Romagna) have imposed constraints to the installation of biomass heating systems in urban areas, due to local air pollution issues.

- The model neglects innovation in competitive gas technologies (e.g., biogas, biomethane, CCS, etc..). Only one indirect electrical technology, namely power-to-gas for hydrogen production, is considered.

The study considers the evaluation of electrification under two different scenarios according to the table 1:

	DRIVERS			
	GDP and population	**Final energy consumption**	**Energy price variation**	**CO_2 Prices**
High electrification	OECD projections	Trend Extrapolation [5]	ETP 2016 [3]	ETP 2016
Beyond high electrification	OECD projections	Trend Extrapolation	Cumulative advantage[5]	ETP 2016

Table 1
Main model macro-scale assumptions.

The bottom-up simulation model estimates the stock accounting variation based on LCOH. For each time step, industrial subsector, and temperature level, the model computes the cost of heat production achieved by different technologies and updates the stock accounting with least-cost solutions assuming an inertial stock substitution estimated at 3% per year conventional technology stock substitution. The model calculates the stock time variation of gas, electricity, coal and oil appliances for heat production and updates the total final energy consumption mix. This part is detailed in Chapter 6.

2.3.4 Assessment of key demand sectors: transport

The transport sector analysis is based on the Fuelling Italy's Future (FIF) study [6], complemented with an additional study of electricity penetration in urban and extra-urban public transport, and then integrated with the projection of other transport modalities.

The analysis of road transport is based on modelling the consumption of different types of vehicles, taking into consideration the aerodynamic and internal friction efficiency, resistance proportional to mass, and inertial load. Based on the stock of vehicles and other constraints, the total consumption of different energy commodities is calculated.

5. In this scenario, electricity experiences a progressive reduction of the competitive disadvantage of price. This is achieved by introducing a synthetic yearly growth rate of 0.9 in retail price for electricity, while setting the gas growth rate to 1.1 for the same period.

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Other transport systems (trains, aircraft and ships) are integrated on the basis of historical data provided by Eurostat and projected considering an increase proportional to GDP growth rate. According to this model, the contribution of each transport mode to the consumption of each commodity is evaluated. The final values are added to consumption for road transport. In order to develop the model for railway, air and water transport, it is assumed that railway electrification will not increase in a relevant way, the penetration of electrification will be null in air transport due to technological constraints, and negligible in water transport due to the very slow substitution rate of ships.

The resulting transport model integrates city and long-range buses, air and maritime transport, trains, light commercial vehicles and passenger cars. This part is detailed in Chapter 7.

The key assumptions are:

- Cost of batteries and electric powertrain decreases by 60% and 25% respectively from 2015 to 2050.
- The efficiency of energy conversion and powertrain of electric vehicles increases 3 points from 2015 to 2050.
- City buses are 100% electric by 2050, assuming that Milan will have a fully electric fleet by 2030, while other cities are assumed to be slower in the substitution of ICE buses.
- Market and stock share of passenger cars is assumed by the Fuelling Italy's Future study– TECH Scenario.
- A slower uptake of EV (including PHEV) in LCV sector will bring EV penetration at passenger cars level in 2030.
- The electrification of long-distance heavy vehicles (coaches and trucks) reaches a penetration of 20% and 25% in 2050, starting to be relevant in 2030.

2.4 ITELEC2050 SCENARIO COMPOSITION

The outputs of sectoral studies are merged as inputs of a single scenario called ITELEC2050. The definition of the ITELEC2050 scenario represents the core of the study, encompassing the analysis and quantitative assessment of the electrification potential for the three main end-use sectors (residential buildings, industry and transport), together with the study of the decarbonization pathway of the Italian electricity generation through future higher penetration of renewable energy sources. The scenario, consistently with the supply and demand sectors analyses, spans until 2050, with intermediate steps for years 2022 and 2030.

To build the ITELEC2050 scenario, the following sub-scenarios at supply and demand sides were selected and used to assemble the overall integrated scenario, to depict a possible evolution of the Italian energy system up to 2050.

- ***RES:*** Current Policy scenario selected. It represents an intermediate among the ones calculated, based on different assumptions on CO_2 prices. This choice is based on the consideration that the impact of higher CO_2 prices is relatively limited in terms of CO_2 emissions and electricity production mix.
- ***Building:*** FB scenario selected. This scenario better reflects the current market regulation and business model in terms of incentives, tariffs and energy prices in comparison with the alternative scenarios, which have been developed to assess the impacts of some key variables on the electrification of the sector. The use of the GCCA indicator is consistent with this choice, representing compliance with current policy targets which are mainly focused on GHG emissions reduction.
- ***Industry:*** High electrification scenario selected. This reflects major international trends in commodity cost variation, learning curves, efficiency gains, and carbon pricing.
- ***Transport:*** TECH scenario was built based on the FIF study [6] related to passenger cars by adding on analyses of public transportation (urban and long-range buses), air and water transport, trains, and light commercial vehicles.

2.5 KEY PERFORMANCE INDICATORS DEFINITION AND ASSESSMENT

In order to assess to what extent the transition towards an all-electric, renewable-based energy system can reduce the impacts of the current system, it is crucial to identify and calculate appropriate Key Performance Indicators (KPIs) to quantify the impacts and benefits of electrification, allowing a comparison with other energy vectors.

Impacts and benefits of an energy transition cross the boundaries of energy systems and affect environmental and socio-economic spheres. The expected consequences of electrification can be related to different dimensions ranging from energy (that in turn includes the physical aspects related to energy flows and the ones related to energy efficiency), to the environment, in which sustainability issues play a key role, to the economy, in which market and business issues are critical, and to the society, related to the more general impacts on citizens and society as a whole. These four dimensions were considered in the framework of the project, in order to evaluate how the integrated multi-focus ITELEC2050 scenario stands in relation to these issues.

- ***Energy:*** this dimension is devoted to the understanding of how the electrification process might represent a viable pathway for energy systems decarbonization and how it will affect energy consumption and production and national energy self-sufficiency.
- ***Environment:*** the electrification process implies a transformation of the energy mix, shifting from the direct use of fossil fuels in end-uses to a

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larger utilisation of the electricity vector (which is by nature emission-free at the point of use) and deploying larger amounts of renewable carbon-free energy sources to match the demand. This dimension refers to how the electrification-driven transition of the energy mix is impacting on the environment at both global and local level. In this sense, both CO_2 emissions (affecting the climate) and air pollutant emissions (impacting on human health) are considered.

- ***Economy:*** electrification impacts on and is influenced by the national economy, policy and market trends. This dimension aims at catching how electrification can contribute to the decoupling between both energy consumption and greenhouse gas emissions with the economic growth.
- ***Society:*** consumers are key players in the electrification process but are also the final recipients of the transformation impacts. This dimension estimates the potential benefits of the proposed ITELEC2050 scenario on society.

These four dimensions are strongly intertwined, since environmental benefits are clearly related to the energy mix evolution, driven by market, business and policy trends, which in turn impact on consumers and, generally, on society. The quantification of the impacts and benefits on the four dimensions, expected by the ITELEC2050 scenario, is undertaken through the definition of a set of 19 literature-based Key Performance Indicators (KPIs), broken down as follows:

- 6 KPIs for the energy dimension, aiming to identify two different effects of electrification related to the overall energy use and to the self-sufficiency of a country. Attention is devoted to the positive/negative effects observed on the overall energy use and on its relationship with population increase/decrease. Specific indicators are used to estimate the role that renewables penetration will play in the power sector, in turn strongly related to the electrification of final uses, and to a higher diversification of energy sources (diversification indicators), this latter impacting on national energy security (national energy dependence).
- 4 KPIs for the environmental dimension, addressing issues at global and local scales. At global level, the CO_2 emissions reduction is estimated, trying to understand how electrification goes together with decarbonization. At local level, the estimation of reduction of pollutants (PM10, NO_x) aims at evaluating how a cleaner energy mix and a higher electrification of end-uses can contribute to better air quality.
- 4 KPIs for the economic dimension, aiming to explore the possible decoupling between both energy consumption and CO_2 emissions and the economic growth (measured by the variations in the gross domestic product, GDP).
- 5 KPIs for the social dimension, allowing to address the health benefits related to higher electrification in monetary terms, as well as to estimate the effects that the energy transition could have on energy expenditures for families.

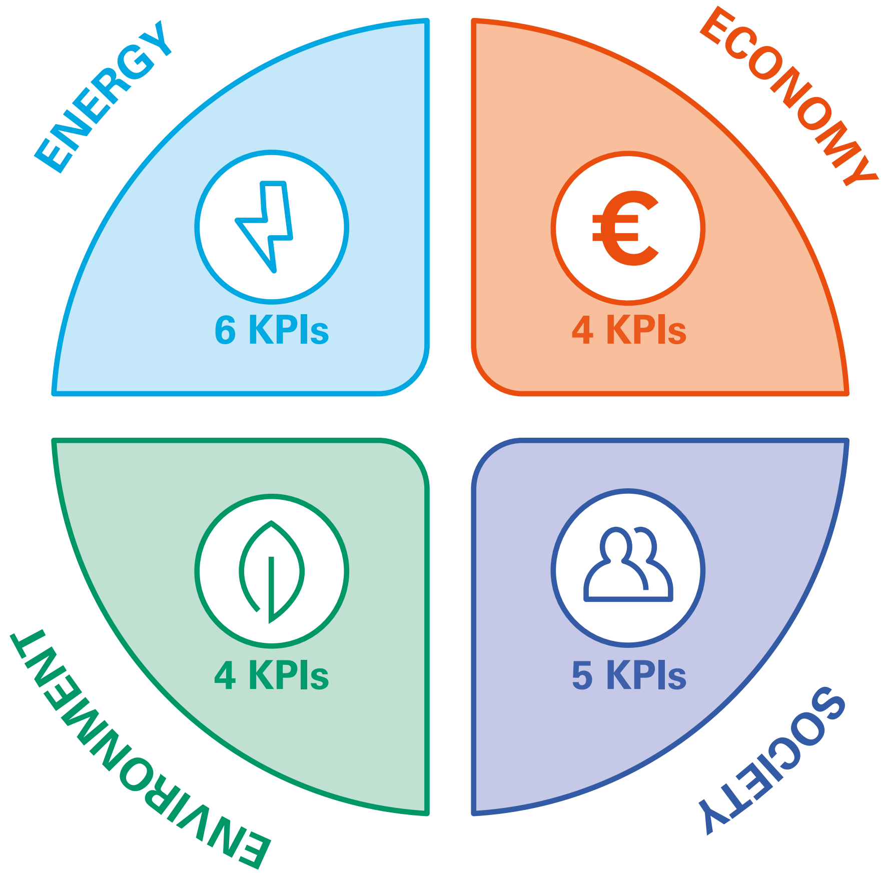

Figure 2
The four dimensions for benefit analysis of electrification.

The KPIs, whose definitions are purely literature-based, are computed for the milestone years (2015, 2022, 2030 and 2050). In Table 1 a detailed overview of the KPIs with their definitions is provided.

The KPIs allow for a multi-dimensional quantitative impact analysis and to extract and synthetize the most relevant information and results of the ITELEC2050 scenario to capture the wide-ranging impacts and benefits of electrification with a scientifically-sound approach. The main computations and highlights are reported in Chapter 8.

DIMENSION	SUB-DIMENSION	UNIT	DEFINITION
ENERGY	**Overall energy use**		
	Total primary energy supply (TPES)[6] variation	% w.r.t. 2015	Total primary energy supply variation, in relation to higher penetration of RES and reduction of end-use consumption.
	Final energy consumption (TFC)[7] variation	% w.r.t. 2015	Final energy consumption reduction from technology stock replacement, fuel switching and energy efficiency.
	Electrification rate	%	Share of electricity consumption over the total final energy consumption. Evaluated per each sector (building, industry and transport) as well as an average weighted value.
	Per capita final energy consumption (TFC) variation	% w.r.t. 2015	Ratio between total final consumption (TFC) and population[8].
	Diversification		
	Renewable share in electricity production	%	Share of electricity produced by renewables over the total produced electricity.
	National energy dependence variation	% w.r.t. 2015	Reduction of the net energy imports, calculated in relation to the total primary energy supply per each year.
ENVIRONMENT	**Decarbonization**		
	CO_2 emission reduction	% w.r.t. 2015	Variation of yearly amount of emitted CO_2 w.r.t. 2015.
	Decarbonization of the power sector	% w.r.t. 2015	CO_2 emission reduction in electricity generation w.r.t. 2015.
	Air quality		
	Particulate Matter (PM) pollution variation	% w.r.t. 2015	PM10 emission savings w.r.t. 2015.
	Nitrogen Oxides (NOx) pollution variation	% w.r.t. 2015	NO_x emission savings w.r.t. 2015.
ECONOMY	Energy intensity variation	% w.r.t. 2015	Ratio between primary energy consumption and GDP [9].
	Final energy consumption intensity variation	% w.r.t. 2015	Ratio between final energy consumption and GDP.
	Carbon intensity of GDP variation	$ktCO_2$/Billion €	Ratio between total CO_2 emissions and GDP.
	Weighted LCOE variation	% w.r.t. 2015	Variation w.r.t. 2015 of the Levelized Cost of Electricity (LCOE)[9], calculated without accounting for decommissioning & carbon costs.
SOCIETY	Healthcare savings related to air pollution variation	Billion € (cumulative w.r.t. 2015)	Cumulative heath savings for the society related to better air quality (PM10, NO_x, SO_2).
	Productivity savings related to air pollution variation	Billion € (cumulative w.r.t. 2015)	Cumulative productivity savings for the society related to better air quality (PM10, NO_x, SO_2).
	Life savings related to air pollution variation	Billion € (cumulative w.r.t. 2015)	Cumulative life savings for the society related to better air quality (PM10, NOx, SO2).
	Healthcare benefits related to air pollution variation	Billion € (cumulative w.r.t. 2015)	Cumulative total savings for the society related to better air quality (PM10, NO_x, SO_2).
	Affordability variation	% w.r.t. 2015	Variation of the share of income devoted to energy expenditures per household w.r.t 2015.

Table 1
Overview of Key Performance Indicators (KPIs) for each dimension.

6. The Total Primary Energy Supply (TPES) corresponds to the overall energy needs of a country and, on the basis of the definition provided by Eurostat [7], can be defined as:
TPES=local production of energy commodities+recovered products + net imports + variations of stocks – bunkers.

7. The TFC is the amount of energy consumed for fulfilling the so-called "services demand" (space heating and cooling, lighting, industrial production, mobility of passengers and goods, etc.) in the different end-use sectors (agriculture, industry, residential, commerce and services and transport).

8. Population projections are assumed from the UN population World Prospects 2017 revision [8] (medium variant).

9. This unit allows to compare the costs of a single unit of electricity produced by different power generation plants over their lifetime, and it is widely used in modelling and policy discussions. The LCOE can be defined as the price that a project must earn per each MWh produced, in order to break even. In other words, LCOE represents the cost that, if assigned to each unit of energy produced by the system over the analysis period (life-time), will equal the total life-cycle cost (TLCC) when discounted back to the base year [10]. The calculations done in this project include the investment, operation and maintenance cost (both fixed and variable), and fuel costs; carbon and decommissioning are excluded from the computation.

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2.6 COMPARATIVE ANALYSIS WITH EXISTING NATIONAL AND INTERNATIONAL SCENARIOS

Finally, the results obtained from the multi-focus ITELEC2050 scenario are compared with a set of selected mid/long-term national (and international including Italy-specific data) scenarios, to provide a more comprehensive view of the future expectations and forecasts about the electrification of Italy. The comparative analysis is performed based on the defined integrated assessment framework of the expected benefits (KPIs).

The scenarios are selected based on:

1. Time horizon (minimum up to 2022).
2. Geographical coverage (Italy/Europe/World).
3. Spatial granularity (national disaggregation).
4. Year of release (not older than 2012).
5. Sectoral coverage (at least one among building, transport, industry and power sector).
6. Data granularity (possibly to get quantitative information for all the needed comparison parameters).

According to the selection criteria, six different studies and the related reference scenarios are considered:

- Ministry of Economic Development, Ministry of Ministry of the Environment, Land and Sea Protection, SEN - Strategia Energetica Nazionale (2017)[10] [11]. The SEN-2017 is the National Energy Strategy proposed for Italy up to 2030.
- Bloomberg, New Energy Outlook (2017) [12]. The report provides an assessment of the key elements that will shape the power sector at global level from now to 2040.
- European Commission, Energy Roadmap 2050 (2012)[11] [13]. The report aims to develop a long-term framework for implementing at European level more effective energy policies, offering perspectives to deliver improved long-term energy security, sustainability and competitiveness.
- Eurelectric, Decarbonization pathways (2018) [14]. The report proposes scenarios at European level for understanding how to accelerate the energy transition and to which extent a shift to electricity can contribute.
- ENTSO-E, ENTSO-G (2018), TYNDP Scenario Report (2018) [15]. The report analyses scenarios to assess what is required, in terms of developing the electricity and gas infrastructure, for society to materialise the benefits of meeting European goals.
- Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations, Pathways to deep decarbonization in Italy, (2015) [16]. The report was written in the framework of the Deep Decarbonization Pathways Project, aiming to undertand how countries may transform their energy system to reduce climate change risks and decarbonising the energy system.

Two of the selected studies have a specific focus on Italy, two on Europe and two on worldwide trends. More details on the comparative analysis are reported in Chapter 9, aiming to understand how the originally-developed ITELEC2050 compares to other scenarios.

10. *Note that SEN has been recently updated to the "Piano Nazionale Integrato per l'Energia e il Clima" for 2030.*

11. *Note that, in 2017, European Union has agreed a comprehensive update of its energy policy framework to facilitate the transition away from fossil fuels towards cleaner energy and to reduce greenhouse gas emissions. This was started by European Commission's proposals named "Clean Energy for all Europeans Package", published in November 2016. The President of the new European Commission Ursula von der Leyen has announced initiatives to further increase the ambition during her mandate starting at the end of 2019.*

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Chapter 3

PLAYERS' PERSPECTIVE

3.1 OBJECTIVE AND FRAMEWORK FOR KEY PLAYERS INTERVIEWS

To effectively assess the long-term potential of electrification as a key option for implementing the energy transition, it is important to identify and discuss which are the current perceptions of various stakeholders on this topic. In particular, the expected changes and impacts, and the possible benefits and issues that can be related to this relevant and increasingly necessary shift of the national energy system should be scrutinized.

For this purpose, dedicated interviews to the major players in the Italian energy sector have been organized, involving experts from manufacturing companies, distribution system operators (DSOs), utilities, regulatory bodies and research institutions, in order to cover, as much as possible, the whole spectrum of stakeholders. The adopted approach allowed to perform a synoptic analysis of those interactions, thus obtaining a "subjective view", synthesised in terms of keywords and key messages, which can represent an important element for the comparison with the "objective view" given by the quantitative assessment of electrification perspectives in Italy carried out in the present study.

The synthesis of the ideas and messages provided by the players represents a sort of embryonic knowledge building process, as it allows creating a new integrated perception of the electrification pattern. The further sharing and dissemination of this knowledge could be helpful to better identify crucial and cross-sectoral aspects and issues and, thus, in defining proper strategies, measures and actions for effectively supporting the penetration of electricity in the country.

In particular, the methodological approach used for the interviews consists of five main steps:

1. Definition of key questions related to the electrification process as a mean for the energy transition.
2. Interviews to members of relevant national and international companies and institutions that play key roles in the electrification process.
3. Comparative analysis of the different perspectives provided by the players through a quantitative assessment of the occurrence of keywords during the interviews.
4. Graphic representation of the analysis of the cross-sectoral keywords related to the electrification through word clouds;
5. Extraction of the crucial keywords and elaboration of the key-messages arising from the interviews.

Each player was asked general questions regarding the concept of energy transition and electrification and then, depending on his/her sector, specific questions about the focuses of this project (building, industry, mobility and power sectors). The rationale of these questions was the identification of the strengths and weaknesses of the electrification process, thus highlighting which could be the advantages of this decarbonization strategy, the key enabling factors and the issues – with reference to different aspects – that must be faced in order to enhance electricity penetration.

The questions were related to the four main layers affecting the electrification process: social, market, policy and regulatory, and technology. The social layer includes the people acceptance of an electricity-based world, also considering the different perceptions (e.g. preparedness to take an active role in managing own energy needs, attitude and concerns about range of EV, quality of life, security) that individuals might have with respect to this new framework, and the needed changes in citizens' habits. The market layer includes the possible new electricity market paradigms (arising from a system configuration characterised by a power generation largely based on renewables, with almost zero marginal costs), and the new business models that may need to be established, in particular those related to the expected change in the role played by DSOs. The policy and regulatory layer considers the policy measures needed for fostering electrification, including possible support or removal of barriers to the penetration of electric technologies in the end-use sectors and the new regulatory mechanisms needed for the recovery of the investments in assets. Finally, the technological layer includes the technical solutions to be adopted in the different end-use sectors in order to better exploit their electrification potential, the identification of the proper paradigm or combination of paradigms for the electricity system (i.e. centralised vs distributed), and the investigation of the role played by storage and digitalisation in its future evolution.

The most relevant keywords were identified, quantitatively assessed and graphically represented. Key messages were identified thanks to a comparative analysis of the interviews, mainly addressing the aspects of digitalisation, paradigm change and evolution of business models.

3.1.1 Comparative analysis of the interviews

The comparative investigation of the contents of the interviews was performed according to two aspects: keywords and key messages.

The most relevant keywords extracted analysing the interviews of each player were ranked according to their occurrence. The list of the top five keywords (excluding most obvious words like "energy" and "electrification") includes "market", "system", "renewable", "technology" and "future". It can be further noticed that some top-ranking keywords for some players are specific, such as "batteries", "vehicle/vehicles" or "building".

The analysis of these keywords underlines that the economic aspects, including both market and financial elements, seem to play a major role for a large part of the interviewed experts. In fact, in the first 22 positions, 6 words are related to economy, namely market (2nd), cost (10th), customer (18th), price (19th), business (21st) and investment (22nd). This fact can be linked to the relevant transformation that the electricity market is expected to undergo with respect to the traditional configuration. This is particularly relevant in the occurrence of an evolution towards small-scale distributed systems, with the implementation of local energy communities that will need ad hoc and new rules and that will imply a possible significant modification in the role that TSOs and DSOs currently hold.

On the contrary, it can be observed that the environmental aspects are not ranked among the top positions: for instance, in the ranking of keywords, the words "sustainability", "environment", "emissions", "pollutions" do not appear. This could be probably explained by the fact that the main focus of players was on the technological options and on the market, political and regulatory perspectives of electrification and energy transition, more than on the causes that make urgent the implementation of an effective long-term decarbonization strategy, which – to some extent – is considered essential. To synthesise, it is not necessary to discuss about if and why the energy transition from fossil fuels to renewables must be carried out, but rather through which pathways, technologies, investments and policy measures it will occur.

In general, considering these keywords altogether, the players' perspectives seem to suggest that the future electrification of energy systems should be strongly based on renewables and on smart, digitalised distributed systems, flexible and highly efficient.

In this framework, the urban scale will have a crucial role, and cities should become the key centres of electrification, also considering the potential penetration of electricity-based technologies in the building and mobility sectors. Furthermore, the effectiveness of this transition will require from one side the essential definition of a suitable regulation, and from the other proper investments to support the technological substitution in the end-use sectors and the infrastructure development. Moreover, the evolution of the ratio between electricity and natural gas prices will deeply affect the speed and extension of transition. At present, this ratio is considered too high and therefore unfavourable to electrification.

The ranking of keywords has been also graphically represented through a "word cloud". Figure 1 shows some examples of this representation.

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Figure 1
Examples of graphical representation of keywords through word cloud for the whole set of interviews (up) and for Players 1, 7, 11, 16 (down), clockwise from top left.

Besides keywords, key concepts were extracted from each interview, and then compared and integrated in order to underline the convergence and divergence points, and to wrap up the crucial messages that define the holistic vision arising from the answers provided by the players.

First, all the players consider the energy transition as already started. Many of the players – essentially the ones related to the manufacturing and business sectors – think that in this transition natural gas could play a supporting role. However, other players (mainly those belonging to the digital sector) believe that the accelerators of the energy transition from the current model should be the electric mobility, the energy storage and the integration of renewables. For them it does not make sense to rely on natural gas and invest in natural gas infrastructures (thus generating stranded assets in the decarbonization perspective) during this transition phase from the actual energy situation towards the future decarbonized energy system.

For all the players, electricity and electrification of final uses are among the key drivers for the transition of the current energy system. The interviews showed that the sectors in which the electrification process could provide the greatest contribution in terms of reduction of pollutants, of transformation of the current system into a more sustainable one and of increase in the use of renewable energy sources are the transport, the heating, and the industrial ones.

Regarding the residential sector, the common idea of the players is that the electrification process of the heating service is already working thanks to available mature technologies like heat pumps, and consequently could be carried out in a relatively easy way, especially regarding space heating. This is coherent with the results obtained in this study, which foresees that in 2022 the number of installed heat pumps for space heating will be 6 times that of 2015, while in 2050 it will be almost 27 times. For water heating, instead, biomass boilers could be still a competitive option with respect to heat pumps, if the effects in terms of PM emissions are not considered as a key parameter for the choice.

Referring to the electrification of the industrial sector, it is considered still complicated but necessary. Looking at the current Italian industrial consumption, based on the estimations provided by the players, about 50% of it can be potentially electrified, especially with reference to thermal processes.

In the transport sector, the common idea is that there will be an increase in the production of electric and hybrid vehicles, but the penetration of these vehicles into the market will be affected by different factors. The recycling cost of batteries and the need for investments needed to enhance the travel range and to improve the recharging infrastructure network are the main ones.

According to the different perspectives proposed by the players, the electrification process shows clear benefits, even if still some barriers need to be overcome.
Interviewed players agree in identifying residential heating, transport and industry as the main sectors in which the electrification process might provide the greatest contributions in terms of emission reduction and an increase in renewable energy use.

The main perceived benefits of the energy transition are:

- Energy efficiency increase, thanks to electric-powered technologies.

ELECTRIFY ITALY / 3. PLAYERS' PERSPECTIVE

- An increase in renewable penetration.
- Subsequent decarbonization and the creation of a sustainable system.
- Creation of new jobs connected to the birth of new industrial value chains.

The main perceived barriers are:

- Need for new customer propositions and to overcome some negative perceptions.
- High initial investment cost for technology development and substitution;
- Current high electricity-gas price ratio.
- Inertia of existing infrastructure.
- Lack of adequate regulation to enhance the recovery of the investments required by the transition.

It is important to underline that the concept of regulation is instead seen in two different, and opposite, ways. From the regulators' standpoint, it is considered a driver for the electrification process. On the contrary, from an industrial perspective, it is considered a barrier to this process, as current regulatory schemes seem not able to allow the recovery of the relevant investments in assets requested by this relevant change in the energy system and new effective mechanisms have to be proposed and implemented. Focusing on the regulatory, policy and market aspects, incentives and a stable regulation are assumed to be necessary for the future.

Despite the differences, both industrial and regulatory players underline the crucial role of the regulator in a similar way, underlining that it should facilitate the energy system transformation. In particular, the common idea derived from the different perspectives is that the regulation about renewables must be adjusted in order to improve their integration in the energy market and, at the same time, to guarantee the security of the system.

In addition, the politicians should take the responsibility to guide and facilitate the energy transition through different forms of incentives. According to the players' perspectives, policymakers should be the main driver of change and the market cannot determine the rules by itself. Especially during the first phase, the transition towards electrification must be directly driven by policy makers, and then, when an equilibrium is reached, the market can enter in this transition. The idea of the evolution of the market is based on a controlled liberalism.

With respect to the technological evolution of the future energy systems, according to the players, the penetration of renewables in the power generation mix will be fundamental: by 2050 the share of renewables into the electricity production system is expected to reach nearly 100%. The results obtained in this study confirm an evolution towards this direction, forecasting an 85.6% share of renewables in the power generation by 2050 in the "Current Policy scenario" (included in the ITELEC2050 scenario), and a share higher than 90% in the "Sustainable development scenario". This renewables penetration is associated, by most of the players, to the concepts of demand response and flexibility. These two aspects are considered a starting point for increasing both RES penetration and electrification of the system. Furthermore, according to the interviewed experts, renewable penetration is strictly linked with the technological evolution in the battery sector. Batteries appear to be the way to overcome the problem of managing the variability of renewables.

Taking into account the role of non-electric options (or indirect electric options, like hydrogen) in this future perspective, some of the players foresee a combination of different solutions that is expected to play a supporting role with respect to the electric option. For instance, hydrogen may be used as a solution for storing renewable energy, municipal wastes may be used (through a proper management) for district heating systems and biofuels may be applied to the long-range transportation.

Focusing on the possible paradigms (centralised vs distributed generation) through which implementing the electrification process, the role of centralised and distributed electricity production is seen in a quite common way by all the players. They foresee an increase in the distributed generation systems, but the complete transformation of the energy system will be achieved through a proper mix of distributed and centralised solutions: both small-scale and large-scale solutions will be deployed, driven by market conditions.

Some players also believe that distributed generation can be helpful in reducing the ratio between electricity and gas prices, which today represents one of the barriers to the electricity penetration.

About the diffusion of distributed systems, some of the players belonging to the regulatory sector added a consideration related to the increase of cost in terms of system charges and the introduction of implicit benefits. In fact, the owners of distributed energy production systems do not pay system charges. Therefore, the amount of system charges that must be paid will remain the same, but the number of final consumers that have to pay will be lower. This means that this cost will be charged to the bill of consumers that do not have their own energy production system, thus determining an extra cost for the final customer, which must be properly redistributed.

Finally, considering the future evolution and the new business models that are expected to arise, the players pointed out that the increase in the distributed energy generation will imply a relevant change from a market perspective: the business is moving towards the sale of services. Consequently, in the future a new type of business model will tend to be predominant, with services linked to the management of the kWh being sold instead of the kWh itself.

Associated to this transformation, according to the players' perspective there will be a modification in the role played by DSOs, which will become

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more active in the market, changing from typical system operators to more sophisticated providers of services to network users. DSOs will continue to be responsible for the planning, management, operation and maintenance of the distribution network; their role will evolve to exploit the opportunities offered by the technology and market evolution and to cope with the challenges brought by intermittent renewable sources and flexible loads. In particular, DSOs will have to face the need for integrating highly volatile and dispersed distributed generation, for managing increased loads and capacity due to the electrification of transport, heating and cooling, and for handling the impact of changing customer behaviour and market requirements. Furthermore, in this evolving context, a better coordination between TSOs and DSOs will be necessary.

The evolution of the consumer is another relevant topic. Consumers, both industrial and residential, are becoming more and more sophisticated, aware of sustainability and efficiency, and they will require to take advantages from the flexibility deriving from the new distributed generation and load control opportunity. In this framework, the traditional producer-consumer-distributor model is expected to significantly change and to enable consumption experiences that are different from those of the past.

Moreover, the energy transition through electrification will be probably matched by increasing role played by digitalisation, which is considered a concrete opportunity. The players agree on the fact that it will help the electrification process and that both these elements (electrification and digitalisation) will be a pillar of the energy transition towards decarbonized systems.

In particular, the digitalisation process will pave the way for new business models, and it will imply the creation of new jobs, characterised by different skills for the operation and maintenance of the digitalised energy systems. This means that the impact of digitalisation – that will spread over the entire energy chain (from production to final uses) – will require to generally rethink the labour market and it is thus expected to have relevant impacts not only from the technical, but also from the social point of view.

Besides these benefits, the digitalisation process could also enhance some energy security issues, especially those related to cyber-security, which will certainly have an increasing relevance and which should be carefully taken into consideration due to the possible large-scale and disruptive effects that cyber-attacks against power networks and, in general digitalised systems, could determine.

In conclusion, the development and the re-elaboration of the key concepts encountered during the interviews have shown that electrification is and will be an unavoidable process for the Italian system. This transition will determine an important paradigm change and an evolution of the final consumer's role and behaviour in the future energy scenario. In particular, it is expected that the final consumer will pay more attention to the sustainability and energy efficiency concepts.

To facilitate these radical modifications, it has been highlighted by players the need for implementing a clear regulation system, aligned with the new requirements arising from this transition phase.

Finally, it became evident the necessity to improve existing infrastructures through proper investments and to find a solution for a better integration of renewables in the national system, since all players expect a significant increase in the percentage of electricity production from renewable sources (that it is hoped to reach almost 100% by 2050).

3.1.2 The word to the players: quotes from the interviews

In this section, some of the most relevant statements extrapolated from the interviews and leading to the previously discussed key messages related to the energy transition and the electrification perspectives are reported.

- "For what concerns the penetration of renewables we are going to have an increase in the share of distributed generation, and to better coordinate the variability of these energy sources we will need a wider and better cross-border integration of markets. So, it's likely we will ask to move in both direction, large scale interconnection and distributed generation."
- "We believe that the most important sectors regarding the electrification process are the transport, the heating and the industrial production ones."
- "Shifting from predictable demand and supply patterns toward more decentralised and volatile power flows in many directions will drastically change the shape of distribution networks. This will also require a transformation of the traditional DSO business model – from 'pipes'-based to platform-based, to meet the growing expectations of customers and enable all types of market parties."
- "We will use digitalisation for improving the operation in terms of efficiency. We are looking at predictive maintenance, at high connectivity for linking systems digitally with different ways of control, at the communication with our customers and at new business models. It is clear that digitalization will create new business models."
- "Energy transition might be the transformation of the energy sector towards a higher sustainability, an evolution that is driven by different forces but the first and most important is urbanization."
- "I think that for the future, incentives, and a stable regulation will be necessary"
- "I think the transformation of the electricity system should pay for itself."
- "I think that the energy transition in the building sector will be the decisive moment to start this process that I call Building 4.0: digitalisation of building sector."
- "One benefit deriving from electrification is distributed energy, because an increased number of distributed power generators will lead to an increase in employment, meaning social benefits for the modern society, as well as environmental benefits."
- "We are on the way to reach a new type of business where the services linked to the management of the kWh instead of the kWh itself will be sold."

Chapter 4

POWER GENERATION FROM RENEWABLE ENERGY SOURCES

4.1 OVERVIEW

A substantial expansion of renewable energy in the electricity sector is needed to achieve future electrification and decarbonization goals. The main objective of this chapter is to evaluate the current status and future outlook (i.e. for 2022, 2030, 2050) for renewable electricity sources (RES) in Italy, considering the present challenges and solutions for relevant dimensions, such as technology advancement and environmental impacts. The chapter aims to provide quantitative projections for future RES penetration levels in Italy and corresponding impacts on selected KPIs, based on recent historical trends, as well as a cost-based analysis of future generation expansion in Italy.

Here RES penetration is explored along different dimensions. In the system paradigm, there are categories of small-scale distributed (e.g. residential solar PV) and large-scale concentrated (e.g. utility-scale wind and solar farms) sources that will contribute to future RES. In order to integrate these resources in the power grid, services and functions such as Demand Response (DR) and building-to-grid solutions may play an important role. In terms of technologies, advances in wind and solar technologies are obviously of major importance for a large-scale RES expansion. Moreover, energy storage solutions (e.g. grid level battery storage, EVs, etc.) and advances in communication and control will contribute to address the uncertainty and variability in RES. In general, technology advancements reduce the cost of RES and related system integration technologies [1], which will make RES more competitive compared to traditional power plant technologies. In turn, this will facilitate a change from traditional generation systems towards a new resource mix where RES plays a much more prominent role.

The move towards more electrification and higher RES shares may also influence important social dimensions, including more engagement of the public in energy choices, e.g. through the establishment of so-called energy communities, and increased customer choice through new market products for trade of RES and flexibility. Moreover, the expansion of RES addresses global environmental challenges and most importantly the desire to combat global warming through reduced greenhouse gas (GHG) emissions. This is an increasingly urgent challenge, as illustrated by the recent report by the Intergovernmental Panel on Climate Change (IPCC), which illustrates that large-scale and rapid reductions in GHG are needed to keep the average global temperature from rising more than 1.5°C [2]. Large-scale expansion of RES combined with electrification of energy supply constitutes one of the key solutions to the climate challenge. Towards this end, it is clear that energy-environmental regulations, as well as electricity market design are critical to enable a rapid transition towards high RES levels in the power grid. Finally, innovations in business models for the energy sector are also important as a mean to attract investments in RES and related grid integration technologies. These aspects are discussed in more detail in the following sections.

4.2 CURRENT SECTORAL STRUCTURE

Thanks to the decarbonization movement in the energy sector and the commitment of European countries to move towards cleaner energy supply, the European Union (EU) has seen a significant increase in its installed capacity of RES in the past decade, leading to a higher share of RES in the final energy consumption. Figure 1 shows the increase in installed RES capacity from 2006 to 2016 in the EU, which more than doubled in 10 years [3]. The RES technologies with the main contributions to growth in this period were wind power and more recently solar power. Similar data for Italy reveals that the RES installed capacity had an even higher growth rate in Italy compared to the EU as a whole between 2006 and 2016 (Figure 2). In Italy, the solar capacity increased from 45 MW to more than 19,000 MW, while wind power also experienced a strong growth to reach more than 9,000 MW by 2016.

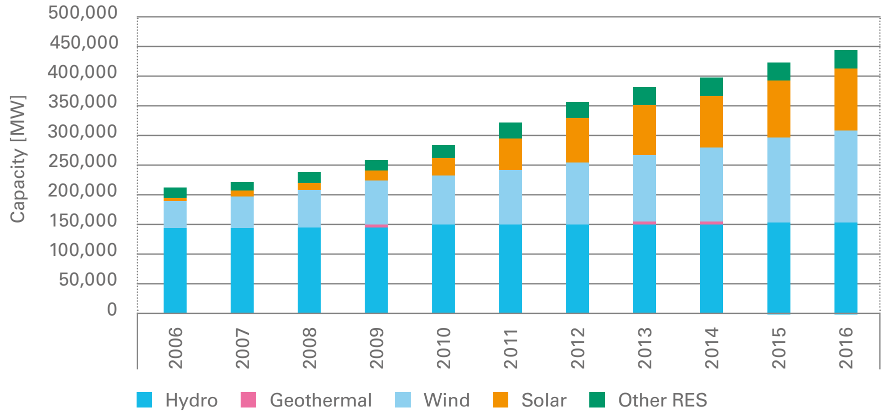

Figure 1
EU 28 RES installed capacity [3].

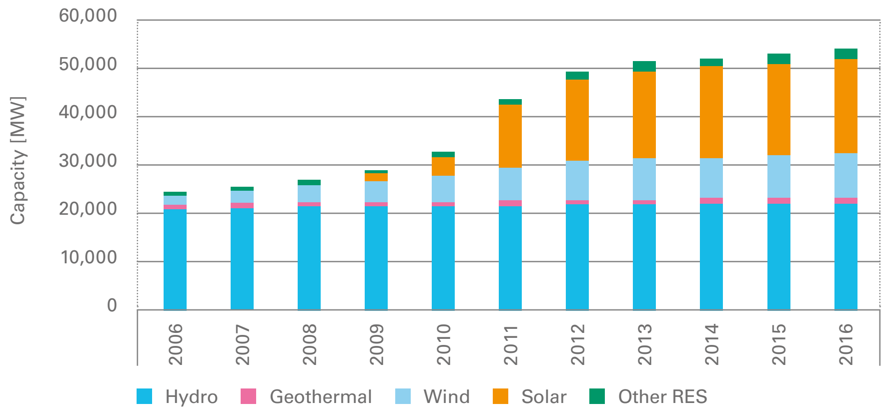

Figure 2
Italy RES installed capacity [3].

The increased installed capacity of renewables in the EU and Italy has also led to increases in RES generation and its share of total electricity supply, as illustrated in Table 1. The percentage share of RES in the EU total electricity generation increased from 15.4% to 29.6% between 2006 and 2016. This growth rate was even higher for Italy, which experienced an increase from 15.9% to 34.0%. The substantial growth over the last decade indicates a promising future for renewable electricity in Italy. Historical data also show that among the different RES technologies, solar energy had the highest growth rate in the last decade from 34.9 GWh in 2006 to 22.1 TWh in 2016. However, hydroelectricity is still the largest RES resource in Italy, with more generation than from wind and solar combined in 2016. Table 1 shows that hydroelectricity was also the largest RES resource in the EU in 2016, but with wind power not far behind in terms of total generation. Moreover, hydropower did not see much growth in the last decade, as available hydro resources are largely exploited already in Europe.

Considering these historical data, renewables are already playing a significant role in the electricity sectors in the EU and Italy. The rapid expansion of RES in recent years was driven by fast technology advances, but also in response to various incentive and subsidy schemes provided by governments for new clean energy technologies. If this trend continues, RES will become the dominant source of electricity within the next one to two decades. In fact, in EU's energy outlook for 2050, decarbonization scenarios, including high energy efficiency, high RES penetration, low nuclear energy, etc., aim to have more than 50% RES share in total energy consumption [4]. Still, the future evolution of electricity supply in the EU and Italy will be affected by many uncertain factors, including the rate of technology advancement, the energy-environmental policy landscape, people's willingness to pay for clean energy, and the saturation of available RES.

ELECTRICITY GENERATION FROM RES [TWh]

	EU		ITALY	
	2006	2016	2006	2016
Hydro	343.7	350.1	42.4	46.2
Wind	82.4	311.2	3.11	16.5
Solar	2.49	110.8	0.035	22.1
Solid Biofuels	48.2	91.4	2.3	4.1
All Other Renewables	36.8	96.4	8.3	21.6
Total electricity from RES	513.6	959.9	56.2	110.5
RES % share of total electricity generation	15.4%	29.6%	15.9%	34.0%

Table 1
Electricity generation from RES and share of total electricity generation [5].

Lowering environmental impacts from the energy sector is an important concern for European governments, with a particular focus on reducing GHG emissions. From 2006 to 2016, the EU-28 countries were successful in reducing their total GHG emissions by 18%. Italy was even more successful, achieving a 26% reduction in GHG emissions over the same time period [6].

One of the major sectors responsible for GHG emissions is the electricity sector. Therefore, reduction in GHG emissions is one of the major drivers for investments in RES. According to [6], the RES expansion in the period 2006-2016 reduced the overall emissions of the electricity sector in the EU and Italy by 25% and 35%, respectively, which account for 8% and 10% reduction in the total GHG emissions. This fact illustrates the importance of focusing on RES in the path towards reaching future GHG emissions reduction goals. Figure 3 shows the GHG emissions in Italy for all sectors and the electricity sector between 2006 and 2016. Moreover, combined EU Emissions Trading System (ETS) and Effort Sharing Decision (ESD) emissions are depicted in Figure 4, showing that the reduction in EU ETS emissions has been higher than reductions in ESD emissions. Overall, the trends displayed in these two figures also illustrate the importance of electrification in GHG emissions reduction efforts across all sectors.

If the recent trends in GHG emissions reduction continue, the future view is promising. For instance, the EU ETS's goal of a 43% reduction in GHG emissions will be achieved before 2030. It is important to note that the efforts should not be concentrated only around GHG emissions, as reduction in pollutants (NO_x, SO_2, PM, etc.) are also important. Among these pollutants, the electricity sector is responsible for substantial portions of SO_2 emissions, but less significant portions of NO_x and PM emissions [7]. Higher penetration of RES will decrease these emissions as well.

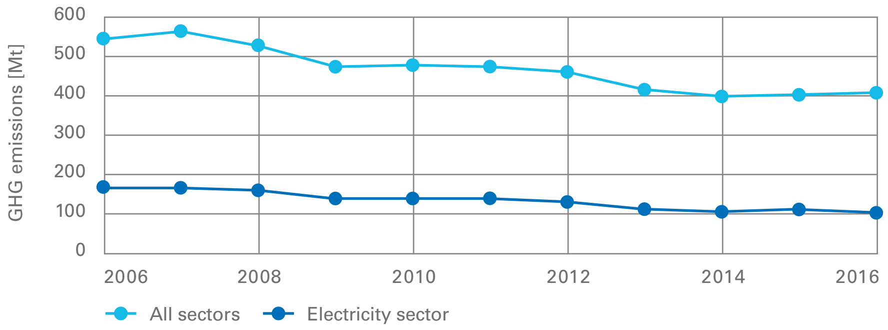

Figure 3
Italian GHG emissions [6].

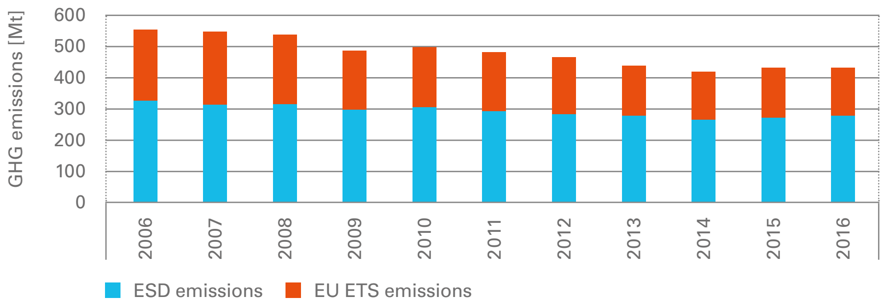

Figure 4
Combined GHG emissions from EU ETS and ESD [8], [9].

4.2.1 Technology perspective

Technological development in the last decade and innovations in RES technologies have led to a significant decrease in the total cost of electricity generation from RES. Globally, from 2010 to 2017, solar energy had a large reduction in its levelized cost of electricity (LCOE) from 0.36 $/kWh to 0.10 $/kWh, according to [10], which estimates a more modest reduction from 0.08 $/kWh to 0.064 $/kWh for wind energy over the same period. Note that the actual LCOE is very location dependent. Looking at data for Italy, solar and wind energy had 75% and 43% drops in their LCOE from 2010 to 2017, respectively [10]. These reductions in the technology costs contribute to more adoption of RES in the future power systems. Although the future trend of LCOE reduction may not be as fast as historical trends since technologies mature, exploring projections of the RES cost is very illustrative. For instance, according to the U.S. Information Administration (EIA) [11], the LCOE for solar plants entering service in 2040 is expected to decline as much as 60% compared to 2018, with the LCOE for wind and hydro also expected to see some decline in the future. These expected trends of technology cost reduction are in favour of more RES penetration in the future power systems.

As pointed out above, the technology cost is location dependent and the future RES penetration in Italy will be dependent on developments in investment, operation and maintenance (O&M) costs for these technologies. In order to gain some insights into the future of RES in Italy, it is therefore important to explore the future expected costs of RES in the EU. Future cost trajectories to 2050 are reported for hydro power, wind, solar, geothermal and bioenergy (electricity production and cogeneration plants) in [12]. Based on this report from the European Commission, the future costs of renewables can have considerable variations depending on the scenario considered. The International Energy Agency (IEA) reports that the motivation for higher RES capacity installations and corresponding reductions in CO_2 emissions is the main driver of RES cost reduction in different scenarios [13]. For example, the investment cost of wind technology is projected to be in the 800-1,200 €/kW range for onshore and 1,300-3,100 €/kW range for offshore in 2050. However, the investment cost for utility scale PV is projected to be much cheaper, 250-750 €/kW, according to [14]. These cost projections indicate a promising future for investments in solar and wind technologies. On the other hand, cost trajectories for hydropower and geothermal does not show significant change in the future, in part because they are naturally limited resources with modest opportunity for further expansion. Bioenergy is another renewable option; however, its fuel cost tends to be substantially higher than for other technologies. Projections of the capital cost and fixed and variable O&M costs for different RES technologies in 2022, 2030 and 2050, based on [12], are presented in Table 2. The cost projections of thermal power plant are also provided for the sake of comparison. It is important to note that the fuel cost is not included in the variable O&M costs and comes in addition. The cost data in Table 2 are used as inputs in the cost-based capacity expansion presented later in this chapter.

	CAPITAL COST [€/kW]			FIXED O&M COST Fixed [€/kW/y]			VARIABLE COST [€/MWh]		
	2022	2030	2050	2022	2030	2050	2022	2030	2050
Wind: onshore	1268	1161	943	14	14	12	0.18	0.18	0.18
Wind: offshore	2632	2048	1891	39.8	31	28	0.39	0.39	0.39
Hydro: reservoir	3000	3000	3000	25.5	25.5	25.5	0.32	0.32	0.32
Hydro: run of river	2440	2400	2300	8.76	8.2	8.1	0	0	0
Hydro: pumped 8-hour	3500	3500	3500	30	30	30	0.4	0.4	0.4
Solar PV	700.6	663	454	12.24	10.8	9.2	0	0	0
Battery Storage 3-hour	1000	570	405	11	6.3	5.5	0	0	0
Geothermal	3760	3198	2613	91	95	105	0.32	0.32	0.32
Bioenergy	1290	1250	1050	27.9	24.3	23.3	2.56	2.56	2.56
Gas combined cycle	714	690	640	15	15	15	2.31	2.31	2.31
Gas open cycle	403.2	403.2	403.2	15	15	15	3.5	3.5	3.5
Coal	2380	2300	2150	46.42	44.9	41.9	5.12	4.96	4.6
Other non-RES (Oil)	1200	1200	1200	20.7	20.7	20.7	2.76	2.76	2.76

Table 2
Technology cost projections [12].

Even though the cost trends of RES technologies are very promising, the uncertainty and variability in renewable resources create challenges in the operation and planning of power systems that can limit future penetration levels for RES. The key challenge to facilitate a cost-effective integration of RES is to increase the flexibility in the power system and thereby its ability to accommodate the varying RES availability. For instance, energy storage represents one prominent solution for RES integration which is receiving increasing attention. However, although energy storage may enable higher levels of RES, the cost of energy storage will add to the total system costs and must be competitive against other solutions. Currently, the main energy storage technology in Italy is pumped hydro storage, with an installed capacity of 7.4 GW, which is partially pure pumped hydro and partially combined with reservoir hydro plants [15]. Other energy storage options for the future of Italy's power system can be electrochemical energy storage technologies, such as Li-ion batteries and flow batteries. The cost of electrochemical energy storage has dropped very fast in recent years and continues to decrease. Figure 5 shows the capital cost trend of one type of Li-ion batteries, i.e. Lithium Iron Phosphate (LFP), and redox-flow batteries' capital cost projections [16], [17]. This cost reduction will encourage the combination of renewables and storage systems to solve the challenge of uncertainty and variability in RES such as wind and solar energy. Note that the effect of demand side management in RES adoption is not studied in this work, but flexible demand and other technologies are also expected to play an increasing role in balancing RES in future power systems.

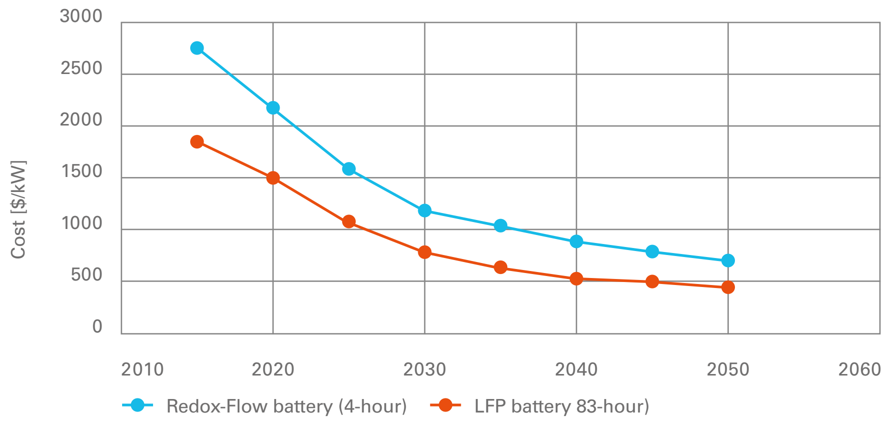

Figure 5
Projected trend for battery storage technologies costs [16], [17].

4.2.2 Market regulation role

The rapid increase in RES in recent years has already had an impact on electricity markets. Analysis of historical market data indicates that low-marginal cost resources, such as wind and solar power, tend to reduce prices in some electricity markets in Europe and in the United States [18]. Moreover, the variability and uncertainty in these resources add complexity in operations and planning for electricity market and power system operators. A key challenge is to enable a more flexible power system in order to integrate RES in a more seamless and cost-effective manner. Below, electricity market design and regulatory options from short- and long-term perspectives are briefly discussed, as well as specific options to provide a more flexible future power grid, building in part on [19]. Most of the proposed solutions are general in nature and apply to Italy, as well as other countries and regions, in the transition towards a future low-carbon electricity supply with high RES shares.

Measures to improve short-term electricity market operations

In short-term market and system operations, the objective is to run the power system at minimum cost while maintaining system reliability and security. This is done through a series of markets from day-ahead scheduling to real-time balancing. The key coordination signals for market participations to make scheduling and dispatch decisions are the prices in energy and ancillary services markets. Increasing shares of RES creates higher variability in net load and therefore increased need for all supply, demand, and storage resources to respond to the grid conditions, which need to be reflected in the market prices. Towards this end, several measures should be considered, including:

- Improved scarcity pricing to ensure that consumers' willingness to pay for electricity is reflected in market prices during scarcity situations. Efficient scarcity prices will provide incentives for investments in flexible resources and also for these resources to respond when needed.

- Moving the closing of day-ahead markets closer to the operating day and/or shortening time frames of intraday markets. This will enable market participants to make better informed operational decisions as RES forecasts improve closer to real-time. Moreover, traditional resources with long start-up times who benefit from today's market time line will play a less important role in markets with high RES shares. The planned introduction of a continuous intraday market in Italy will address these issues.

- Higher frequency of real-time dispatch and market clearing will provide price signals that better reflect the continuously changing status in the grid, and provide improved incentives for system flexibility from supply, demand and energy storage.

- Improved representation of transmission in market clearing to better reflect congestion in prices. For instance, the recent introduction of flow-based market coupling across Europe is a step in this direction, although it does not provide the same granularity in prices as markets in the United States based on locational marginal prices.

- Co-optimization of energy and reserves ensure the most cost-effective dispatch solutions. Ideally, this should be done not only in real-time balancing as is currently the case in Italy, but also in day-ahead and forward markets. Provide incentives for flexibility through forward markets for reserves.

- Treating RES as dispatchable resources that respond to market prices, thereby providing additional flexibility in grid operations, particularly during surplus conditions.

- Enabling market participation of distributed energy resources and demand response through improved coordination of transmission and distribution systems and markets. This may be achieved by further introducing additional pricing structures and recognizing distribution system operator's role in the management of distributed supply, demand, and storage resources.

Solutions for long-term resource adequacy

In the long-run, the key challenge for electricity markets is to provide incentives that ensure that sufficient resources are available to meet system adequacy and reliability needs. Capacity adequacy has been a long-standing challenge in most regions that embarked on industry re-structuring and the move towards competitive electricity markets in the 1990s and 2000s. Although prices for energy and operating reserves in principle should give rise to optimal capital investments, several factors may prevent this from happening, such as price caps, limited price responsiveness of demand, and the nature of reliability as a public good. The downward pressure on electricity prices from low marginal cost RES, which have been introduced at least partly in response to specific RES incentive schemes, tend to exacerbate the so-called "missing money problem" in electricity markets. However, the key challenge in future electricity markets will still be to get the price formation right in the short-term, as long-term prices and incentive signals are based on short-term price expectation. With improved price formation, the reliance on explicit and administrative capacity remuneration mechanisms will be reduced. Currently, several different mechanisms have been proposed and implemented in various parts of the world, with the main categories illustrated in Figure 6. However, these administrative mechanisms remain controversial in many places and no consensus is emerging regarding what is the best approach to resource adequacy. For instance, Italy is currently in the process of establishing a capacity market, while other solutions are present in other parts of Europe, including capacity payments and strategic reserves as well as energy only markets. The different national solutions to resource adequacy and capacity remuneration mechanisms may give rise to challenging cross-border implications.

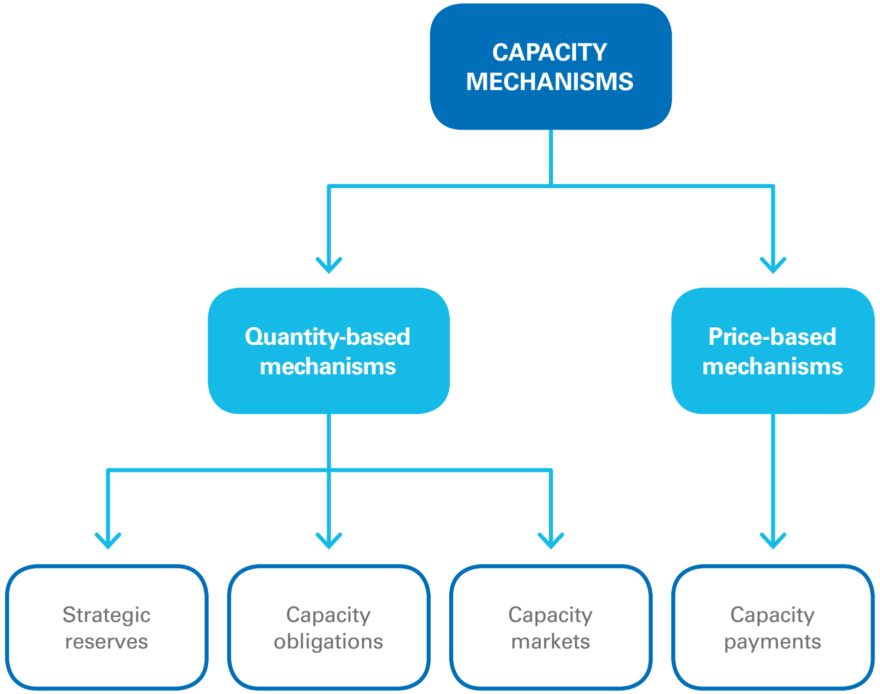

Figure 6
Overview of the main capacity remuneration mechanisms [19].

The measures to improve short-term electricity market operations discussed above will contribute to better price formation in electricity markets and thereby provide better investment signals. From a long-term resource adequacy perspective, additional solutions to achieve an efficient market in the long run include a gradual removal of technology specific subsidy schemes for RES to remove the biases they introduce on electricity prices. A better approach would be to establish adequate pricing of carbon emissions and other environmental externalities as a more market compatible incentive scheme for clean energy resources as they reach technological maturity. A carbon price would allow different technologies to compete on equal footing with operating costs adjusted based on their greenhouse gas emissions and corresponding impacts on the environment. A European-wide carbon price also reduces the cross-border challenges from different national solutions. Another key challenge for resource adequacy is to ensure liquid long-term markets for efficient risk management and sharing. Innovations in contract design between different market participants may also contribute to improved risk management, revenue sufficiency and resource adequacy in the long run. Overall, reforms to improve price formation in short- and long-term energy markets will ideally reduce the need for regulatory market interventions through explicit capacity remuneration mechanisms in the long run. Still, the current situation in Italy is characterized by insufficient market signals for new investments in dispatchable capacity and cost recovery of existing capacity in order to support system adequacy.

Flexibility solutions for renewable energy integration

System flexibility becomes more important in power systems with high RES shares, given the need to address the uncertainty and variability in wind and solar energy. It is therefore important to consider system flexibility in future electricity market designs. In principle, system flexibility can arise from multiple sources, from improved system operations (e.g. with use of advanced RES forecasting), better markets (e.g. through high-resolution dispatch and pricing and other measures discussed above), transmission expansion and topology control, and increased used of flexibility in demand, supply, and energy storage resources. In order to achieve a cost-effective integration of RES it is important to consider all of these measures, which include “software” as well as “hardware” solutions. It should also be recognized that the relative economics of the various renewable integration solutions change over time. For instance, electrochemical energy storage has traditionally been considered an expensive technology for RES integration, but recent and expected future technology improvements and cost reductions (Figure 5) contribute to make batteries a more viable option for the future. Overall, an important objective for electricity market design is to provide incentives for the most cost-effective flexibility solutions to prevail over time.

4.2.3 Business models

Another critical aspect of a high RES future is the business models that underlie investments in RES technologies. Important considerations for large-scale RES investments include the possibility of signing long-term contracts for energy delivery, for instance through power purchasing agreements (PPAs). Such contracts, which are commonly used in the United States, provide investors with reduced revenue risk and therefore more favourable financing conditions than sales into the volatile spot market. In the short-term, direct RES incentives, e.g. through auctions, feed-in-tariffs, or other instruments, are also important drivers for investments in clean energy resources. However, in the long run it is likely that these incentives will gradually disappear. At that point, carbon pricing will be the main environmental policy influencing short-term electricity prices, long-term contract prices, and therefore investments in new generation capacity. Another important consideration for RES is the participation in capacity markets – if they exist – as well as potential provision of operating reserves, as additional sources of income beyond energy sales. Large generation companies will also have to consider the role of RES among other technologies in their resource portfolio, both in terms of profitability and risk exposure.

Investments in distributed energy resources, including RES, are partly also driven by other factors. For instance, innovation in resource allocation and pricing of distributed RES may increase the interest in local energy communities and other energy sharing solutions. Emerging technologies such as block chains may potentially serve as an enabler for such solutions. An important and unresolved question is the role of aggregators in facilitating the interaction between prosumers and wholesale markets. Tariff design under increasing shares of distributed resources also has a major impact on business models. For instance, net metering tariffs typically encourage investments in distributed resources such as solar PV, but, depending on the design of the mechanism, may reduce revenues for distribution companies [20].

4.3 METHODOLOGY

Based on the analysis of the historical trends presented above, which shows that there has been a significant increase in the RES penetration in Italy’s power system in the last decade, attention is focused on exploring how the RES share may evolve in future years. First, present projections based on the assumption that the historical growth rates in RES investments from the last decade will continue through 2050 are presented. Not surprisingly, this scenario results in very high penetrations of RES in the future Italian energy system. Next, a least-cost generation expansion model is used to investigate the future supply portfolio of the Italian power system, based on assumptions about future technology costs and carbon emissions policies. The objective of the latter analysis is to investigate under what conditions a high RES future, like the one indicated by extrapolating historical trends, may emerge.

4.3.1 Future projections based on the last decade’s trend

If the average growth rate of RES in the Italian power system over the last decade continues at constant pace, simple projections indicate that RES will reach 25%, 33% and 52% share of the final gross energy consumption by 2022, 2030 and 2050, respectively. These results are in line with similar studies, e.g. IRENA predicts 30% share of variable RES in Italy by 2030 in its roadmap for a renewable energy future [21]. Also, the goal of the EU in its Energy Roadmap is to have 50% RES share in primary energy consumption in Italy by 2050 [4]. As the RES role in the electricity sector is the focus of the study, the percentage values of RES share in electricity consumption are also projected. Extrapolation of the historical data estimates that 59.3% and 95.5% of electricity in Italy will be met by RES by 2030 and 2050, respectively. Although these projections seem to be very optimistic, other studies have concluded with similar estimates, e.g. Strategia Energetica Nazionale (SEN) have predicted 55% RES share in electricity production by 2030 [22] and IDDR/ENEA in Pathways to Deep Decarbonization in Italy have predicted up to 93% RES by 2050 [23]. The projections for RES share in energy and electricity supply obtained based on historical trends are summarized in Figure 7 for EU and Italy.

The projected high RES penetration decreases the use of fossil fuels for energy supply, i.e. primarily oil and gas in Italy. In 2016, gas and oil combined supplied 75% of total energy consumption in Italy, while renewables supplied roughly 15% [24]. However, the trend is that fossil fuels use is decreasing as the share of RES is increasing. Figure 8 shows the energy consumption by source in Italy, for historical as well as projected future years. The general trend in recent years has been a reduction in the total energy consumption, possibly due to the more efficient energy infrastructure systems and also the global economic downturn that started ten years ago. If these trends continue to 2050, RES reaches an energy supply share above 50%, with natural gas being the dominant supply of non-RES sources.

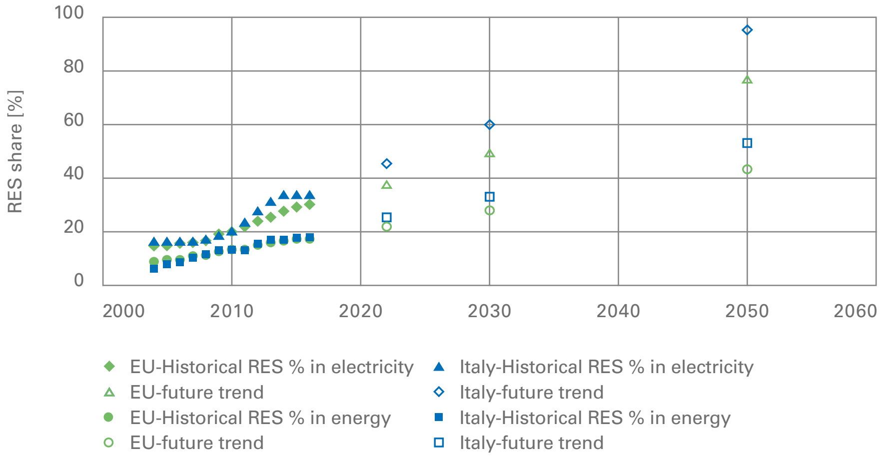

Figure 7
Historical and projected RES percentage share in electricity sector and final energy consumption in the EU and Italy.

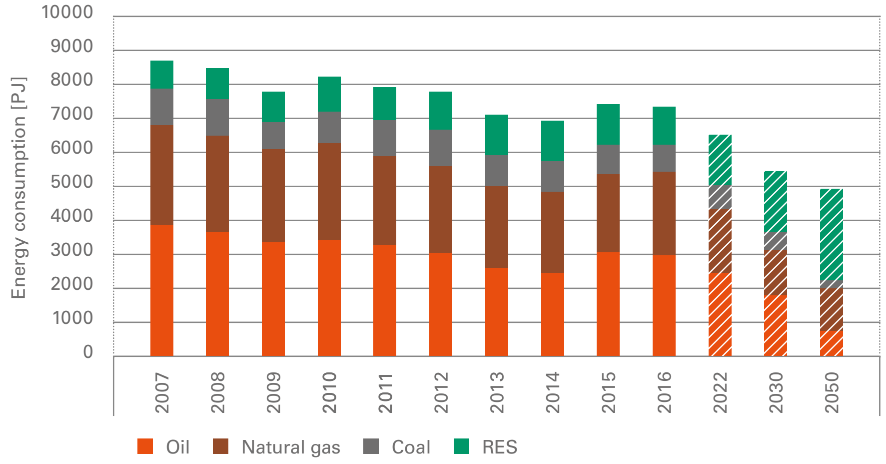

Figure 8
Historical and projected energy consumption by source in Italy.

Three RES technologies, i.e. hydro, wind and solar will play the main roles in the future of electricity generation in Italy. The installed capacity of wind and solar technologies will increase significantly (281% and 373% increase by 2050), if the current trend is continued. In contrast, the installed capacity for hydro will have limited growth (30% by 2050 compared to 2015), as it has also seen limited growth in the last decade due to the natural water resource limitations. Figure 9 shows projected installed capacity growth for these technologies in future years based on the continuation of historical trends.

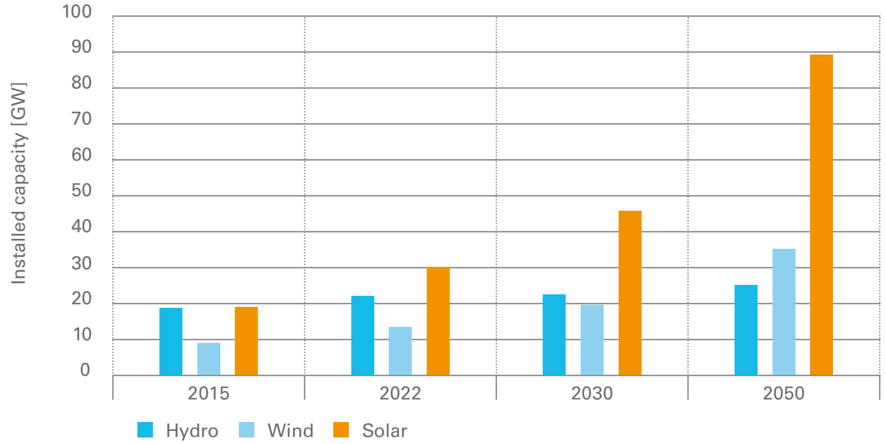

Figure 9
Historical and projected capacity of hydro, wind and solar energy.

Another important result of high RES share is a corresponding decrease in emissions of CO_2 and other pollutants from the electricity sector. If the trend of RES growth is continued, Italy's electricity sector will have a 50% and 88% decrease in its CO_2 emissions by 2030 and 2050, respectively, with similar reductions to other pollutants. Figure 10 illustrates the amount of emissions in 2010 and 2015 and the projected estimates for 2022, 2030 and 2050. As a point of comparison, in the European climate and energy framework, the goal for emission reduction is 40% by 2030 [25], and as much as 80% by 2050 in a low-carbon economy scenario [26]. Interestingly, these emissions reduction goals at the European level are in the same range as the projected emissions reductions in Italy under the assumption that historical reductions from the last decade continue at constant pace.

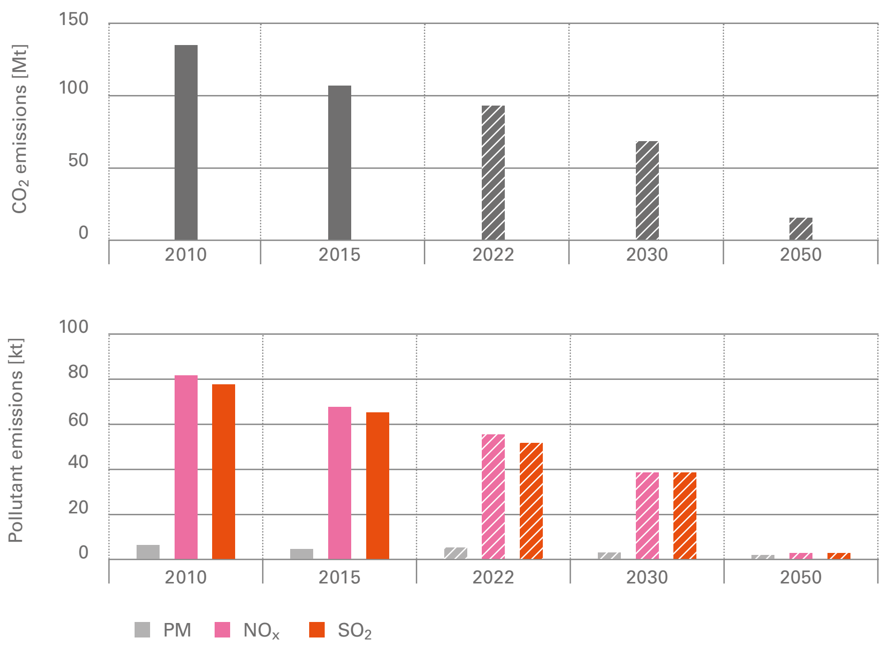

Figure 10
Historical and projected emissions of CO_2 and pollutant emissions (Particulate Matter, NO_x, SO_2).

It is important to note that the projections presented above are simple extrapolations of recent historical trends. RES growth and other developments in the power sector will be affected by many factors, as the evolution of cost and performance of RES and other technologies, availability of RES resources, future energy-environmental policies and incentives, and electricity market design. These are substantial uncertainties around all these factors, which make it difficult to predict how the future grid will change.

4.3.2 Least-cost generation expansion analysis

In order to present an alternative view of how the Italian electricity system may evolve, a formal capacity expansion analysis is developed. In order to take into account some of the limiting factors of RES growth in Italy's future electricity generation and provide an economically optimal solution for the expansion of the power system, "GenX" is used, a tool developed at Massachusetts Institute of Technology (MIT) for generation expansion planning (GEP). GenX is an optimization model that determines the optimal mix of electricity generation and energy storage capacity and their generation dispatch to meet the electricity load in a future planning year at lowest cost, subject to a variety of power system operational constraints and specified policy considerations, such as CO_2 emissions, and natural resources limits [27].

The GenX model performs a simultaneous co-optimization of multiple decision layers in the power system, including capacity expansion, unit commitment and dispatch, and operating reserves, transmission and distribution power flows. Depending on the problem, it is possible to run the GenX model for all or some of these decision layers. Similar to many other GEP models, GenX uses hourly load time series as the input and optimizes the total annual capital and operating costs of generation across different generation technologies (traditional fossil fuel plants and renewable resources). Fuel costs, different generation technologies' capital and O&M costs and availability factors, which consist of hourly time series for variable RES, are other inputs to GenX. The model also considers the possibility of investing in energy storage. The main outputs are the installed capacity of different technologies and hourly generation of each technology to meet the load requirement. The total cost of the electricity generation, as well as GHG emissions are other outputs of the model. Policies like carbon costs and RES requirements can also be represented in the model.

In this project, capacity expansion, hourly unit commitment and dispatch of energy and operating reserves are considered within the GenX optimization model. The main input parameters are summarized below.

Generation units

Italy's current generation system is a combination of conventional thermal power plants (gas, coal and oil) and renewables (hydro, solar, wind, geothermal and bioenergy). The same generation technologies, as shown in Table 3, are used as candidate generation technologies for the capacity expansion model. Also, two types of energy storage systems (8-hour pumped hydro and 3-hour battery storage) contribute to reserves and support RES integration if needed. Technology costs and performance characteristics, as shown in Table 2 and Table 3, are used as input to the capacity expansion analysis.

Unit	Type	Fuel	Efficiency	Unit commitment (UC) and reserves (R)	Average availability factor		
					2022	2030	2050
Gas combined cycle	Thermal	Gas	0.517	UC, R	1	1	1
Gas open cycle	Thermal	Gas	0.341	UC, R	1	1	1
Coal	Thermal	Coal	0.331	UC, R	1	1	1
Other non-RES (Oil)	Thermal	Oil	0.348	UC, R	1	1	1
Wind: onshore	VRE	-	NA	-	0.209	0.229	0.249
Wind: offshore	VRE	-	NA	-	0.325	0.354	0.506
Hydro: reservoir	Hydro	-	NA	UC, R	1	1	1
Hydro: run of river	VRE	-	NA	-	0.445	0.445	0.445
Hydro: pumped 8-hour	Storage	-	NA	R	1	1	1
Solar PV	VRE	-	NA	-	0.145	0.153	0.173
Battery storage 3-hour	Storage	-	NA	R	1	1	1
Geothermal	VRE	-	NA	-	0.8	0.8	0.8
Bio: Electricity only	Thermal	Biofuel	0.341	UC, R	1	1	1
Bio: Cogeneration	VRE	-	NA	-	0.54	0.54	0.54

Table 3
Generation technologies in Italy: technological specifications for GenX model.

For thermal units, the fuel price in the candidate years must be provided, and also the fuel CO_2 content to calculate the CO_2 emissions and cost, in scenarios with a CO_2 price. Fuel price projections were collected from the European Commission report on energy, transport and GHG emissions trends to 2050 [28]. Also, the CO_2 contents of each fuel type were obtained from the U.S. EPA [29]. Table 4 summarizes the fuel prices in the projection years and their CO_2 content. For the units that have unit commitment decisions and participate in providing operating reserves, the minimum output power is set, which is 40% for the oil and coal plants, 30% and 20% for the combined cycle and open cycle gas plants,10% for the hydro reservoir units, and 20% for bioenergy (i.e. for the electricity only category, similar to open cycle gas turbine). It is important to specify that, for computational reasons, power plants are aggregated and clustered into groups, where plants in each group have identical characteristics, as described in [27]. In the model, there is no constraint on retirement or expansion for gas and oil power plants, but coal power plants are assumed to be retired by 2025 due to the expected coal phase-out in Italy[1].

1. Sensitivity analysis was run without imposing a coal phase-out in the model. The results indicate that the coal phase-out policy has only a modest effect on the installed capacity of RES. The impact on gas-fired generation is more prominent, with less gas-fired generation being installed in the absence of a coal phase-out. Moreover, the CO_2 tax makes a larger difference with respect to expansion plans and carbon emissions without the coal phase-out, since it forces coal fired generation to be retired for economic reasons.

FUEL	PRICE [€/BOE]			CO_2 CONTENT [t/MMBtu]
	2022	2030	2050	
Oil	79	94	111	0.07
Coal	16	21	26	0.1
Natural gas	51	60	68	0.053
Biofuel	108	108	108	0

Table 4
Fuel price projections and CO_2 content [28], [29].

Regarding RES, a cap on expansion of onshore and offshore wind in Italy of 20 GW and 1 GW in 2050 were imposed on the model, based on inputs from ENEL experts, while no constraint was imposed on the expansion of solar. The model keeps the installed capacity of hydro power constant. Reservoir hydro is optimized over the course of the year based on historical inflows and reservoir limits, whereas run of river hydro has a constant availability for all hours. Additional input data for reservoir hydro include the initial water level in the reservoir, inflow data, power to energy ratio of the reservoirs, and maximum and minimum reservoir levels. The water level at the end of year is limited to be within a 10% deviation from its value in the beginning of year [30]. The reservoir hydro inputs were calibrated based on historical hydro data for 2015. Installed capacity for geothermal energy is considered to remain constant with no expansion potential. Also, two different types of bioenergy are modelled. First, cogeneration units that are considered as variable renewable energy without expansion potential. Second, electricity-only production units are assumed to have expansion potential. The electricity-only units are assumed to have similar characteristics as thermal units with unit commitment and contributing reserves. Due to the low capacity of geothermal and bioenergy compared to the other plants, they do not play a significant role in the capacity expansion results.

The model finds the optimal expansion for a given year. In order to simulate the gradual development of the system, the current installed capacity of each technology is considered as existing capacity when the model calculates the optimal generation mix for 2022. Next, the optimal output capacity of the model for 2022 is used as input capacity for 2030. From 2030 to 2050, given the long-time horizon, the model optimizes the generation portfolio without considering existing capacity, except hydro, geothermal, and bio-cogeneration, which are assumed to have fixed capacities[2]. The initial capacity of each technology (existing capacity) for the 2022 optimization and their expansion/retirement constraints are summarized in Table 5.

2. Sensitivity analysis indicates that whether or not existing RES capacity from 2030 are considered as input to the 2050 optimization does not give significant changes in the 2050 results.

Unit	Capacity [MW]	Surce	Capacity Expansion Retirement Constraints
Gas combined cycle	40023	ENTSO-E	No constraint on retirement and installation
Gas open cycle	9000	ENTSO-E	No constraint on retirement and installation
Coal	8700	ENTSO-E	Maximum of current installed capacity in 2022, Zero capacity in 2030 and 2050
Other non-RES (Oil)	9690	ENTSO-E	No constraint on retirement and installation
Wind: onshore	9200	Terna	Total of 15GW until 2030, and 20GW until 2050
Wind: offshore	0	-	0 until 2030 and 1GW until 2050
Hydro: reservoir	12126	Terna	No retirement and installation
Hydro: run of river	5332	Terna	No retirement and installation
Hydro: pumped	5732	ENTSO-E	No retirement and installation
Solar PV	18900	Terna	No constraint on retirement and installation
Battery storage	0	-	No constraint on retirement and installation
Geothermal	869	ENTSO-E	No new installation
Bio: Electricity only	2017	Terna	No constraint on retirement and installation
Bio: Cogeneration	2040	Terna	No new installation

Table 5
Initial installed capacity of generation technologies in 2015.

Availability Factors

Another important input to the model is hourly availability factors of different technologies. These factors define how much energy can be harvested from each technology every hour. Data for thermal, reservoir hydro, and storage units are set to 1, assuming that their nominal power capacity is always available (i.e. no outages considered). However, for variable renewables the availability varies on hourly, daily and seasonal basis. The resource availability data for wind and solar is collected from Ninja renewables [31], [32] which is a database with historical resource data for these technologies. For future years, projected future average capacity factors [33] for these technologies, reflecting expected technology improvements, are used to scale up the hourly availability factors. For hydro, the weekly production and inflow in 2015 are collected from ENTSO-E and kept constant for all simulated years. The average availability factors of each technology for different years are summarized in Table 3.

Load data

To obtain the hourly forecast of load data for future years, the total load considers the electricity demands from the sectoral analyses and the electricity consumption from the other sectors (not accounted in the study, i.e. services and agriculture). After calculating the total electricity demand, the percentage losses of transportation and distribution systems in Italy (assumed constant at 7%) was added to the load and the projected import of electricity was also deducted. The resulting load is the total electricity that should be supplied by the generation system in Italy. Imports are assumed to be constant through 2030, i.e. equal to 35 TWh, but then reduced to zero by 2050. Having estimated the total annual demand from the Italian generation system, hourly load forecasts from ENTSO-E for 2020, 2030, and 2040 [15] were scaled up to calculate the total load in 2022, 2030 and 2050 respectively. These calculations led to an electricity demand of 326, 356 and 402 TWh in 2022, 2030 and 2050, respectively. Figure 11 depicts the estimated hourly load profile for 2022 as an example, indicating relatively limited seasonal variability in loads.

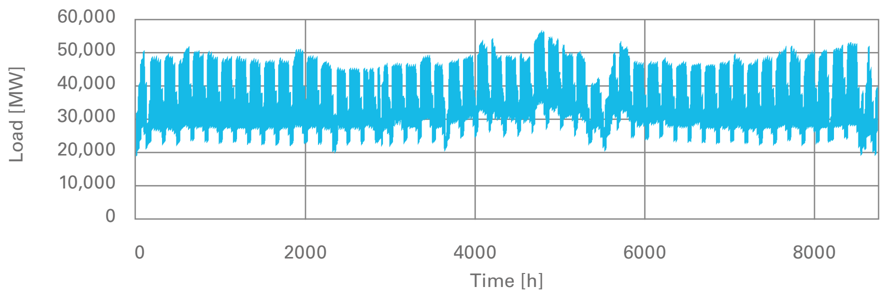

Figure 11
Hourly load data for 2022.

Energy storage

This analysis considers two types of energy storage systems; existing pumped hydro storage, which has 8 hours storage capacity, and battery storage, which is considered to have 3 hours of storage. The roundtrip efficiency of pumped hydro and battery storages are considered 80% and 85%, respectively. Both technologies are providing operating reserves. The total installed capacity of pumped hydro in Italy is 7.4 GW, which is a combination of pure and mixed (with reservoir) pumped hydro. In this study, the mixed hydro plants are modelled as reservoir plants and their storage capacity is not considered in the pumped hydro category.

CO_2 price

The 2017 World Energy Outlook from the International Energy Agency (IEA) [34] projects European CO_2 prices for three different decarbonization scenarios (Current Policies, New Policies, Sustainable Development from low to high) in 2025 and 2040 (Table 6). Based on these projections, the CO_2 prices defined in the Current Policies and Sustainable Development scenarios are used for the target years as input to the generation expansion model, in addition to a case with no CO_2 price, in order to analyse the impact of CO_2 prices on RES investments.

SCENARIO	2022	2030	2050
Current policies	18.4	28	52
New policies	20.4	32.6	63.3
Sustainable development	47.6	88.6	191.3

Table 6
CO_2 price ($/ton) projections [34].

4.4 RESULTS

Using the above-mentioned input data and assumptions, the GenX optimization model is run for three cases of CO_2 prices, i.e. zero CO_2 price, Current Policies (CP) and Sustainable Development (SD) pricing scenarios (Table 6).

For the case of zero CO_2 price, the power plants are selected based purely on their cost characteristics. The shares of RES and non-RES installed capacity in this scenario in candidate years are shown in Figure 12. This result shows that even without a CO_2 price, most of the future capacity installation consists of RES technologies, illustrating an expected competitive advantage for these technologies even in the absence of a carbon price, i.e. based on minimizing total system generation costs.

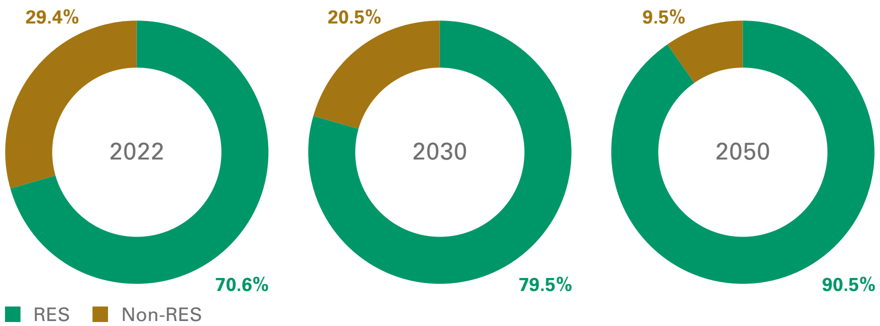

Figure 12
Share of total new capacity expansion in the scenario with zero CO_2 price (RES, Non-RES).

The breakdown of the total installed capacity of all generation technologies across the three CO_2 price scenarios are presented in Figure 13, along with the historical installed capacity from 2015, which was used as the initial capacity for the model. These results are also summarized in Table 7. According to the capacity expansion model results, in 2022 due to the substantially lower fuel cost of coal power plants compared to gas power plants (Table 4), the economic optimum is to retire a substantial share of the gas-fired power plants, including all the open cycle gas turbines, while maintaining the coal capacity. The economically optimal solution also retires the existing oil-fired power plants due to the higher price of oil compared to gas and coal. Note that the Italian government in its national energy strategy from 2017 aimed at phasing out coal plants by 2025. Therefore, in 2030 and 2050, there is no contribution from coal and natural gas is the only fossil fuel power plant technology. In the cases with carbon emissions prices, the model tends to increase the capacity of solar while decreasing the gas-fired power plants.

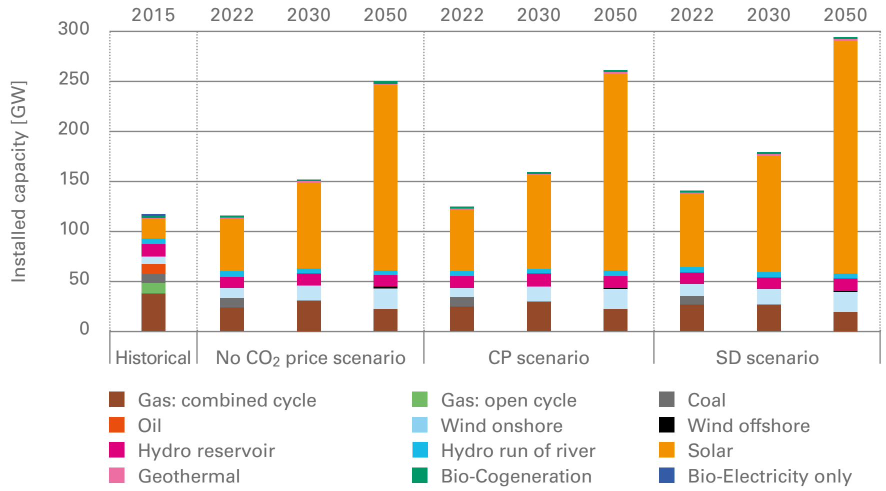

Figure 13
Current and future installed capacity in different scenarios.

Unit	Historical	No CO_2 price scenario			CP scenario			SD scenario		
GW	2015	2022	2030	2050	2022	2030	2050	2022	2030	2050
Gas: combined cycle	40.0	25.6	31.0	23.2	25.6	30.6	22.7	27.5	27.5	20.0
Gas: open cycle	9.0	0.0	0.3	0.7	0.0	0.0	0.2	0.0	0.0	0.0
Coal	8.7	8.7	0.0	0.0	8.7	0.0	0.0	8.7	0.0	0.0
Other non-RES (oil)	9.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind onshore	9.2	9.2	15.0	20.0	9.2	15.0	20.0	11.2	15.0	20.0
Wind offshore	0.0	0.0	0.0	1.0	0.0	0.0	1.0	0.0	0.0	1.0
Hydro reservoir	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
Hydro run of river	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3
Solar	18.9	52.6	85.6	185.3	61.3	94.0	197.3	73.2	116.7	233.6
Geothermal	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Bio-Cogeneration	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Bio-Electricity only	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7
Historical and future installed capacity results [GW].

For further insights into new installations and retirements, Table 8 presents the capacity expansion results for 2022 for the zero CO_2 price scenario. As the total load is increasing from 2022 to 2050, while the thermal power plants are limited due to their costs and emissions, and the wind and hydro plants are constrained by their imposed resource limitations, the optimal solution is to install a large share of solar power plants. The relatively low availability factor of solar plants means that higher capacities of solar is required to meet the demand growth. The increase in solar installations is even higher in the scenarios with non-zero CO_2 prices (Figure 13). Comparing these results with the projections of historical trends indicate that the wind and hydro will not be able to continue recent growth

ELECTRIFY ITALY / 4. POWER GENERATION FROM RENEWABLE ENERGY SOURCES

RETIRED AND INSTALLED CAPACITIES

MW	Start Capacity	Retired Capacity	New Installed	End Capacity
Gas combined cycle	40023	14425	0	25598
Gas open cycle	9000	9000	0	0
Coal	8700	0	0	8700
Other non-RES (Oil)	9690	9690	0	0
Wind: onshore	9200	0	0	9200
Wind: offshore	0	0	0	0
Hydro: reservoir	12126	0	0	12126
Hydro: run of river	5332	0	0	5332
Hydro: pumped	5732	0	0	5732
Solar PV	18900	0	33732	52632
Battery storage	0	0	0	0
Geothermal	869	0	0	869
Bio: Electricity only	2017	2017	0	0
Bio: Cogeneration	2040	0	0	2040
Total	123629	35133	33732	122229

Table 8
Detailed capacity expansion results in 2022 for no CO_2 price scenario.

rates, whereas solar energy will grow faster than its historical trend.

Energy storage can address the variability and uncertainty in RES. Italy's power system already has installed pumped hydro storage which is assumed to stay at a constant level, but additional battery capacity may be needed in the future. The total installed storage capacity of pumped storage hydro and batteries are shown in Figure 14. Interestingly, the economic optimum does not include battery storage until 2030, where some investments in battery storage occurs under the high emissions price scenario. However, in 2050, when the cost of battery storage is assumed to be substantially lower, the model finds it economically beneficial to install large amounts of battery storage, particularly

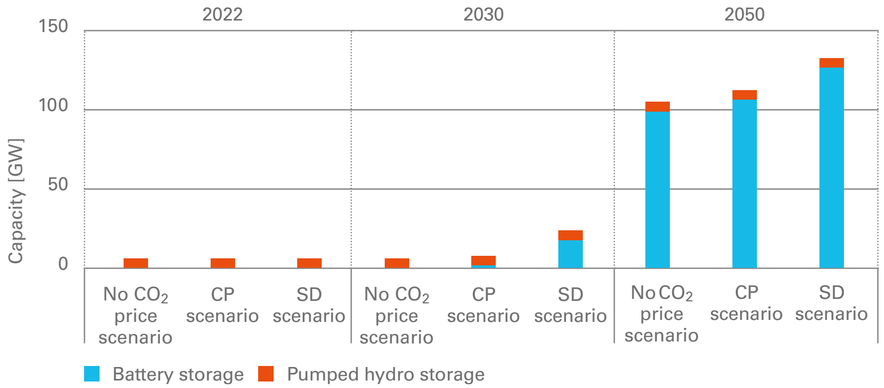

Figure 14
Installed energy storage capacity.

in scenarios with CO_2 prices.

Higher installed capacities of RES increase their contribution to the total electricity consumption (Table 9). Exploring the electricity harvested from each technology, Figure 15 shows that in 2022 gas and coal power plants combined will still have the highest dispatch contribution in all three scenarios. Increased CO_2 price decreases the generation of fossil fired power plants and replaces it over time with solar. In fact, by 2050 solar energy will be the dominant generation technology in all scenarios. Hydro power plants will have close to constant total generation in all years since its installed capacity is constant, however it uses the water with slightly different profiles in different years and different scenarios (Figure 16). Note that the water level in reservoirs is assumed limited to operate within 40% and 70% of the total reservoir capacity, based on historical aggregated reservoir levels. Wind energy generation increases from 2022 to 2050, but the growth is limited by the imposed caps on installed capacity.

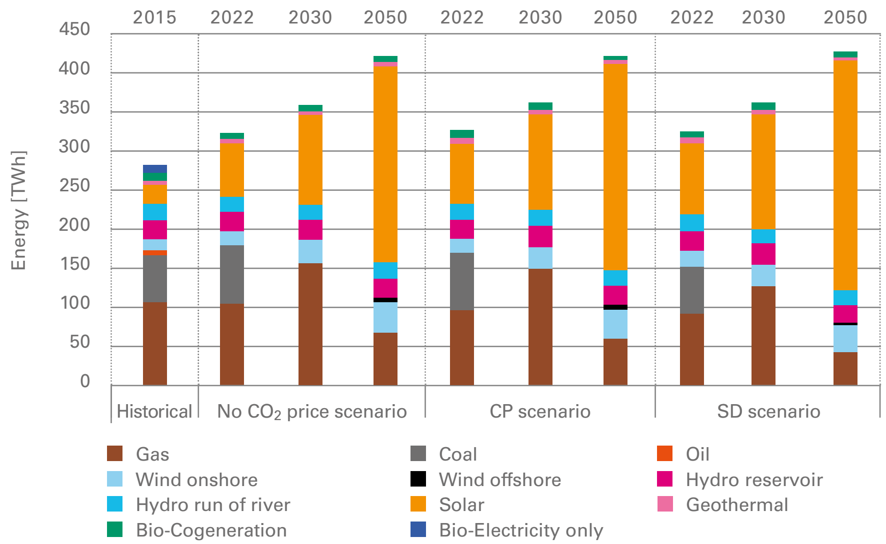

Figure 15
Historical and future electricity generation by technology.

CO_2 price not only limits the generation from thermal units, but also increases the share of RES in general. To illustrate the effect of CO_2 price on the RES percentage share, Figure 17 shows the total RES share under different CO_2 price scenarios for three candidate years. Based on these results, RES shares of 45-53% in 2022, 56-65% in 2030 and 84-90% are achieved with increasing CO_2 prices. Note that these numbers are very close to the presented projections from the historical trends earlier in this chapter. The results underscore that high RES shares are likely to unfold under the assumptions made in this capacity expansion model, mainly due to the expected cost reduction of solar. Moreover, climate emissions reductions policies, such as carbon prices, make a substantial impact on the capacity expansion results and contribute to even higher RES penetration levels.

ELECTRIFY ITALY / 4. POWER GENERATION FROM RENEWABLE ENERGY SOURCES

	Historical	No CO_2 price scenario			CP scenario			SD scenario		
TWh	2015	2022	2030	2050	2022	2030	2050	2022	2030	2050
Gas	108.1	104.6	157.2	68.2	96.7	149.2	60.5	92.3	127.4	41.8
Coal	59.3	74.3	0.0	0.0	72.4	0.0	0.0	60.0	0.0	0.0
Other non-RES (Oil)	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wind onshore	14.8	16.8	28.7	38.5	16.7	28.2	37.2	19.7	27.5	34.3
Wind offshore	0.0	0.0	0.0	3.8	0.0	0.0	3.6	0.0	0.0	3.0
Hydro reservoir	24.6	25.5	25.5	25.3	25.5	25.5	24.7	25.5	25.5	22.1
Hydro run of river	20.9	20.7	20.2	20.8	20.6	20.6	20.8	20.8	20.6	20.8
Solar	22.9	66.8	112.8	250.3	77.7	121.9	262.5	91.2	147.1	292.5
Geothermal	6.2	6.0	5.8	5.3	6.0	5.6	5.1	5.8	5.5	4.5
Bio-Cogeneration	9.6	9.5	8.9	7.8	9.3	8.8	6.9	9.0	8.5	5.6
Bio-Electricity only	9.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 9
Historical and future electricity results.

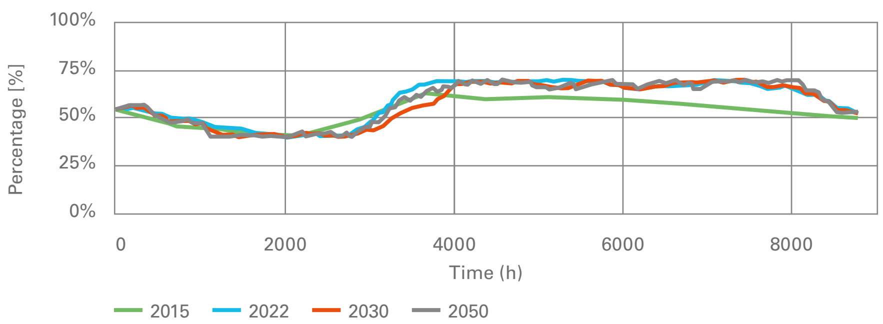

Figure 16
Reservoir water level percentage in CP scenario.

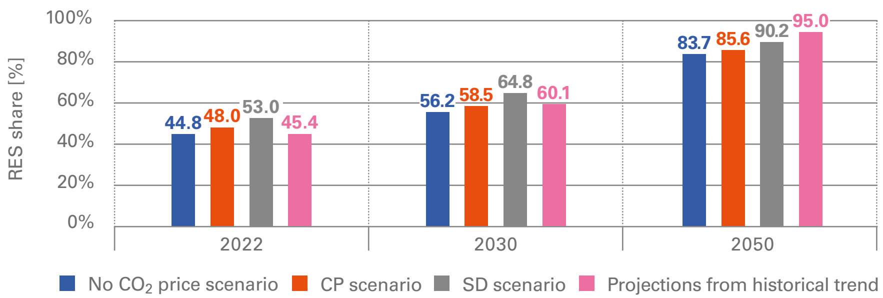

Figure 17
Percentage share of RES in total electricity generation for different scenarios.

The transition of the generation portfolio from conventional units to RES changes the generation system costs. In general, the generation costs will go up from 13.6 Billion € in 2022 to 16.3 Billion € in 2030 and 23 Billion € in 2050, on average across the scenarios (Figure 18). It is important to keep in mind that some of these cost increases in the electricity sector will be compensated by cost reductions in other segments of the energy system due to the increased electrification rate in other sectors. In 2022 and 2030, variable costs will remain the dominant cost of generation, because the thermal power plants constitute the larger share of electricity generation with substantial fuel and O&M costs. However, in 2050 the fixed costs will be dominant, due to the high installed capacity of RES which primarily impose fixed expenses on the system. Another important fact to note is that introducing CO_2 costs increases the system costs. In 2022 and 2030, the variable costs increase with the CO_2 costs, because although the generation from thermal units are reduced, the CO_2 prices are added to their variable costs. In contrast, the variable costs decrease with higher CO_2 prices in 2050 due to the corresponding shift towards RES generation with high capital costs and no fuel costs. Note that this analysis only considers the direct costs in the electricity supply system and does not consider the impacts of reduced emissions on the environment. In order to do a complete cost-benefit analysis, the benefits from reduced environmental externalities must be monetized and factored into the analysis.

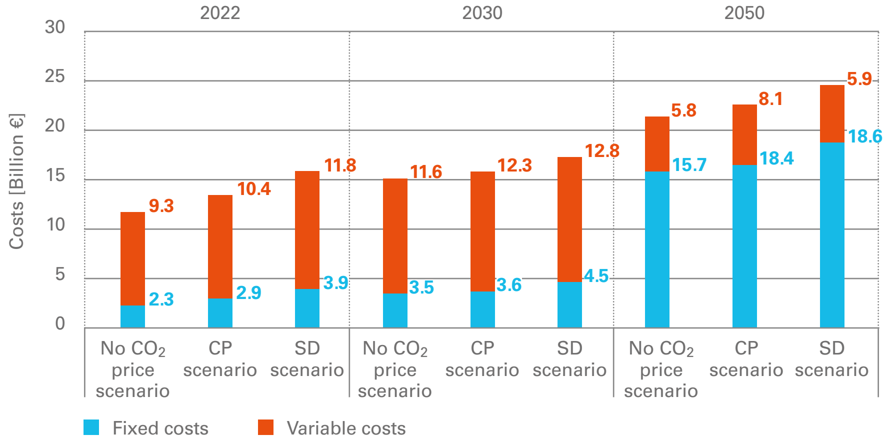

Figure 18
Generation system costs in different scenarios. Variable costs for all units. Fixed costs include fixed O&M for all units, and capital costs for new units.

In Figure 19, CO_2 emissions from the electric power system are explored in different years under the three CO_2 price scenarios and compared with the projections from the historical trends. An interesting observation is that the impact of higher CO_2 prices is relatively limited. In particular, the CP scenario does not give substantial reductions beyond what already occurs in the case without a CO_2 price for all three time stages. The SD scenario with a high CO_2 price does give more substantial reductions and gives the same CO_2 emissions level in 2050 as the projection of historical trends. These results indicate that the current strategy of a coal phase-out in Italy, combined with the assumed future technology advancement for RES and energy storage technologies, will go a long way in enabling the transition from fossil fuels to RES and thereby bring about a large reduction in carbon emissions. Overall, our analysis of projections based on historical trends as well as the more formal cost-based capacity expansion indicate that renewables are likely to see substantial growth in Italy through 2050.

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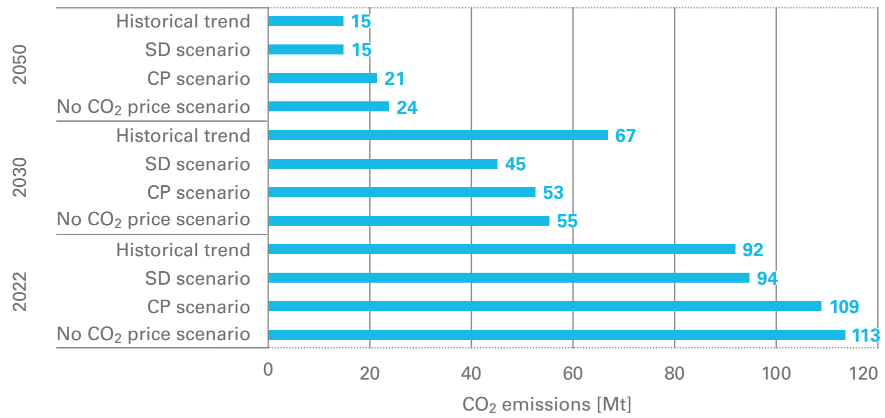

Figure 19
CO_2 emissions in different scenarios.

FOCUS BOX: ILLUSTRATIVE EXAMPLE

Figure 20 illustrates how the demand for electricity in a selected day in 2050 is mostly supplied by renewable generation (especially solar) along with a substantial contribution from battery storage. In contrast, in 2022 and 2030 thermal units still provide most of the electricity supply under the CP scenario. From 2022 to 2030, the generation from coal power plants is largely replaced by gas and solar power.

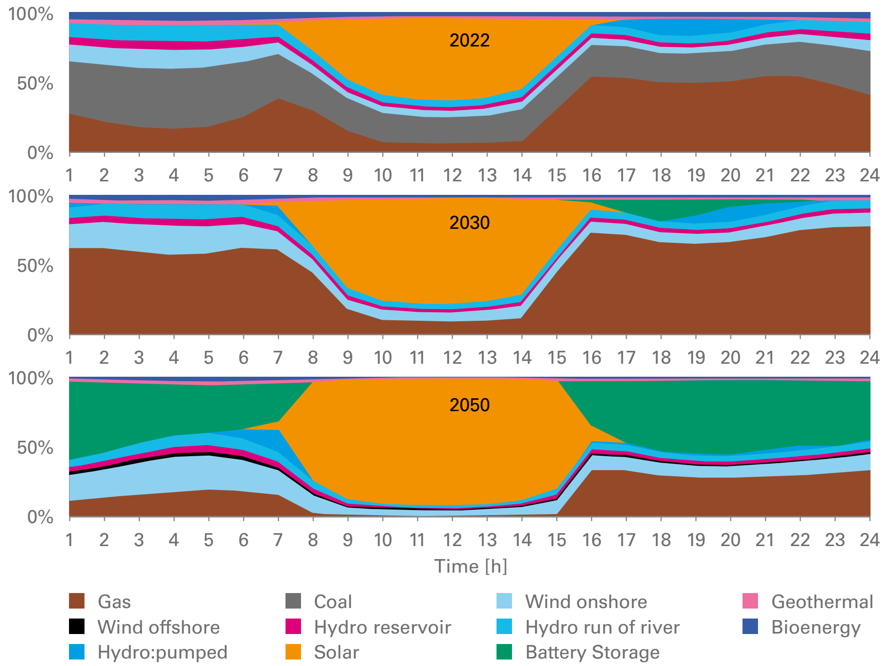

Figure 20
Dispatching result of CP scenario for January 2nd in different years.

By 2050, the combination of solar and energy storage has reduced the need for conventional thermal units. While wind resources have limited diurnal variation, the surplus generated by solar during the day is stored and is used to meet demand during evening peak and night hours. To provide additional insights into the hourly loads and how the units are dispatched to supply that demand, the dispatching result for the first week of January in 2050 is shown in Figure 21. The figure illustrates that solar has a high peak with generation far exceeding demand during day hours, which is then stored in energy storage for later use. The resulting aggregate charging and discharging of the storage systems (i.e. pumped storage hydro and batteries) is shown in Figure 22 for the same week. The main contribution of gas-fired units is to support load during evening hours when there is no solar energy available. Figure 21 clearly illustrate that the gas units dispatch is dependent on each day's solar generation, with less gas power dispatch in days with high solar generation.

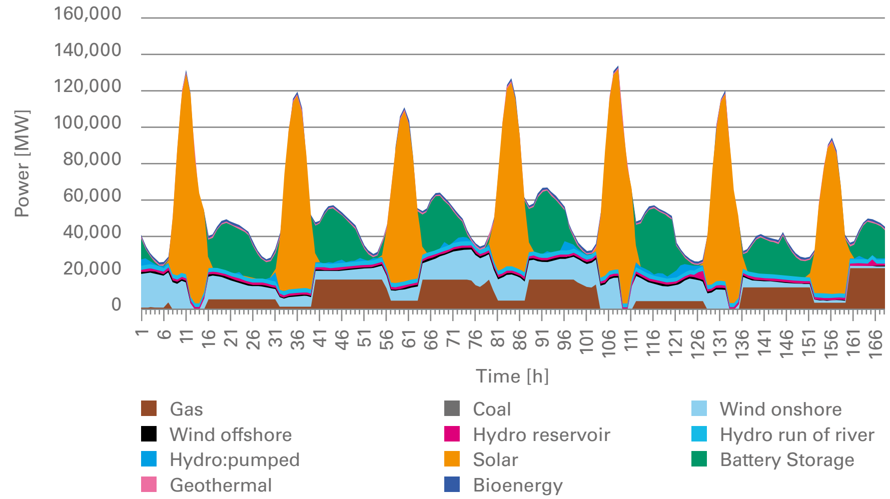

Figure 21
Hourly dispatch result of CP scenario for first week of January in 2050.

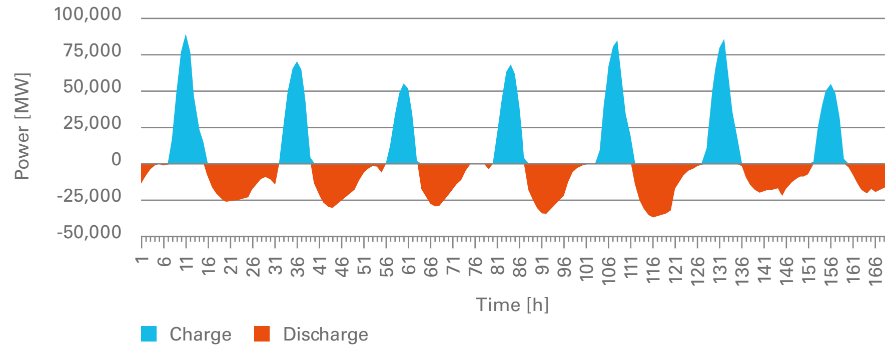

Figure 22
Charge/discharge of storage systems of CP scenario for first week of January in 2050.

4.5 SUMMARY

In summary, the performed estimation of the RES penetration levels in the future of power system in Italy based on analysis of both historical trends and capacity expansion optimization indicates that Italy's electricity supply is likely to be shaped by RES in the future. The results show that the pace of transition from fossil fuels to RES depend on carbon policies. Still, the economic expansion analysis indicates that by 2050, more than 80% of the electricity will be provided by RES, even in the absence of a CO_2 price. This share can even go above 90% if CO_2 emission reduction measures such as a CO_2 price are applied. With these high penetrations of RES, it is possible to reduce the CO_2 emissions from the electricity sector up to 80%.

However, it is important to keep in mind that these results are obtained under a set of assumptions that are highly uncertain over such a long planning horizon. For example, no constraint is applied for the expansion of solar power, which in reality may be limited by both technical constraints and societal preferences. Moreover, the future cost assumptions for different energy technologies used in the study, which include substantial reductions in RES costs, may turn out to be inaccurate. Future fuel costs are also highly uncertain, while environmental policies and other incentives for different technologies may also change substantially in the future. The obtained results are only valid under the given set of assumptions and should be interpreted accordingly. More research should be conducted to analyse a wider set of possibilities for the future evolution of the power system in Italy.

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Chapter 5

ELECTRIFICATION OF RESIDENTIAL BUILDING SECTOR

5.1 OVERVIEW

This focus analyses the potential of further electrification of the residential sector, referring to different final uses (space heating, space cooling, lighting and appliances, cooking, and domestic water heating) and diverse alternative technological options (heat pumps, electrical boilers, condensing boilers, biomass boilers, induction stoves, led lighting, electrical appliances, etc.). Starting from the current state of the buildings stock from a physical, energy and environmental point of view, the Italian policy framework is depicted, analysing present and perspective market adjustment instruments (e.g. financial supporting incentives, regulation for reducing emissions) and pricing models (energy prices and contract formulation) influencing technological preferences. Their capability to foster electrification is discussed, defining drivers and barriers.

5.2 CURRENT SECTORAL STRUCTURE

In this section current conditions of the Italian building sector in terms of consumptions, emissions and polity framework are depicted. Contextually, the aim and the boundaries of the research are identified.

5.2.1 Building sector energy consumption overview

Worldwide, the building sector is responsible for more than one third of total primary energy consumption. Focusing on the Italian situation, the whole sector, comprehensive of residential and non-residential buildings, in 2015 consumed approximately 41% of total final energy supply (47.6 Mtoe) [1].

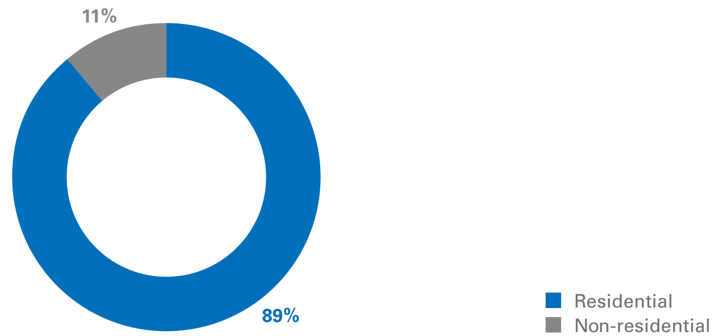

Figure 1
Distribution of Italian building stock [2].

According to Italian statistics [2], around 90% of the built volume in Italy is for residential use (Figure 1), and residential buildings are less electrified than non-residential ones. Indeed, non-residential buildings (commerce and office buildings) are already highly electrified. This is due to widespread use of electric appliances (i.e. refrigerators, servers, computers, etc.) and high air-conditioning penetration. Indeed, as it is possible to capture from Figure 2, electricity represents 51% of the final energy demand in non-residential buildings, while the same value for residential buildings is currently lower than 18% [3]. Therefore, in face of the current situation, the highest potential for further electrification of the building sector lies in residential buildings. Thus, the analysis hereby presented is concentrated on the sole residential sector, due to its prominence in the Italian stock, the greater availability of data for this sector, and the highest potential for further electrification.

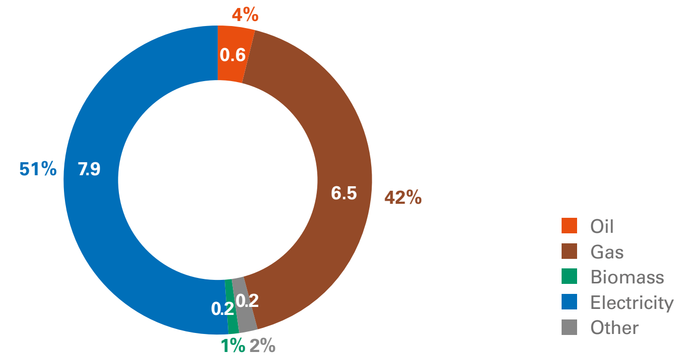

Figure 2
Fuel mix in non-residential buildings, Mtoe and percentage distribution [3].

Concerning the residential sector only, Figure 3 shows the energy share of the different final uses, revealing that space heating and water heating account for three quarters of the overall energy demand of the entire sector (68% and 12% respectively) in Italy. Furthermore, as shown in Figure 4, which represents the electricity share in the different final uses, space cooling and electrical appliances are completely electrified, while there is space for further improvement in the other final uses. In particular, electricity represents 2%, 14% and 15% of the final energy demands for space heating, water heating and cooking, respectively. Therefore, in line with current situation, the analyses here reported concentrate in the first instance on space heating and water heating final uses, aiming to evaluate the electrification potential for these thermal uses in the residential sector. The other final uses are included with an aggregate approach, as they do not represent the main focus of the study.

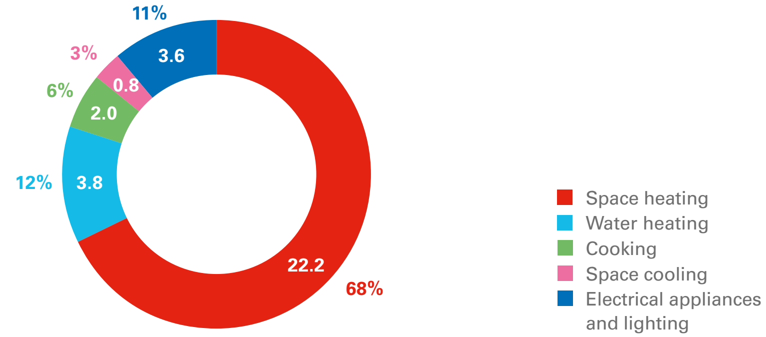

Figure 3
Share of final uses, Mtoe and percentage distribution [3].

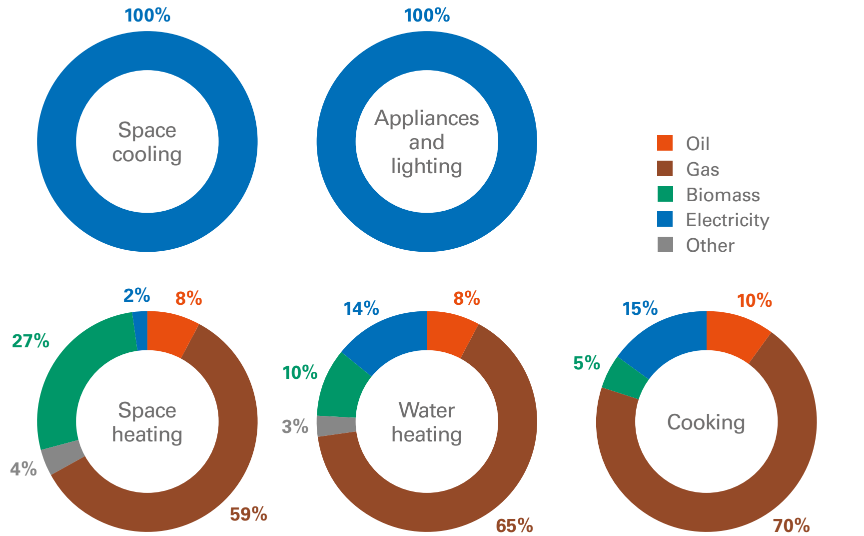

Figure 4
Electric energy share in final uses, percentage distribution [3].

5.2.2 Building sector environmental impact

From an environmental point of view, the building sector is responsible of 36% of total greenhouse gas (GHG) emissions in atmosphere worldwide. Even though the European Roadmap [4] has identified the need of the sector to achieve by 2050 a 90% reduction of GHG emissions in atmosphere (with respect to 1990 levels), great effort still must be made, since the carbon emission reduction potential is still mostly untapped. Figure 5 represents the distribution of direct and indirect CO_{2eq} emissions in Italy among the final uses according to Enerdata statistics. The residential and non-residential sectors[1] together caused 38% of total Italian emissions in 2015.

1. Enerdata statistics [3] references residential sector as "Households" and non-residential as "Services".

The contribution of the residential sector only (21%) accounts for more than half of the entire building sector.

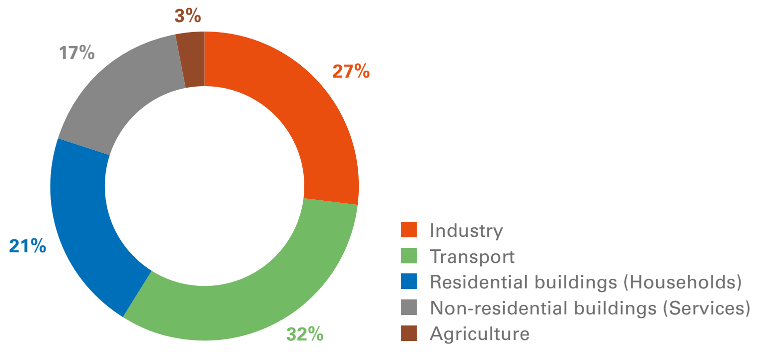

Figure 5
Share of CO_{2eq} emissions for final uses in Italy (2015) [3].

Figure 5 presents both direct and indirect emissions caused by the different final uses. Each energy-consuming sector produces direct emissions, which derive from in-situ combustion of fossil fuels. The portion of emissions defined as indirect is caused by the transformation operations pertaining to that sector but not taking place locally. In the case of the building sector, both residential and non-residential, direct emissions are due to natural gas, oil or biomass used inside the perimeter of the building, while indirect emissions represent the ones due to the production of the electricity that is delivered to the buildings themselves. The majority (65%) of the residential sector emissions are direct [3], mainly caused by fuel combustion in heating systems. In particular, emissions due to space heating and water heating were above 80 Mt of CO_{2eq} in 2015.

Besides the GHG emissions, which are connected to climate change and therefore relevant at global level, when dealing with the environmental performances of energy systems, it is important to tackle also the local effects of air pollution, in terms of particulate matter (PM), which is of critical relevance especially in urban environments. PM can have both natural or anthropic origin, but it is worth noting that in 2015 more than 90% of the emissions came from human activities. In particular, considering PM2.5 emissions, about two third of these emissions were attributable to heating systems in the building sector, which includes both residential and commercial buildings [5].

5.2.3 Energy-related building legislation overview

Given this energy-environmental picture and knowing its potential in terms of energy and emissions savings, it is not surprising that the building sector is at the centre of the debate on energy efficiency. However, in Italy, there are many barriers to the intervention on the existing building stock [6]. One of the main factors hindering the roll out of building retrofits is represented by evaluation uncertainties, especially in relation to energy savings verification by the building owner, typically a private citizen without a particular technical background. In detail, the methodologies for evaluation of the building energy performances are well defined, and their results are clear and easily readable for sector experts. Nevertheless, they are not easily understandable by the vast majority of the people directly responsible for the energy efficiency interventions. This uncertainty implies a slowdown in the diffusion of innovative technologies when a retrofit intervention occurs. In addition, financial barriers (high investment costs, long payback periods, difficulty in accessing to capital) and reluctance in contracting debt, further hamper retrofit interventions. Decision problems related to multi-owner contexts (i.e. multi-family houses) decelerate energy efficiency interventions, whose spreading is also hampered by the lack of customer knowledge, reliable advice and of skilled service providers. Public building sector has to face even more severe problems related to financial barriers.

In face of these and other barriers, the Italian energy efficiency trend is supported by:

- The definition of legislative/regulatory and planning actions.
- The provision of dedicated funds (like the National Fund for Energy Efficiency).
- The exploitation of European funds.
- The exploitation of Energy Performance Contract (EPC) formula.
- The provision of incentives mechanisms.

The following tables summarize the current framework of regulations and action plans regarding energy efficiency in buildings and affecting the building sector in general.

NATIONAL LEGISLATION	TOPIC	STATUS
Legislative Decree 192/2005 and s.m.i.	Transposition of 2002/92/CE.	Updated by Law n. 116/2014
Decree Law 63/2013	Energy efficiency in buildings. Transposition of 2010/31/UE • Cost-optimal level and NZEB concepts; • UNI/TS 11300 as mandatory technical reference for the calculation methodology of buildings performance; • Compulsory energy performance certificates for renting and selling buildings.	Translated in Law 90/2013
Legislative Decree 102/2014	Transposition of 2012/27/UE. • New definition of energy performance contract (EPC); • Compulsory requalification rate for public buildings (3%); • Need for new action plan on energy efficiency (PAEE).	Modified by Legislative Decree 141/2016
Decree of the President of Republic 74/2013	Operation, maintenance and inspection of buildings plants.	In force
Ministerial Decree 26/06/2015	Building energy performance assessment methods definition of minimum performance requirements.	In force

Table 1
National legislation on energy efficiency in buildings.

NATIONAL PLAN	TOPIC	STATUS
Energy Efficiency Action Plan (EEAP)	Energy efficiency of energy services in accordance with 2006/32/CE	Replaced by PAEE
National Action Plan (PAN)	Use of renewable energy sources in accordance with 2009/28/CE	In force
Action Plan for Energy Efficiency (PAEE)	Energy efficiency goals in accordance with 2012/27/UE	In force

Table 2
National plans affecting the building sector.

In the framework of the latest action plan, called PAEE (Action Plan for Energy Efficiency) [7], in 2014 Italy stated its policy pathway related to interventions on national existing buildings, providing also for incentives mechanisms as means to address barriers to retrofit interventions.

Generally speaking, the Italian strategy to foster the interventions on existing buildings includes regulatory, informative/voluntary, and financial instruments. The first ones consist of the normative actions described in the tables above and of all the related implementing rules; the second group of tools cover all the issues related to R&D, communication campaigns, labels, etc.; finally, financial instruments include both funds and grants and financial incentives. In addition, the exploitation of innovative financial tools (Energy Performance Contracts and Energy Efficiency Obligations) is promoted by European directives and national legislation, providing a framework for contracts between service providers and private owners of buildings willing to take energy efficiency measures; with this formula, the service providers take the burden of the financial risks of energy efficiency actions, alleviating the private owners and contributing to the spread of energy efficiency interventions. Financial tools are the most employed [8], mainly in the form of "Ecobonus" and "Conto Termico 2.0".

5.2.4 Energy-related building incentives mechanisms overview

The main incentive mechanisms currently in force are the so called "Ecobonus" and "Conto Termico 2.0".

Ecobonus first application dates back to 2007. Until today, it has been annually confirmed and enforced in the framework of the "stability" law. It consists of a tax rebate for interventions on buildings aiming at increasing their energy performance and it is calculated as a percentage (50% or 65%, according to the intervention typology) of the initial investment cost, deduced by tax on a ten-year basis. The interventions that can have access to this kind of incentive mechanism are thermal insulation of opaque envelope, windows replacements, installation of solar panels (for thermal energy production only), substitution of thermal plants with new systems (50% rebate for biomass heaters, condensing boiler; 65% rebate for heat pumps, more performing condensing boilers, condensing heaters, micro CHP) and building automation systems.

Conto Termico 2.0 is the new scheme for the incentive defined by Ministerial Decree 16/02/2016, firstly introduced by Ministerial Decree 28/12/2012. It consists of a financial contribution provided in 1, 2 or 5 annual instalments, depending on the type and entity of the intervention. The interventions included in the incentive mechanism are different for private and public users. Private subjects can access to Conto Termico 2.0 for interventions of substitution of plants for space heating with heat pumps (fuelled by gas or electric energy, also geothermal ones) or biomass heaters, substitution of electric boilers for domestic hot water production with heat pumps and installation of solar panels for thermal energy production (solar cooling solutions are included). Public administrations benefit from this incentive mechanism for all the interventions just mentioned, and in addition, also for insulations of opaque envelope, windows replacement, system shielding and shading installation and substitution of plants for space heating with condensing boilers.

Since the entry into force of Ecobonus and Conto Termico, 3,000,000 and 97,000 submissions to these incentive schemes have been registered respectively. Between 2014 and 2016, more than 55% of the requests for accessing to Ecobonus were related to windows replacement interventions and only 20% were for space heating system substitution, a percentage comparable to the one relative to solar shading devices installation. Out of the total, space heating units installed in 2016 under Ecobonus incentive regime, almost 70% were condensing boilers, 5% biomass heaters, while the remaining 25% were heat pumps for domestic hot water production, heat pumps for space heating and geothermal plants (in decreasing order of penetration). In the very small rate of request of Ecobonus for global intervention on building (1% of the total requests between 2014 and 2016), heat pumps and condensing boilers for space heating were chosen almost equally. Concerning Conto Termico and Conto Termico 2.0, more than the 90% of the interventions incentivized until March 2018 were developed by private entities, which can have access to this form of incentive only for interventions on plants. Among this percentage, almost 60% of installations are biomass heaters, almost 40% are solar panels and only in 4% of cases heat pumps were chosen.

In face of the energy-environmental and political context described so far, electrification is commonly recognized as enabler of better environmental performance of buildings. Within the study possible technological trends are studied in order to investigate the electrification potential for the residential building sector.

5.3 METHODOLOGY

5.3.1 Overview

This study aims to assess the potential for further electrification of the residential sector, analysing different final uses and different alternative technological options. To do it, a three-steps-methodology is adopted:

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Step 1: Baseline definition. Characterization of current residential building stock of non-fully electrified uses (baseline 2015). The analysis focuses on thermal uses (space and water heating) and aims to evaluate the current consumptions of the residential sector. Consumptions are assessed using the Reference Building (RB) approach, as detailed in paragraph 5.2.2.

Step 2: Potential evolution assessment. Assessment of possible future scenarios (2022, 2030, 2050) for electrification evolution of non-fully electrified uses. The analysis focuses on thermal uses (space and water heating). The evolution in 2022, 2030 and 2050 is computed at two different scales, starting from the analysis of the single Reference Building and then scaling up at stock level:

A. Single Reference Building level. The model forecasts the most competitive technological options in 2022, 2030 and 2050 for each RB when a system renovation occurs. Competitiveness is assessed based on the "Global Cost per CO_{2eq} avoided" indicator (called GCCA indicator), which is a newly-developed index, defined as the cost for CO_{2eq} savings in buildings, able to include both the private and public perspectives in forecasting the possible technological choices when a system substitution occurs. Indeed, the aim of this step is to define the most likely technological shifts in residential buildings when a retrofit intervention occurs, based on the minimization of the emission abatement cost. The choice of the index to be minimized approximates the implementation of policies for decarbonization and energy efficiency and the financial issues driving private choices, as will be explained later in this chapter.
B. Stock level: The technologies identified in step A are then scaled up to the whole stock, according to an annual renovation rate of 1.8% [9] of the total surface of the stock itself. The aim is to assess the impacts on consumptions and electrification of the forecasted technological shifts when they are applied to the whole residential sector.

Step 3: Inclusion of all final uses in the definition of possible future electrification scenarios (2022, 2030, 2050). The analysis is extended to all final uses (cooking, space cooling, electrical appliances and lighting). For that purpose, two additional models are used to estimate the replacement of the existing gas-fired cooking systems with electric technologies and to assess the contribution of cooking, space cooling, appliances and lighting to final consumptions over the time period considered.

Both in baseline characterization and future scenarios development, attention is devoted to the differentiation between urban and extra-urban context.

The complete residential sector model is therefore composed of three sub-models, each devoted to asses a cluster of final uses: the first for space and water heating, the second for cooking, the third for space cooling, electrical appliances and lighting. Each model adopts a specific approach, which will be further detailed in the following sections:

1. Space heating and domestic hot water. It adopts an optimization approach, namely the minimization of the GCCA indicator, to determine the shifts from current technologies towards new ones (condensing gas boilers, biomass boilers, heat pumps) computed under specific constraints (costs of technologies, energy prices and incentive mechanisms) for each building typology. The extension of the analysis to the whole stock is based on assumptions related to renovation and new construction rates (i.e. 1.8% and 1% annual renovation rates for retrofit and new constructions, respectively) and major trends (oil dismission by 2030, new buildings as full-electrified).
2. Cooking. Substitution of gas-fired cooking systems with induction stoves is assumed concurrent with the electrification of space heating and water heating services as computed in step A.
3. Space cooling, electrical appliances, lighting. This model is based on projections of historical trends.

Finally, since the model outputs depend on the defined constraints (incentive mechanisms, taxes, energy prices, etc.), sensitivity analyses are carried out to investigate how the changes of these complex variables can influence the electrification potential, providing some suggestions on how current and potential future market regulation and pricing models schemes could push the electrification of thermal uses in buildings.

5.3.2 Step 1: Baseline definition

The baseline is identified with an in-depth analysis of non-fully electrified services (space heating and water heating). The analysis is based on appropriately identified Reference Buildings (RBs), each defined as a typical building considered representative of a portion of the building stock [10].

To properly define the RBs, the first step consists in the analysis of the current state of the Italian residential stock, represented in Figure 6 and Figure 7. The whole building stock is classified according to its age, location and main typological classes. Referring to building age, three milestone construction periods (before 1980, between 1981 and 2000, and after 2001) are selected to represent the different energy performances of buildings, in turn connected with the legislative requirements in force in the respective period of construction. As far as location is concerned, buildings are divided into five geographical areas (North-West, North-East, Centre, South and Islands), according to ISTAT classification [2], to take into account the different climate conditions. Finally, the stock is classified based on its construction typology, grouping buildings into two main classes, obtained by the aggregation of the classes proposed by TABULA project[2]: single family houses (SFH) and multi-family houses (MFH) (i.e. buildings with two or more apartments).

2. Typology Approach for Building Stock Energy Assessment (TABULA) was a three-year project (June 2009–May 2012) within the European programme Intelligent Energy Europe (IEE), involving thirteen European countries, among which Italy. The objective of the project was "to create a harmonised structure for "European building typologies" in order to estimate the energy demand of residential building stocks at national level and, consequently, to predict the potential impact of energy efficiency measures and to select effective strategies for upgrading existing buildings" [10], [11].

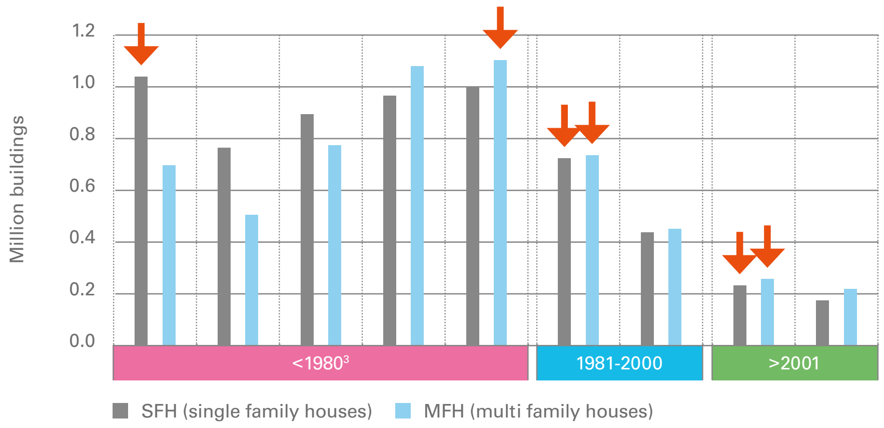

Figure 6
Distribution of residential buildings per typological class and construction period. The red arrows identify the most relevant building typology for each construction period according to frequency. Elaboration on [2] and [11].

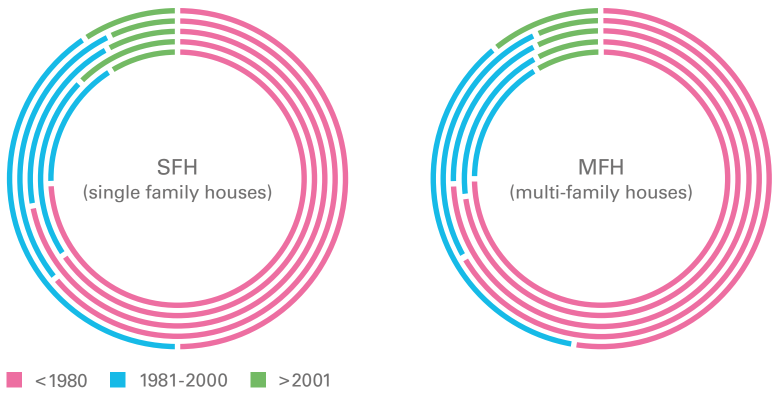

Figure 7
Distribution of residential buildings per typological class and geographical zone (from innermost to outermost circle: North-west, North-east, Center, South and Islands areas). Elaboration on [2] and [11].

For each construction period ("<1980", "1981-2000", ">2001") and typological class (SFH, MFH), a RB is selected within TABULA database according to the relevance of the classes in terms of frequencies within the whole Italian stock (see Figure 6). The resulting six RBs are modelled by means of quasi steady-state assessments using MasterClima software [12] and simulated for five geographical zones (represented by the climatic conditions of Milan, Venice, Rome, Bari and Palermo), resulting in a set of thirty RBs.

Energy needs for space and water heating are obtained by means of simulations. Thanks to this approach, it is possible to assess with sufficient accuracy the different energy needs (thermal loads requested by the buildings for space and water heating) across different periods of construction and geographical zones. In particular, energy needs are higher for RBs built before 1980, being their envelope less efficient, and they decrease in later periods, when requirements on energy demands reduction were in place.

Once energy needs are calculated, energy consumptions are defined considering the efficiency of the installed heat generators (the most common ones, defined according to the RBs approach: gas boiler, oil boiler, biomass boiler, electric heat pump and electric boiler), assuming fixed the efficiencies of other subsystems (storage, distribution, regulation and emission), thus excluding the possibility to have energy efficiency interventions on them to reduce their thermal losses. Finally, reference thermal consumptions for space and water heating per square meter are obtained. Thanks to this approach, the defined values of specific consumptions can be considered representative of the whole Italian residential building stock.

Ideally, knowing the stock distribution in the different classes and the specific consumptions of these classes, it is possible to have a complete picture of the whole stock. However, when extending the analysis done at RB level to the overall Italian building stock, some adjustments based on real technological distribution are required. For this purpose, final energy consumptions obtained with the simulations are compared to statistical data of fuels mix for thermal uses in residential buildings in 2015 [3]. Starting from this comparison and based on generation technologies distribution information [13], adjustments to the model are applied. At the end of this process, some new RBs (variants of the ones already included in the analysis) are added to the initial set of 30 RBs, in order to depict the Italian stock in its baseline situation (2015) in the most realistic way possible, accordingly to the used RB approach. The obtained model allows to highlight the distribution of the most relevant generation technologies for space and water heating in residential buildings (gas boiler, oil boiler, biomass boiler, electric heat pump and electric boiler), and represents the starting point for the subsequent analyses.

5.3.3 Step 2: Potential evolution assessment

A. Single Reference Building level

This step aims to define the future possible technological trends for the residential sector through the assessment of competing technological options in the occurrence of a system retrofit per each RB.

To estimate the future potential electrification of residential buildings, two aspects must be understood: which technologies the buildings owners are willing to choose and in which direction the market and the policy context is going to push their choices. For this reason, in this study, two possible drivers towards buildings electrification are defined, both at private and public sides. From the building owner perspective, a possible driver towards electrification is identified in the global cost, a financial parameter

3. <1980 includes: before 1918, 1919-1945, 1946-1960, 1961-1970, 1971-1980; 1981-2000 includes: 1981-1990; 1991-2000; >2001 includes: 2001-2005, after 2005.

useful to compare different alternatives for retrofit interventions, as specified below. This index is particularly interesting having in mind that 70% of residential buildings are owner-occupied, meaning that investor and beneficiary coincide, and that all the cost items of the global cost formula are charged on the same stakeholder, who, having to bear all the expenses, would perceive the global cost as a relevant figure in taking his own investment decisions. From the policy perspective, the European Roadmap foresees for the building sector a 90% emissions reduction by 2050 with respect to 1990 [4], achievable only through a combination of demand reduction, energy efficiency and renewable energy sources integration actions. For this reason, policy makers are interested in putting into force measures able to reduce the environmental impact of the building sector. This desirable scenario is the foundation of the choice of the avoided CO_{2eq} emissions as a driver towards electrification from the public point of view. In fact, being the international policy targets defined based on GHG emissions, it is presumable that policy makers will invest on actions able to force the market towards the adoption of solutions having as main requirement a low carbon intensity, making them financially attractive for the investors. Then, in this study, the two equally influencing parameters are coupled creating an indicator, the "Global Cost per CO_{2eq} avoided" (GCCA indicator) as a criterion in the choice of alternative technologies available in the market. This indicator advantages the technology with the lower global cost vs. GHG emissions ratio.

For the reasons outlined above, for each of the RBs considered, the use of the GCCA indicator to compare the different competing technological options (condensing gas boiler, biomass boiler, electric boiler and electric heat pumps) available in the occurrence of substitution of the space or water heating systems allows to identify which option can guarantee the best compromise between costs and CO_{2eq} emission savings. The GCCA indicator is calculated for all the technological alternatives and for each RB across the timespan considered, taking into account the forecasted conditions of the market (i.e. energy prices, incentive mechanisms in force) and of the power sector (i.e. emissions due to electric consumptions).

The GCCA indicator is defined as the ratio between the global cost of a specific technology and the amount of CO_{2eq} emissions (€/kg$CO_{2eq,avoided}$) avoided by using that technology to replace another one (retrofit or overhaul cases), and is described by the following equation:

$$GCCA = \frac{Global\ cost}{Avoided\ CO_{2eq}} \left[\frac{€}{kg\ CO_{2eq,avoided}}\right]$$

The lower the indicator, the more convenient the retrofit is, leading to a lower cost per avoided CO_{2eq} emissions, with respect to other competing solutions. The global cost is a financial parameter often used to analyse building retrofits, and is defined as the total cost of a system over its lifetime. The calculation accounts for the initial investment cost of the intervention and the annual costs (discounted at the present value with a constant interest rate), including maintenance and energy costs [14]. In this study, global cost is defined for each alternative technology over a 20 years period (lifetime of typical heating systems) and incentive mechanisms are added to the formula, discounted at the present value. Regarding the denominator of the GCCA index, the avoided emissions are calculated per each RB as the differences between CO_{2eq} emissions caused by the original system of the RB and the ones potentially caused by each and every new technological option.

The possible technological options considered in the analysis for space and water heating are reported in Table 3 and Table 4, with details in terms of generation efficiency, investment and maintenance costs (the latter expressed as percentage of the investment costs, as defined by [14]). The options of biomass boiler and electric heat pump, for the sole space heating, require the addition of a thermal storage, whose cost is not included in the table, being dependent on the size of the plant. However, these storage system costs are added in the global cost formula, for the sake of completeness.

SPACE HEATING SYSTEM			
Technology	Generation efficiency	Investment cost	Maintenance cost
Condensing boiler	0.97	100 – 135 €/kW	1.5%
Biomass boiler	0.89	460 – 570 €/kW	2%
Electric heat pump	3.8 – 4.1	580 – 615 €/kW	3%

Table 3
Technological options for space heating system interventions.

WATER HEATING SYSTEM			
Technology	Generation efficiency	Investment cost	Maintenance cost
Condensing boiler	0.97	100 – 135 €/kW	1.5%
Biomass boiler	0.89	460 – 570 €/kW	2%
Electric boiler	0.75	225 €/kW	1%
Electric heat pump	2.6	580 – 615 €/kW	3%

Table 4
Technological options for water heating system interventions.

For the calculation of global costs, the existing incentive mechanisms described before are considered (see Table 5).

ELECTRIFY ITALY / 5. ELECTRIFICATION OF RESIDENTIAL BUILDING SECTOR

EXISTENT INCENTIVE MECHANISMS				
Name	**Law**	**Type**	**Description**	**Technologies included**
Ecobonus	Stability Law	Tax rebate	Percentage of the initial cost deducted by taxes on a ten-year timespan. It includes: thermal insulation of opaque envelope, windows replacements, installation of solar panels (for thermal energy production only), substitution of thermal plants with new systems (50% rebate for biomass heaters, condensing boiler; 65% rebate for heat pumps, more performant condensing boilers, condensing heaters, micro CHP) and building automation systems.	• Condensing gas boiler • Biomass boiler • Heat pumps
Conto Termico 2.0	DM 28/12/12	Financial contribute	Money directly provided in 1, 2 or 5 annual instalments. For private citizens* it includes: substitution of plants for space heating with heat pumps (fuelled by gas or electric energy, also geothermal ones) or biomass heaters; substitution of electric boilers for domestic hot water production with heat pumps and installation of solar panels for thermal energy production (solar cooling solutions are included).	• Biomass boiler • Heat pumps

Table 5
Incentive mechanisms included in the study.

* Public investors are not the target of this study, then the financial contribute reserved to them is not reported

Furthermore, the non-progressive tariff, already in force for single family houses with heat pumps as the only space heating system, is considered, consisting in a 5% reduction of the fixed component of electricity prices and a unique variable component, not related to actual level of electricity consumption [15]. Current energy prices for the different carriers, according to [15] and [16], are considered as the basis for the projections of energy prices in the years 2022, 2030 and 2050.

In summary, according to the methodology so far described, the GCCA indicators are calculated for 2022, 2030 and 2050 for each of the thirty RBs (plus their variants resulting from the adjustment process), varying the context conditions (incentives, energy prices growth rates and CO_{2eq} emission factors for electricity). To do it, the following assumptions are made:

- ***Fixed incentive mechanism:*** the percentages of tax rebate of Ecobonus and the financial contribute of Conto Termico 2.0 are considered the same for the entire timespan.
- ***Energy prices growth rates:*** set according to IEA projections based on the 2DS scenario from the Energy Technology Perspective 2016 [17]. They are applied to 2015 energy prices [15], [16].
- ***Electricity CO_{2eq} emission factors variation:*** set according to the calculation from Chapter 4.

Thanks to this calculation, technological trends are forecasted for 2022, 2030 and 2050 through the identification of the most competing technological options when a system retrofit occurs, the measure of competitiveness being defined by the GCCA indicators; the lower the indicator, the more convenient the retrofit option.

B. Stock level

As explained so far, the RB level analytical approach is based on the evaluation, per each technological option, of its life-cycle cost and its potential to reduce the CO_{2eq} emissions, foreseeing future trends (2022, 2030 and 2050) through the comparison of the obtained GCCA indicators.

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This process leads to the definition of a possible future scenario for the overall Italian building stock. The analysis carried out at RB level is extended to the overall Italian building stock, divided into urban (67% of the total floor area) and extra-urban buildings (33% of the total floor area) according to ISTAT data [2], where urban areas are defined as municipalities with more than 10,000 inhabitants. The scaling up of the analysis to the overall stock is performed by fixing some constraints. In particular, a renovation rate of 1.8% [9] and a new construction rate of 1% [18] are assumed. While in extra-urban context the technological choice driven by the GCCA indicator computed for the different milestones (2022, 2030 and 2050) is between gas, electric and biomass technologies, the latter is excluded from the alternatives available in the urban context due to policy environmental constraints[4]. Moreover, to reflect the fact that heat pumps guarantee both space heating and cooling with a single machine, the investment cost for a multi-split is computed as part of the global cost of the gas technologies for interventions in urban context, allowing to compare the alternatives on equal terms. The cost for the air conditioning system is added only in buildings located in urban areas because the impact of AC is significantly higher in these areas, as in cities the temperatures are higher than in extra-urban areas [19] and the quality of the external air is worst, preventing an effective use of free cooling. In both urban and extra-urban buildings, a single generator substitution over the entire period of study is considered and total oil generators decommissioning by 2030 is set. Finally, it is assumed that all new buildings are electricity-fuelled (for both space and water heating services).

Based on this approach, a baseline scenario is developed (scenario FB[5]); once the technological distribution for space heating and water heating in the residential sector in 2022, 2030 and 2050 is defined according to the GCCA-based technology ranking, the final consumption per heated square meter is calculated for each energy carrier, weighting it on the number of RBs adopting it to meet their respective energy demand. Therefore, composing these parameters with the existing heated square meters of residential buildings [2], and including an annual increase of new constructions of 1% in volume, total consumptions for the analysed thermal uses are computed for 2022, 2030 and 2050.

4. Some Italian regions (i.e. Piemonte, Lombardia, Emilia Romagna) have imposed constraints to the installation of biomass heating systems in urban areas, due to local air pollution issues.

5. "FB" stands for "Focus Building".

ASSUMPTIONS SUMMARY
1% annual new construction rate [18];
1.8% annual renovation rate [9];
Single generator substitution over the entire timespan;
New construction as electricity-fuelled for space heating, water heating and cooking;
Complete oil generators disposal by 2030;
No biomass adoption in urban areas (due to environmental policy constraints).

Table 6
Main FB scenario assumptions.

5.3.4 Step 3: Inclusion of all final uses

To analyse the variations of final energy consumptions, and therefore the electrification of the residential sector, the study is extended from thermal uses to the whole sector including all final uses, namely cooking, space cooling, appliances and lighting. Given the model on thermal uses, other two models are built aiming, respectively, to estimate gas-fired cooking systems replacements, and to assess the contribution of cooking, cooling, appliances and lighting to final consumptions over the same timespan. As far as cooking is concerned, new constructions are assumed to be equipped with induction stoves, while for existing buildings a progressive substitution of gas stoves is considered to happen concurrently with the electrification of other final-uses. As for the other final uses, once the technological mix potential variation for space heating and water heating at stock level is defined (the output of step 2 described in 5.3.3), the energy consumptions of space cooling, appliances and lighting are projected based on historical data and adjusted according to the «energy efficiency index» (ODEX, [20]), which is applied to adjust consumptions, in order to take into account their expected increase, but also the effect of energy efficiency policies in final energy consumptions management.

In summary, each cluster of final uses is assessed with the respective models and the results are then combined to compute the overall residential sector consumptions in 2022, 2030 and 2050. In line with the objective, the study allows to get insights on the electrification potential of the whole residential sector in the milestone years.

5.4 RESULTS

In this section the results of the study are presented, following the methodological steps defined in the previous sections.

5.4.1 Baseline definition: results

The baseline model for 2015, obtained according to the step 1 of the methodological section, highlights that the most relevant generation technologies for space and water heating in residential buildings are gas boilers, oil boilers, biomass boilers, electric heat pumps and electric boilers. In particular, all the mentioned technologies are present in the Single Family Houses (SFH), while only gas and oil boilers are installed in Multi-Family Houses (MFH). Figure 8 consists of a snapshot of the distribution of technologies for thermal uses in residential buildings, based on their statistical frequencies across the Italian building stock per geographical area and expressed in terms of number of households.

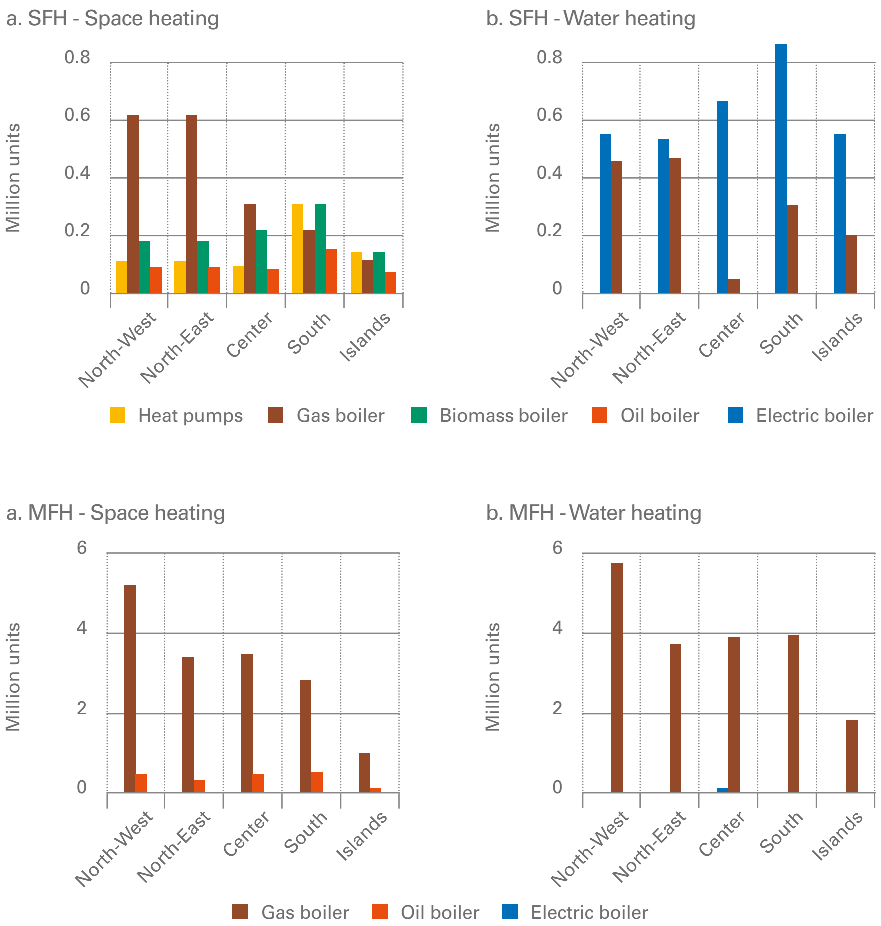

Figure 8
Distribution of residential buildings (SFH and MFH) per supply technology and geographical area [2], [13] for 2015. a) left: space heating; b) right: water heating.

The model so far described represents the starting point for the analyses addressed within the study reported in this chapter.

5.4.2 Potential evolution assessment: results

As explained in the methodology section, the evolution of thermal uses in 2022, 2030 and 2050 is studied at two different scales:

A. Single Reference Building level.
B. Stock level.

Results are reported in the following paragraphs.

A. Single Reference Building level

Customers' choices are a key factor in the process of electrification of residential sector and are driven by a variety of factors. Financial convenience (which is expressed in terms of global cost in this study) is one of the most important and, in some cases, can still favour traditional technologies. Even though electric technologies are already competitive in the market, still there is a slight disadvantage. This is due mainly to higher investment costs of electric technologies with respect to traditional ones, as well as to higher energy prices for electricity. Nevertheless, with current conditions, the extra global costs of electric technologies with respect to gas ones are always lower than 15% (Figure 9a). Relating to biomass technologies in extra-urban context (Figure 9b), they are still slightly economically viable in 2022 and 2030 (extra costs range between +15% and +25%), while energy commodities prices projections clearly advantage heat pumps in 2050.

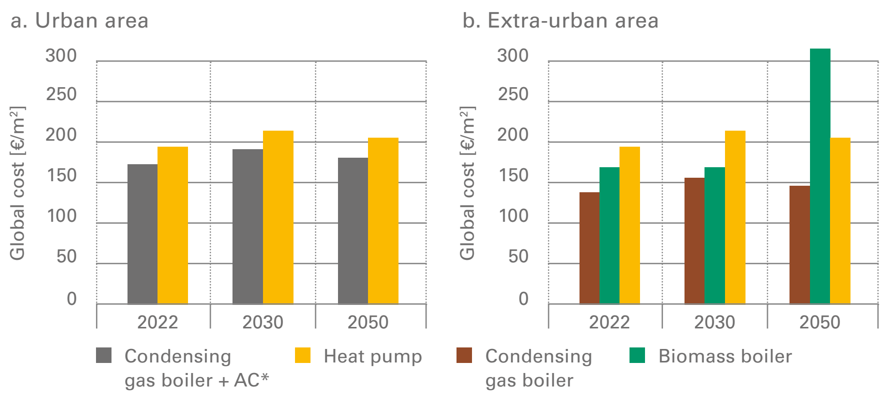

Figure 9
Global cost (corresponding to the numerator of the GCCA index) in 2022, 2030 and 2050 for MFH < 1980 North-West – space heating. a) left: in urban areas; b) right: in extra-urban areas.

* In urban area[6], the cost for a multi-split air conditioning system (AC) is added to the global cost for gas techs, representing an opportunity cost that permits to compare the services that the solutions can provide in equal terms (heat pump can provide both heating and cooling services at once).

6. The cost for the air conditioning system is added only in buildings located in urban areas because the impact of AC is significantly higher in these areas: in cities the temperatures are higher than in extra-urban areas [19] and the quality of the external air is worse, preventing an effective use of free cooling.

However, electric technologies are the most environmentally sound, representing, among the analysed technological solutions, the best compromise between PM10 and CO_{2eq} emissions. Conversely, gas technologies are the worst in terms of CO_{2eq} emissions, while biomass is the highest PM10 emitter. The capability of the different technologies for thermal uses in buildings to catch the better trade-off among the two metrics (CO_{2eq} and PM emissions) is analysed in the followings (Figure 10).

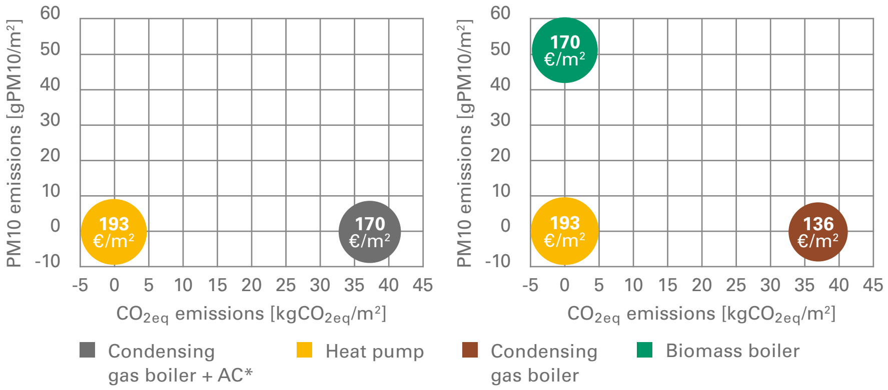

Figure 10
Environmental performances of technologies in 2022 for MFH < 1980 North-West – space heating**. a) left: in urban area; b) right: in extra-urban area.

* In urban area, the cost for a multi-split air conditioning system (AC) is added to the global cost for gas techs, representing an opportunity cost that permits to compare the services that the solutions can provide in equal terms (heat pump can provide both heating and cooling services at once).
** Bubbles dimension represents the global cost of each technology over the entire 20 years lifetime.

Figure 10 presents the competing technological options for space heating in 2022 (three in extra-urban context and just two in the urban one, where biomass is excluded due to environmental constraints) in terms of absolute values of CO_{2eq} and PM10 emissions caused.

The charts pinpoint an important result in favour of electric technologies; the heat pump clearly represents the best solution under the assumptions defined in this study, being able to satisfy the thermal needs with zero CO_{2eq} and PM10 emissions at once (considering direct emissions only). Gas and biomass boilers have opposite behaviour. Biomass boilers are the highest particulate emitters, even though they guarantee the lowest CO_{2eq} emissions, while gas boilers produce over the entire lifetime the highest CO_{2eq} emissions. In conclusion, coupling greenhouse gases and local air pollution reduction, heat pump appears to be the best trade-off. Conversely, global costs (represented by the sizes of the bubbles in Figure 10) are higher for electric technologies, due to higher investment costs and price of energy carrier.

In order to couple financial and environmental performances, the GCCA indicator is used as a measure of competitiveness of the different technological options for the thermal uses. The higher the GCCA indicator is, the less competitive the alternative is, since its cost is higher compared to the capacity of reducing CO_{2eq} emissions. This means that, when an intervention occurs in a specific building, it is most likely that, among all the possible technological alternatives, the owner is going to choose the one with the smallest indicator, calculated with respect to the current conditions of the building under intervention. This is true assuming the probable scenario in which the carbon intensity of the options will be the main criterion for future incentive mechanism, that will adjust the market towards the adoption of low-carbon intense technologies. Indeed, the indicator advantages the technology which choice implies a low ratio between its global cost and the GHG emissions reduction that it permits to get, even if from a purely financial point of view it is not the best option.

As an example of the possible alternative technologies that could be adopted when a retrofit occurs, the case of a specific RB (MFH built before 1980 in North-West climatic zone) and of a specific final use (space heating) is reported in the following graph (Figure 11).

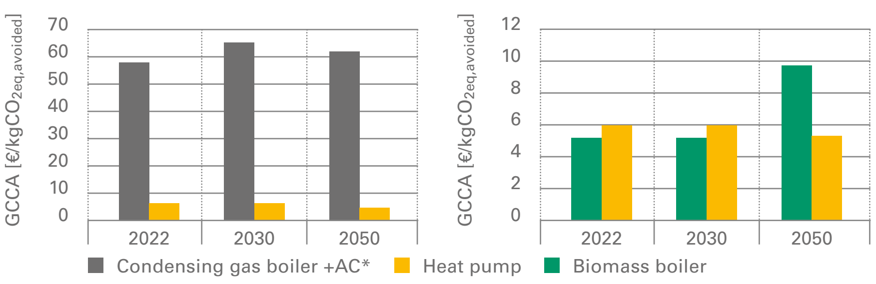

Figure 11
GCCA indicators in 2022, 2030 and 2050 for MFH < 1980 North-West – space heating. a) left: in urban area; b) right: in extra-urban area.

* In urban area, the cost for a multi-split air conditioning system (AC) is added to the global cost for gas techs, representing an opportunity cost that permits to compare the services that the solutions can provide in equal terms (heat pump can provide both heating and cooling services at once).

Based on the GCCA indicator (Figure 11), in urban areas electric technologies are always preferred to gas ones in the milestone years. This is because, even though gas technologies are more economically viable compared to heat pumps, their environmental performances are much worse than those of electric technologies, resulting in higher GCCA indicators. In extra-urban areas, biomass and electricity still compete until 2030, while in 2050 electric technologies are always preferred, mainly due to the energy prices projections, which disadvantage biomass with respect to the other commodities.

B. Stock level

In this stage, the forecasted technological shifts are scaled up to the whole residential building stock, with the aim to assess the impacts on consumptions and electrification of the thermal uses (space and water heating), when they are applied to the whole residential sector. Therefore, a reference scenario, called scenario FB is built based on the minimization of the GCCA indicator for the overall residential stock. The forecasted technological distribution for the two thermal uses according to that scenario is reported in Figure 12.

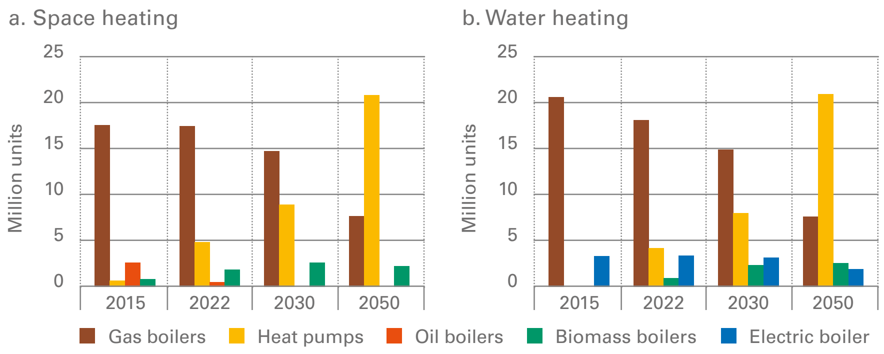

Figure 12
Technological mix in 2015, 2022, 2030 and 2050 for thermal uses (space heating and water heating) in residential buildings (both urban and extra-urban) in terms of number of units. a) left: space heating; b) right: water heating.

A rapid shift away from oil-fuelled technologies, a steady adoption of biomass boilers between 2022 and 2030 and then a progressive increase of shifts towards heat pump solutions can be observed. According to the developed model, the number of units of electric technologies for space and water heating is expected to increase from 2015 to 2050 by 27 times and 7 times, respectively. More precisely, the number of heat pumps for space heating increases by 11, 21 and 45 times in 2022, 2030 and 2050 with respect to 2015 in the urban context, and of 3, 5 and 15 times in the extra-urban context across the same timespan. The major contribution to the electrification of space and water heating comes from the buildings in urban areas, where the application of biomass technologies is restricted by environmental policy constraints. The margin of competitiveness of biomass solutions in less energy-intensive final uses (as water heating) and for extra-urban context lies in the fact that the efficiency of electric technologies combined with low consumptions makes the biomass-fuelled and electric solutions comparable, with a disadvantage for heat pumps when high electricity costs occur. In both thermal uses, gas technologies are expected to decrease, either in urban or extra-urban context, having a bad performance in terms of equivalent carbon emissions.

5.4.3 Inclusion of all final uses: results

Finally, the study is extended to all the final uses (cooking, space cooling, appliances and lighting), by coupling the model for thermal uses described so far, with the projections for space cooling, appliances and lighting, based on the historical consumption trends, and the forecasting of induction stoves adoption. The aim is to assess the impacts on consumptions and electrification of the reference scenario FB when cooking, cooling, appliances and lighting services are included in the analysis.

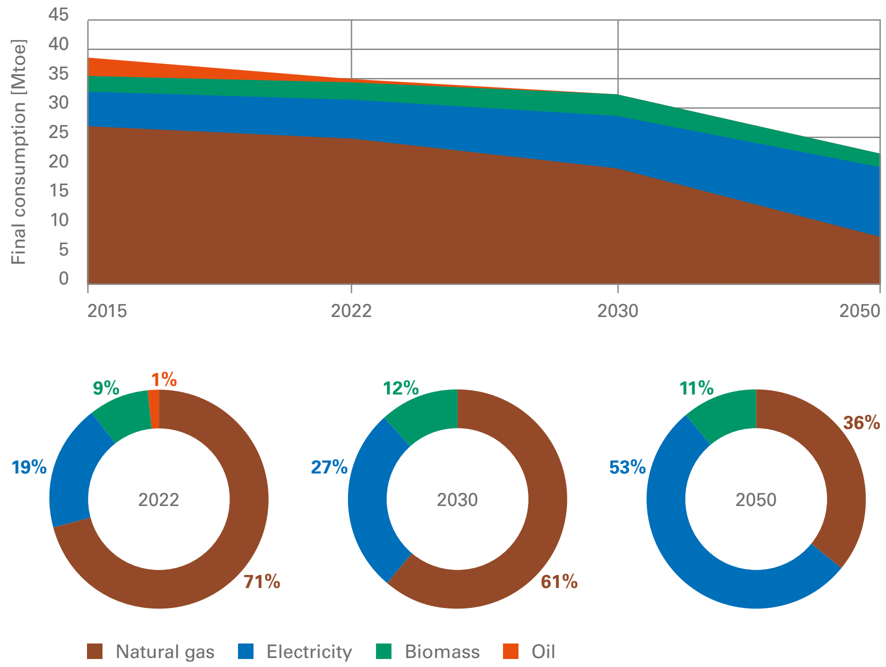

Figure 13
Final energy consumption by fuels for the overall residential sector.

Considering the overall residential sector, thus including into the analysis also the other final uses (space cooling, cooking, lighting and appliances, in addition to space and water heating), the study results in a forecasted electrification potential of 53% for the Italian residential sector, including both urban and extra-urban buildings (against the 15% electrification of 2015, characterized by low levels of electrification for space and water heating services, equal to 1.5% and 14.3%, respectively). It means that the energy consumption of electricity up to 2050 is expected to represent more than half of the total consumptions for the overall sector, as depicted in Figure 13. The electrification potential per each final use is reported in the followings (Table 7).

	FINAL USES					
Milestones	Space heating	Water heating	Appliances and Lighting	Cooling	Cooking	TOT
2022	3.6%	17.4%	100%	100%	24.4%	18.7%
2030	11.7%	26.2%	100%	100%	33.6%	27.1%
2050	36.3%	50.3%	100%	100%	66.7%	53.1%

Table 7
Electrification* of residential sector per final use.

* Defined as the ratio between the electric consumptions and the total ones.

5.5 SENSITIVITY ANALYSES

The analysis so far presented permits to build the reference scenario FB for the residential sector. However, since the calculated GCCA indicators are strictly dependent on the established boundary conditions (incentive mechanisms, taxes, energy prices, contract formulation, etc.), the following sections aim to investigate how the changes of these complex variables can influence the electrification potential, providing some suggestions about how current and potential future market regulation and pricing models schemes could push the electrification of thermal uses in buildings. Moreover, since the speed of renovation rate of thermal generators is a key influencing factor on results at the stock level, a sensitivity analysis on this parameter is developed to assess its impact on the electrification potential of the whole residential sector.

5.5.1 Market regulation and pricing model

Innovative elements in terms of market regulation mechanisms (mainly environmental costs) and pricing models (energy prices and contract formulation variations) are investigated, in order to explore their impact on the global costs associated to each technological alternative. These elements are used to build alternative scenarios, to be compared with the reference scenario (scenario FB), to depict key barriers and drivers for residential buildings future electrification.

In detail, an analysis (scenario TRF) is carried out considering the application of a non-progressive tariff to electricity for heat pumps, with the aim of investigating how this structure could be a way of incentivizing electric technologies. Scenario FB considers this tariff only for single family houses with heat pumps as the only space heating system, as defined by current regulations. Here, the non-progressive tariff is extended to heat pumps installed also in multi-family houses for space heating and to heat pumps in both single and multi-family houses for the water heating service (excluded in the current regulation). This assumption results in a variation of the energy costs in the global cost formulation and, thus, in terms of indicators.

Energy price influence on results is also analysed (scenario SP), considering gas and electric prices constant across the timespan (from 2015 up to 2050), while biomass and oil prices were kept changing according to ETP16 growth rates [17], as in the reference scenario (scenario FB).

Finally, the introduction of environmental taxes as market regulation mechanisms is analysed (scenario TX). Indeed, one of the biggest issues that countries are facing nowadays is local air pollution, mainly in urban areas, where, during the last decades, concentration of pollutants is drastically increasing, especially during the winter season. Due to the severe consequences that these harmful pollutants can have on health, local governments should promote adequate policies and precautions, to prevent serious consequences on the people and the environment. In the building sector, fuel combustion for heating represents the major source of emissions of air pollutants. Two sensitivity analyses are developed:

- Scenario TX_CO_2, which considers the adoption of a taxation on CO_{2eq} emissions (0.2 €/kgCO_{2eq} [21], weighted for SFH and MFH proportionally to their relative consumptions) for space and water heating systems.
- Scenario TX_PM10, which assumes the adoption of a taxation on PM10 emissions (0.87 €/gPM10 [21], weighted for SFH and MFH proportionally to their relative consumptions) for space and water heating systems.

All the above-mentioned assumptions are summarized in Table 8, comparing them with the ones on which reference scenario FB is based. The texts reported in blue represent the assumptions characteristic of each sensitivity scenario.

	MARKET REGULATION		PRICING	
Scenario	**Incentives**	**Enviromental costs**	**Price levels**	**Price modulation**
FB	• Ecobonus • Conto termico 2.0 (table 5)		Energy price growth rates according to ETP16	Non progressive tariff for SFH with heat pumps for space heating
TRF	• Ecobonus • Conto termico 2.0 (table 5)		Energy price growth rates according to ETP16	Non progressive tariff extended to heat pumps also in MFH for space heating and in SFH and MFH for water heating
SP	• Ecobonus • Conto termico 2.0 (table 5)		Fixed prices for gas and electricity	Non progressive tariff for SFH with heat pumps for space heating
TX_CO_2	• Ecobonus • Conto termico 2.0 (table 5)	CO_{2eq} taxation for space and water heating systems	Energy price growth rates according to ETP16	Non progressive tariff for SFH with heat pumps for space heating
TX_PM10	• Ecobonus • Conto termico 2.0 (table 5)	PM10 taxation for space and water heating systems	Energy price growth rates according to ETP16	Non progressive tariff for SFH with heat pumps for space heating

Table 8
Main assumptions of sensitivity analyses.

The variations summarized in Table 8 imply the re-calculations of the GCCA indicators (since these assumptions induce changes into the global cost computation). In particular, focusing on the variations of global cost, the latter being the key driver for the private investor behaviour, an analysis of the difference in global cost between electric and gas technologies for the urban area (where biomass is excluded), and between electric and biomass technologies in extra-urban area (where biomass can be still convenient) is performed, to evaluate to what extent other technologies are still more financially convenient than the electric ones.

ELECTRIFY ITALY / 5. ELECTRIFICATION OF RESIDENTIAL BUILDING SECTOR

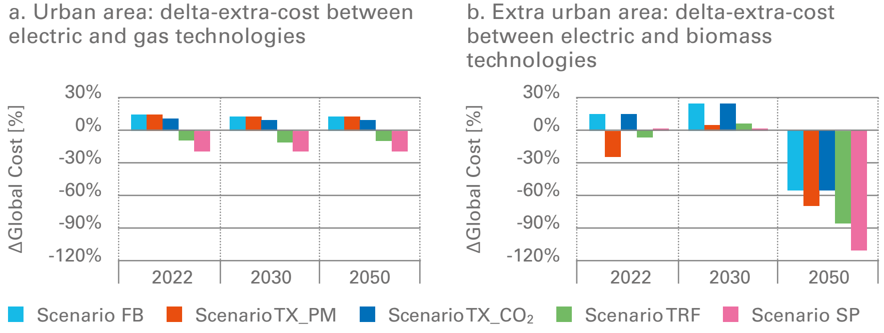

Figure 14
Delta global costs of heat pumps with respect to global costs of the competing technological option for MFH < 1980 North-West – space heating. a) left: gas-heat pump competition (urban area); b) right: biomass-heat pumps competition (extra-urban area).

In the urban context (Figure 14.a), where gas and electric technologies compete, a PM taxation (scenario TX_PM) has a marginal effect, while a taxation on CO_{2eq} (scenario TX_CO_2) can help in reducing the extra-cost for the electric technologies with respect to gas ones. However, in these situations environmental costs are still not enough to make heat pumps economically convenient in all contexts. Appropriate financial measures, such as the extension of the non-progressive electric tariff for heat pumps (scenario TRF) and equal prices growth rates for gas and electricity (scenario SP), can reverse results, clearly advantaging heat pumps over competitors (in scenario FB, the growth rates for electricity prices are higher compared to gas ones, according to IEA projections [17]).

In the extra-urban context (Figure 14.b), instead, consumers' choices can massively go in the electric direction if environmental cost is reflected in the energy bills. Here, the difference in the financial burdens borne by consumers choosing electric technology with respect to biomass technologies can advantage heat pumps (delta global cost equals -26% in 2022) if a tax on PM10 (scenario TX_PM) is associated to the environmental impacts of the solutions, due to the high PM emissions caused by biomass technologies. On the contrary, financial measures (scenario TRF and scenario SP) have lower impact on the competition in this context. However, the trends in energy prices of electricity and biomass is what is mostly influencing the overturning of the delta costs in 2050, meaning that the price model is a key influencing factor to be carefully treated.

In the urban context, where the competition between electric and gas technologies is stronger, the identified financial measures can advantage heat pumps from a purely financial point of view (as expressed by the global cost index). Their capability to foster the electrification at the whole stock level is further investigated in the followings. Looking at the entire residential sector and at its technological trends as forecasted by the computation of the GCCA index, the adoption of the non-progressive electric tariff for heat pumps (TRF) could further push the electrification for the whole sector up to 55% in 2050 (Figure 15), moving the sector in the same direction forecasted in the scenario FB, based on the GCCA indicator, which combines financial and non-financial variables. Keeping constant prices of gas and electric energy (SP) across the years results in a 56% of electrification in 2050, 3% higher with respect to scenario FB. Therefore it is possible to conclude that, looking at the GCCA-based analysis, although the scenarios TRF and SP have significant impact on the global costs of the technological options, they have a marginal impact on results at the stock level. Indeed, given the assumptions of these scenarios, the ranking of the technologies based on the GCCA indicators are unchanged with respect to the scenario FB, where gas is already excluded, being the most emitting technology in terms of CO_{2eq} emissions. However, scenarios TRF and SP slightly advantage heat pumps over biomass in the extra-urban context (where the strongest competitor of electric technologies is biomass solutions), causing the variations in terms of total electrification of the building sector (compared to scenario FB).

Then it is possible to conclude that appropriate financial measures can influence consumers' choices by driving the sector towards the condition in which environmentally-friendly choices are advantaged, paving the way to a higher electrification rate, as expressed by the GCCA indicator. Financial measures introduction could further push the sector electrification, as depicted in Figure 15.

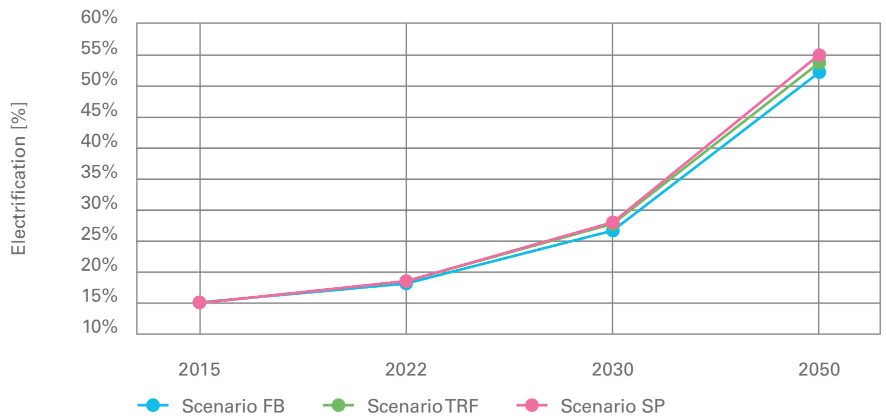

Figure 15
Electrification potential in residential buildings.

However, the factor that mostly influences the electrification potential of the sector is the renovation rate; without a speed up in the annual renovation rate of buildings, a huge part of the electrification potential risks to be untapped. This issue is investigated in the following section.

5.5.2 Renovation rate

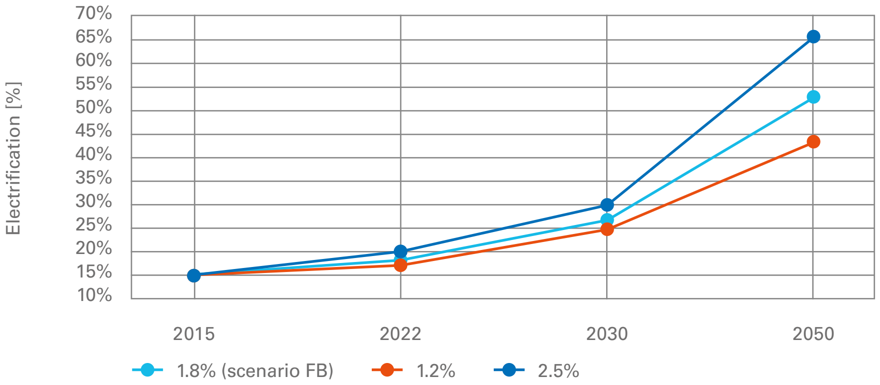

Figure 16
Comparison between different renovation rate scenarios in terms of electrification.

Varying the renovation rate from 1.2% to 2.5%, the electrification potential can range from 43% to 66% (Figure 16). It can be concluded that, to unlock the electrification potential that could be captured with the existing technologies, the speed up of the renovation rate would be a key driver. Measures aimed at incentivizing buildings renovation can therefore contribute to speed up the electrification of the sector, contributing to an increase in the environmental performance (defined in terms of CO_{2eq} saved) of the stock. As already highlighted, the translation of the environmental costs in costs for the final users can support this process.

FOCUS BOX: COOLING

Nowadays, it is well established that global warming and climate change have an impact on external temperature, and it is particularly true during summer periods. This will have clear consequences on the needs for air conditioning, clearly increasing the demands for space cooling in buildings, both residential and non-residential. This illustrative box deepens the theme of space cooling demand forecasting, for the whole building sector in Italy, aiming to depict the effect that climate change might have in future years on cooling consumptions. According to the estimations of the Climate Impact Lab [22], in Italy the number of days with temperature above 25°C (also called hot days [2]) is expected to increase. In this work, in order to estimate the actual rise of hot days, the approach used in the Heat Europe Roadmap [23] is adopted, supposing the increase of hot days proportional to the rise of Cooling Degree Days (CDD). According to this calculation, days with temperature above 25°C are expected to increase by 0.38% per year on average (2.4 more hot days per year). The evolution of CDDs and hot days during the milestone years (2022, 2030, 2050) is shown in Figure 17. It is assumed that the increase of hot days will induce the driving up of the demand for air cooling, both in terms of increase of households equipped with air conditioning systems and of number of hours of cooling operation, with a subsequent increase of energy demand. As an example, during the 2003 heatwave in France, peak power demand grew by about 4 GW, around 10% more than the normal peak summer demand [24].

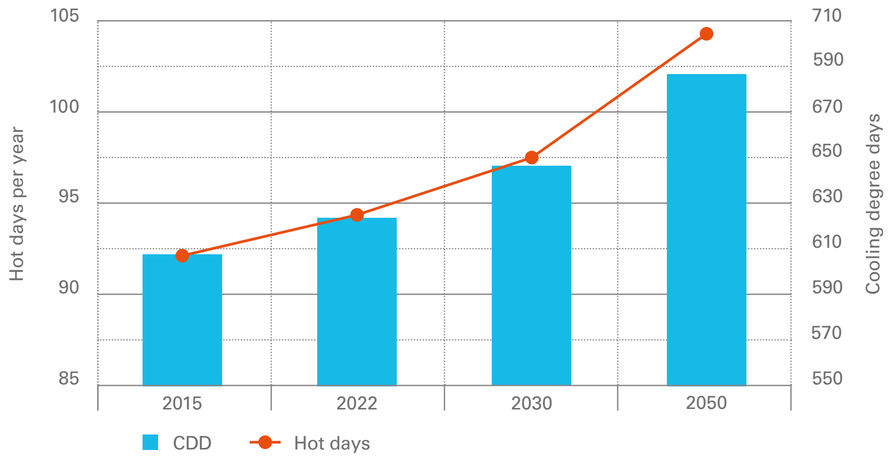

Figure 17
Comparison between hot days and cooling degree days in Italy.

Furthermore, the increment of external temperature has a direct impact on people health. In particular, the aging of population is another factor that suggests that the need for air conditioning will go dramatically up, since older people are in general more sensitive to heat, and high ambient temperatures may increase the mortality rate [25]. The INSERM has reported that in 2003 almost 15,000 more than the usual died in France due to the unusual high temperatures. Almost 80% of them were over 75 years old [26].

Starting from this past occurrence and considering that in Italy, according to ISTAT projections [2], the share of people over 75 is going to steadily grow and reach 21% in 2050 (Figure 18) and that the number of hot days will increase, it is necessary to implement adequate mitigation strategies.

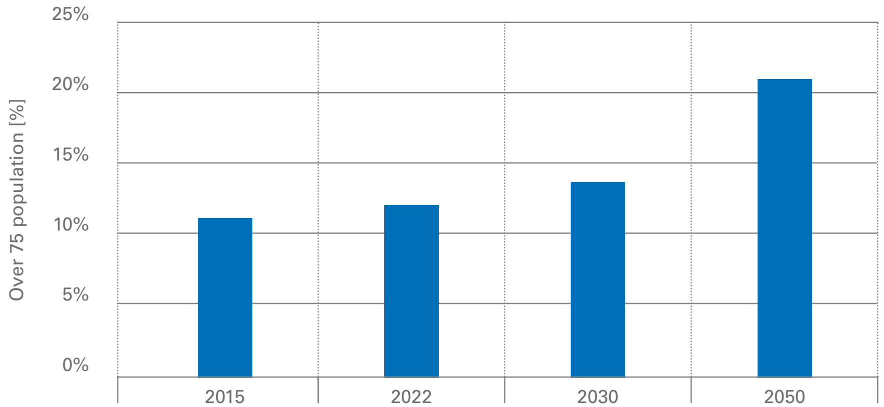

Figure 18
Population over 75 years old share in Italy.

For all the above, it is reasonable to expect that, to tackle this issue and to simply address the need to maintain an adequate comfort level in buildings, the energy demand for air conditioning will grow. In this framework, a further deepening on air conditioning was performed, aiming to evaluate the potential rise of space cooling final consumption due to the increase of annual hot days, the latter attributable to climate change [25]. The analysis of residential and non-residential sectors is developed separately.

Residential sector

For the residential sector, after the analysis of the real Italian stock described in 5.3.2, 30 reference buildings are modelled using MasterClima software [12] and the space cooling energy needs (in kWh/m²) are extrapolated. The daily operation hours of the air conditioning systems and the total square meters cooled in buildings are obtained from ISTAT database [2] for 2015 and for each geographical zone. Given the previous data, the final consumption for space cooling for 2015 is calculated by multiplying the cooling energy needs by the cooled surface and using a coefficient of performance (COP) equal to 2, supposed constant over the years, obtained as an average between the efficiency of a traditional multi-split and that of a heat pump. Once estimated the consumption for air conditioning for 2015 for the entire residential sector, the consumptions for space cooling for the three milestones are predicted considering two different approaches. The first one considers the increase in cooled surfaces, due to the construction of new buildings (annual new building rate of 1% [18]) and by the replacement of existing heat generation technologies (annual renovation rate of 1.8% [9]) through the introduction of the heat pump that allows both heating and cooling services as the only driver for the increase of space cooling demand. The second approach, instead, links the increase of space cooling consumption with the increase of the number of hot days over the years (shown in Figure 17) caused by climatic changes. For this approach, the daily operating hours are kept constant during the years, while the total operating hours increase consequently to the increase of the days in which the air conditioning system is switched on.

Non-residential sector

For the non-residential sector, which includes commercial and public services, the reference building approach applied for the residential sector is not used, due to lack of data. Starting from the percentage contribution of space cooling in total final energy consumption of non-residential buildings (10% [23]), the total space cooling consumption (in kWh/m²) in Italy in 2015 is estimated from statistical data [27]. Moreover, the square meters of the non-residential stock are extrapolated from ISTAT data [2]. Multiplying the kWh/m² by the cooled square meters, the estimation of the total space cooling consumption for non-residential buildings in 2015 is carried out.

Given the previous data, the methodology followed for forecasting the consumptions in the milestone years is identical to the one described for the residential sector, even though the initial assumptions are different. Consumptions are estimated firstly by considering only an increase of square meters due to the new buildings (annual rate of new of 0.68% [27]) and then adding the quota of space cooling consumptions related to the increase of the number of hot days.

Results

According to the analysis so far described, the penetration of air conditioning in the building sector is estimated in the milestones by merging the results coming from residential and non-residential sectors. With an annual rise in hot days of 0.38%, due to climate change effects, the total cooling consumption of the entire building sector is expected to reach 47 TWh by 2050, 81% more with respect to 2015 level.

Figure 19 shows the evolution of the space cooling consumptions in residential and non-residential buildings. In particular, the dark red blocks represent the increase in consumptions due to the growth of cooled floor area, while the red one includes the sole effect of the increase of hot days. In 2050, the analysis considering the hot days will lead to an extra-consumption of 13% and 11.5% in residential and non-residential buildings, respectively. Together with the stronger penetration of air conditioning in households and non-residential buildings, this leads to an extra-consumption of electricity for cooling purposes of 2.6% in 2022, 6.1% in 2030 and 13.2% in 2050 in residential sector and of 2.7% in 2022, 6% in 2030 and 11.5% in 2050 in non-residential sector.

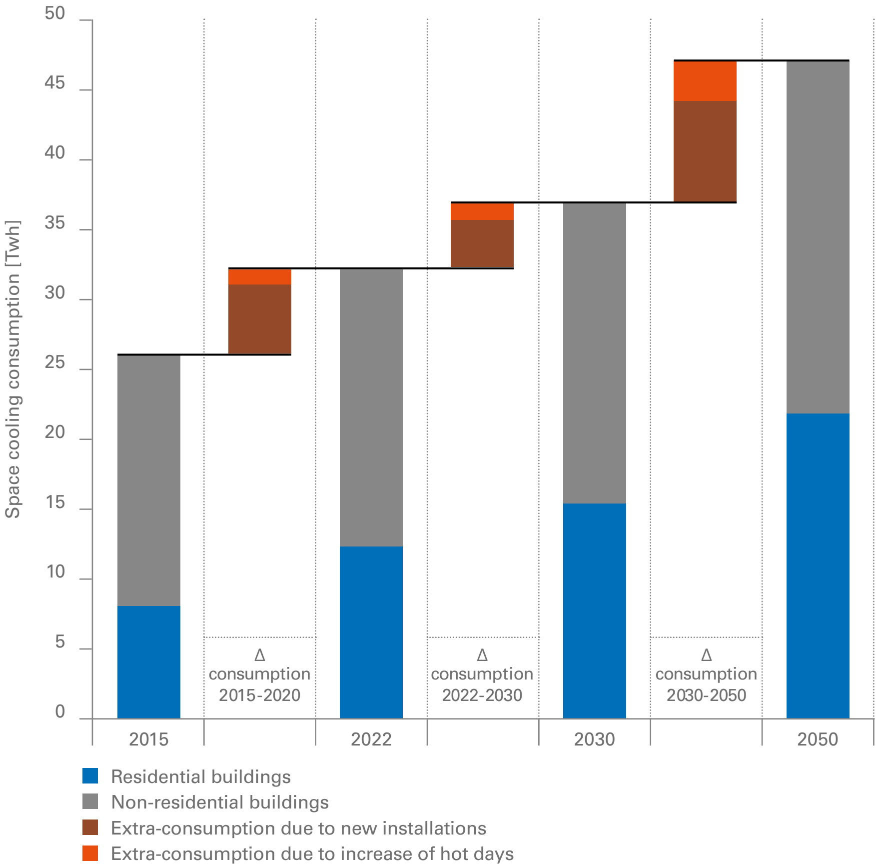

Figure 19
Space cooling consumption forecasts in residential and non-residential buildings.

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Chapter 6

ELECTRIFICATION OF INDUSTRY SECTOR

6.1 CURRENT SECTORAL STRUCTURE

As reported by the International Energy Agency (IEA) and the US Energy Information Administration through their international energy outlook reports [1], [2], industry was by far the largest consumer of electricity in 2016 across the world. Electrification of industry sector is increasing and OECD countries, including Italy, play a major role in this process, as shown in Figure 1 and Figure 2 [3]. In particular, Figure 1 shows the trends of the Italian industry electrification during the last 50 years, in comparison with OECD countries and global average shares. Electrification rate in Italian industry was around 39% in 2016, as shown in Figure 2, with a total amount of electricity consumption of around 9,900 ktoe.

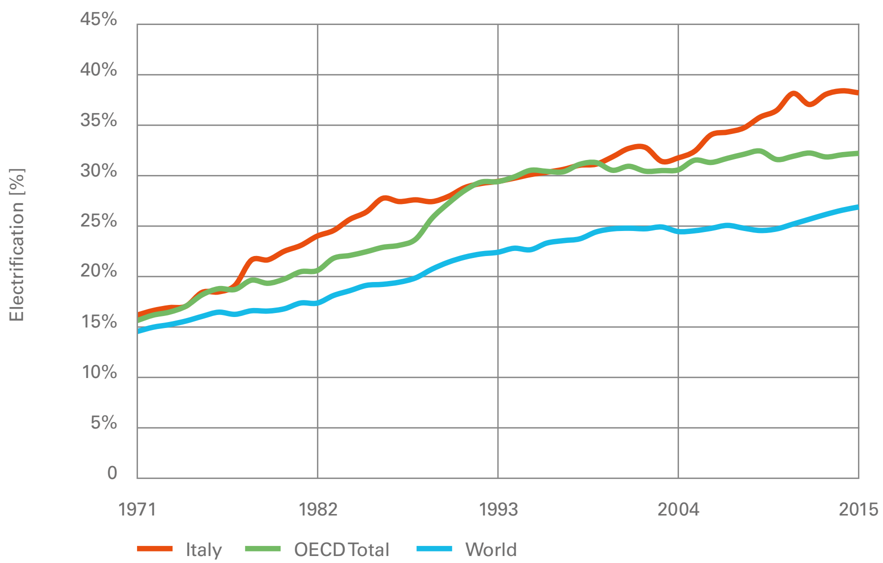

Figure 1
Share of electricity consumption in industry. Elaboration from [3].

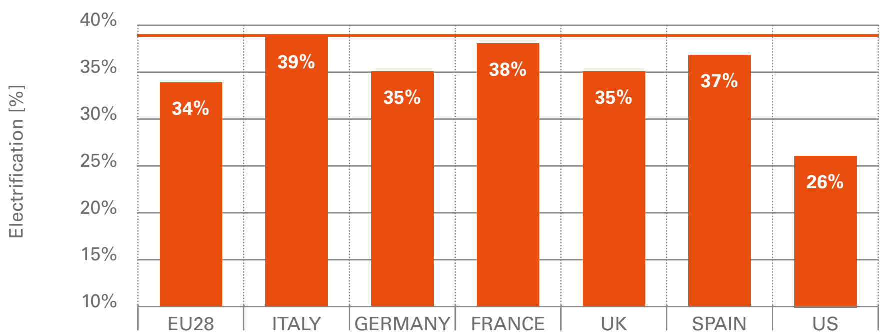

Figure 2
Industry electrification: an international comparison.

Industry in Italy represents 19% of total GDP and accounts for more than 21% of final energy consumption. Energy consumption in industry ensures the provision of services that can be divided in three main groups: heat for thermal processes, mechanical or chemical energy, and energy for auxiliary services such as lighting or air conditioning. Figure 3 shows energy services by type for the most relevant sectors; according to the type of demand, the three groups can be divided into relevant sub-classes, including refrigeration or compression, mechanical work and heat supply at different temperature levels. Heat consumption in Italian industry in 2015 was of about 133 TWh, equivalent to almost 46% of final energy consumption of the sector. Figure 4 illustrates heat utilization in 2015 at different temperature levels for the main industrial sectors. Notably, heat utilization at low temperature (<100°C) accounts for 15.8 TWh, with food products, fabricated metal products and non-metals accounting for 85% of the total. Heat utilization at low-to-medium temperature (100-to-200 °C) accounts for 21.3 TWh, with non-metals, food products and fabricated metal products accounting for 80% of the total. Heat utilization at medium temperature (500-to-1000 °C) accounts for 13.5 TWh utilized in basic metals, non-metals, and chemical sectors. High temperature (<1500°) heat accounts for 34.3 TWh mostly (75%) concentrated in non-metals sector. Finally, ultra-high temperature (>1500 °C) heat is used in basic metals sector only. In 2015, heat supply at different temperatures (100.5 TWh) was supplied burning gas, oil, and coal, while the remaining (32.5 TWh) was obtained by biomass and waste heat recovery (BWH). Figure 4 and 5 represent heat consumption with an outline of the above mentioned five temperature levels.

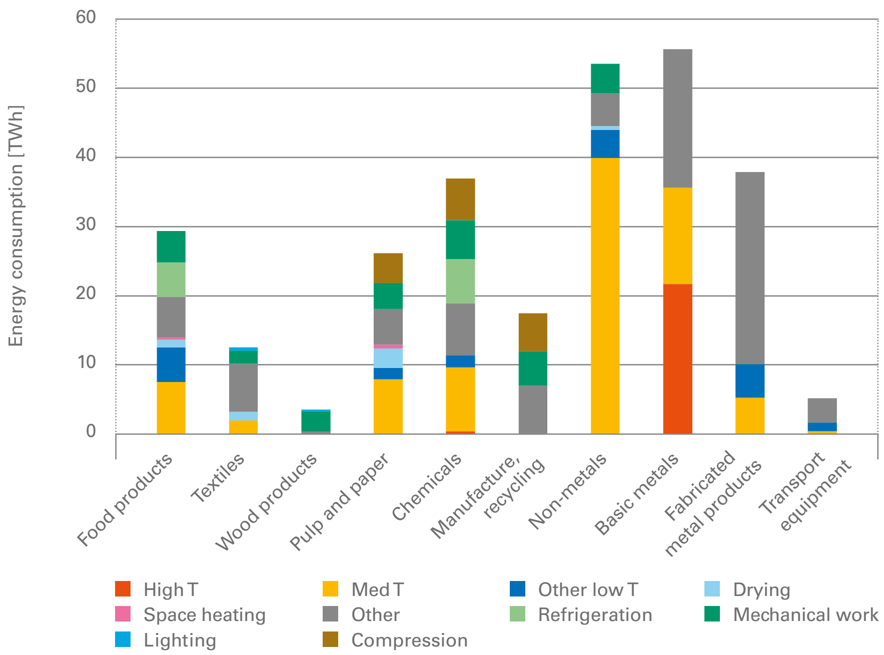

Figure 3
Energy services for the most relevant sectors of Italian Industry in 2015.

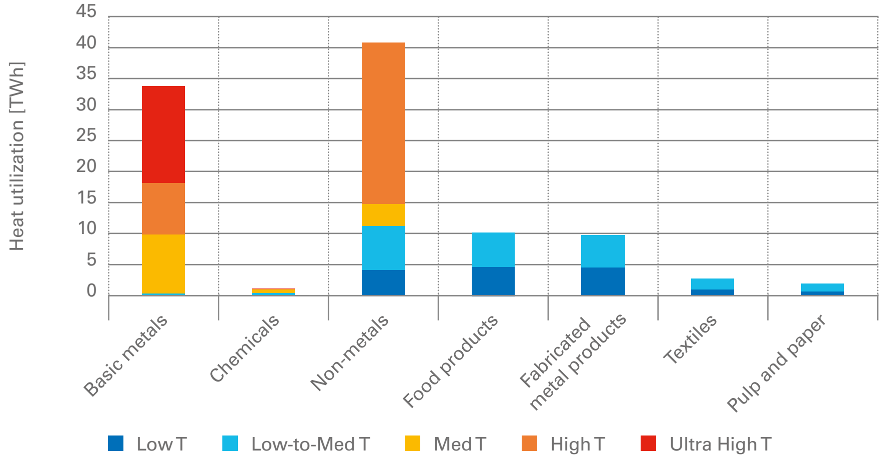

Figure 4
Heat utilization in main industrial sectors in Italy in 2015.

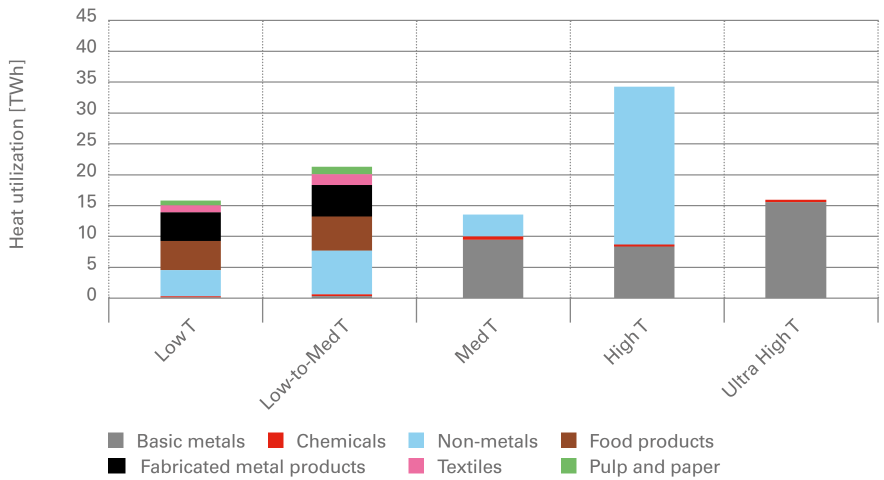

Figure 5
Heat utilization in main industrial sectors in Italy in 2015 at different temperature levels.

6.2 METHODOLOGY

The focus of this analysis is to study the electrification of the Italian industry sector in 2022, 2030, 2050. The specific objectives are:

- To identify key electrical technologies to provide energy services to the Italian industry sector.
- To analyze the theoretical potential for the electrification of the Italian industry sector.

- To analyze the techno-economic potential for the electrification of the Italian industry sector.
- To assess the impact of the electrification of the Italian industry sector in 2022, 2030, 2050 in terms of GHG and pollutants emissions reduction.
- To study drivers for and barriers to the achievement of an increased electrification level of the Italian industry.

The Italian industrial sector is investigated using an input-output model able to assess the direct and indirect final energy consumption and intensity of 14 industrial sectors. All the input data are harmonized following the International Standard of Industrial Classification (ISIC) guidelines [4]. Italian and European data available in NACE (Nomenclature statistique des Activités économiques dans la Communité Européenne) classification [5] are adjusted to ISIC through international guidelines.

The theoretical potential for the electrification of the Italian industry sector is assessed based on the study of the energy services (mechanical work, refrigeration, heating, lighting, etc…) delivered to industry. Nine key electrical technologies, listed in Table 1, are studied for potential electrification of industry. The study includes the assessment of capital cost, learning curves, conversion efficiency and technology improvement (i.e. increase in efficiency over time). Furthermore, conventional gas, coal and oil technologies providing heat, at 5 different thermal levels, are modelled, so to compare the whole set of technologies and find the least cost solution. The model neglects innovation in competitive gas technologies (e.g., biogas, biomethane, CCS, etc.). Only one indirect electrical technology, namely power-to-gas for hydrogen production, is considered in this study.

TECHNOLOGIES	TEMPERATURE LEVEL	STATUS
Heat pump – LT	Low (<100°C)	Available
Micro Wave heating	Low (<100°C)	Available
RF heating	Low (<100°C)	Available
Heat pump – LMT	Low-to-Med (100°C - 200°C)	Not yet mature in the whole temperature range
Induction heating (HT)	Low-to-Med (100°C - 200°C)	Available
Direct heating	Med (500 - 1000°C)	Available – large scale may be an issue
Resistance heating (direct and indirect)	Med (500 - 1000°C)	Available – large scale may be an issue
Electric arc furnace	Ultra High T (>1500 °C)	Available
Power to Hydrogen and hydrogen boiler	High and Ultra High T (>1000 °C)	Under development

Table 1
Summary of electrical technologies assessed in this study.

This study uses a bottom-up simulation model able to estimate the stock accounting variation based on the Levelized Cost of Heat (LCOH). For each time step (2022, 2030, 2050), each industrial subsector, and for different temperature levels, the model computes the cost of heat production achieved by different technologies (electrical, gas, oil and coal) and updates the stock accounting with least-cost solutions. The model includes inertial stock substitution, estimated at 3%/year conventional technology stock substitution [6]. LCOH is calculated assiuming a 5% discount rate, obtained adopting the Weighted Average Cost of Capital method.

Table 2 outlines the main model assumptions for electrical technologies including cost and conversion efficiency in milestone years. For the intermediate time steps, a linear variation is assumed.

TECHNOLOGY	COST [€/KW][1]				EFFICIENCY/COP			
	2015	2022	2030	2050	2015	2022	2030	2050
Heat pump – LT [7], [8]	600	558	447	390	3.50	3.90	4.36	5.50
Microwave heating [9], [10], [11], [12]	500	465	372	325	0.50	0.54	0.59	0.70
RF heating [9], [13], [11], [12]	500	465	372	325	0.50	0.54	0.59	0.70
Heat pump – LMT [8], [7], [11], [12]	1200	1116	894	780	2.00	2.20	2.43	3.00
Induction heating (HT) [9], [13], [11], [12]	100	93	75	65	0.75	0.78	0.81	0.90
Direct heating [9], [13], [11], [12]	100	93	75	65	0.75	0.79	0.84	0.95
Resistance heating (direct and indirect) [9], [13], [11], [12]	100	93	75	65	0.75	0.79	0.84	0.95
Electric arc furnace cost (€/ton); efficiency (kWh/ton) [14]	80	75	71	56	400	376	349	280
Power to Hydrogen and hydrogen boiler [15]	1000	900	720	500	0.61	0.63	0.66	0.72

Table 2
Main model assumptions for electrical technologies.

Table 3 reports the main model assumptions for conventional gas technologies, including cost and conversion efficiency in milestone years. For the intermediate time steps, a linear variation is assumed.

1. Please note that cost and energy consumption for electric arc furnaces are expressed in €/ton and kWh/ton respectively.

TECHNOLOGY	COST [€/KW][2]				EFFICIENCY			
	2015	2022	2030	2050	2015	2022	2030	2050
Gas								
Gas boiler – LT [16]	50	47	38	5	0.75	0.78	0.81	0.90
Gas boiler – LMT [16]	50	47	38	35	0.70	0.73	0.76	0.85
Combustion gas furnace [16]	50	47	38	35	0.70	0.73	0.76	0.83
Conventional gas oven [17]	50	47	38	35	0.70	0.73	0.76	0.83
Gas dryer [18]	50	47	38	35	0.50	0.52	0.54	0.60
Blast furnace BF - BOF cost (€/ton); efficiency (kWh/ton) [14]	250	235	223	175	1200	1120	1028	800
Coal								
Blast furnace BF - BOF cost (€/ton); efficiency (kWh/ton) [14]	250	235	223	175	1200	1120	1028	800
Oil								
Oil boiler [16]	50	47	38	35	0.80	0.82	0.84	0.90
Oil boiler [16]	50	47	38	35	0.75	0.77	0.79	0.85

Table 3
Main model assumptions for conventional technologies.

Figure 6 summarizes conversion efficiencies of different technologies in the different considered years. It is possible to see how energy performance of electrical appliances is in many cases better than gas and oil ones.

The model includes time price variation of commodities and change in carbon pricing. Higher efficiency, low capital and low operating cost technologies lead to reduced LCOH. Gas, electricity, coal, oil prices determine the cost of heat production by gas, electricity, coal and oil appliances respectively. CO_2 prices determine the cost of heat production by fossil-based appliances and electricity, based on varying emission factors. The model calculates the stock time variation of gas, electricity, coal and oil appliances for heat production and updates the total final energy consumption mix.

Simulations are carried out and the forecast for the electrification of Italian industry in 2022, 2030, and 2050 is calculated. In particular, the study considers the evaluation of electrification under two different scenarios, as reported in Table 4. Both scenarios account for socio-economic drivers, namely Gross Domestic Product (GDP) and population. In addition, energy prices variations are considered for electricity and fossil fuels. Finally, carbon dioxide price changes are considered according to IEA – ETP2016 [19]. The two scenarios incorporate the evolution of electricity and gas prices; while the High Electrification scenario refers to IEA estimates for energy prices (i.e. IEA - ETP2016 [19]), the Beyond High Electrification scenario considers a synthetic yearly growth rate of 0.9 in retail price for electricity, and of 1.1 for gas price in the same period. Historical trends for energy consumption variation in industry are used to estimate the final energy demand in the industry sector in the 2015-2050 period (for High Electrification and Beyond High Electrification scenarios) [3].

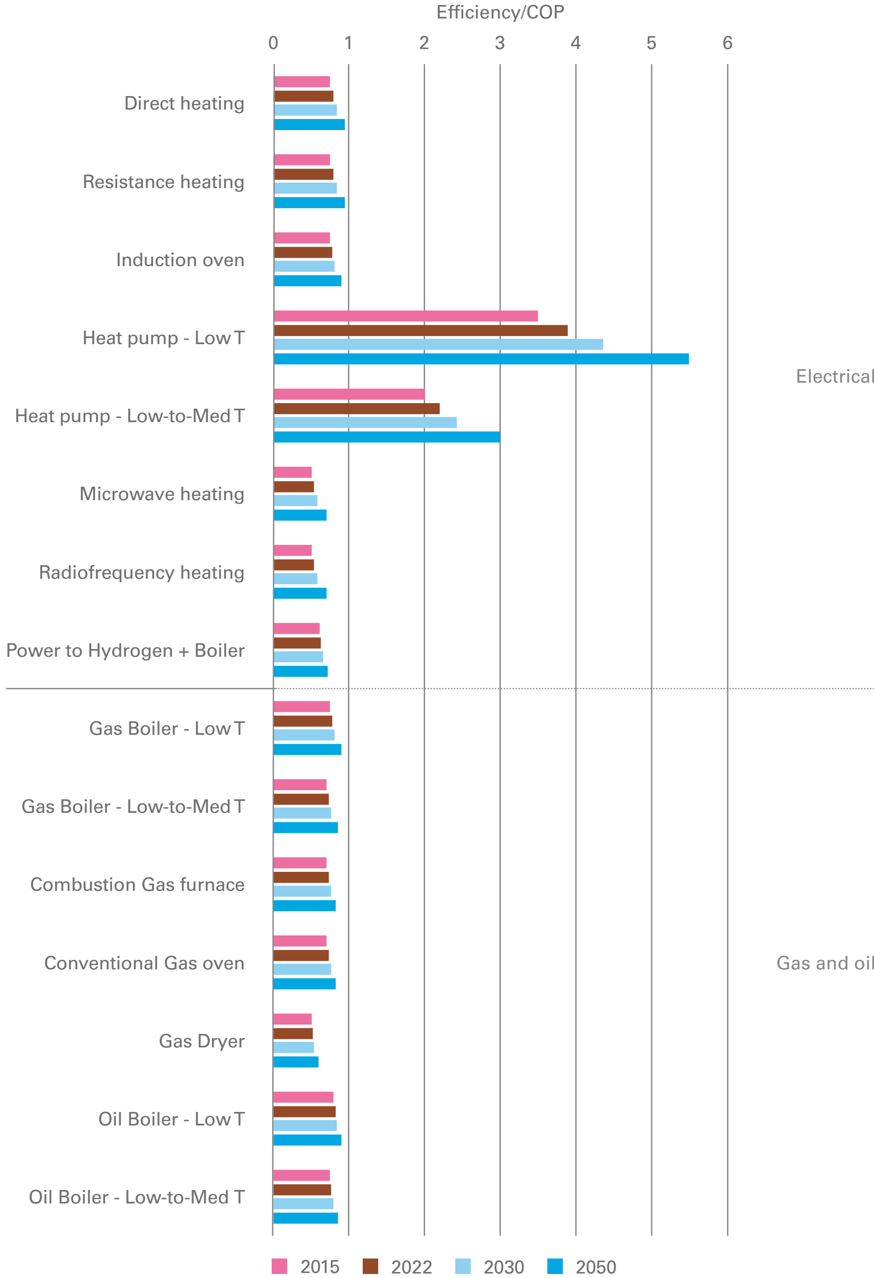

Figure 6
Performance of electrical vs gas appliances.

2. Please note that cost and energy consumption for blast furnaces are expressed in €/ton and kWh/ton respectively.

Table 5 summarizes the main input data of the considered scenarios.

DRIVERS				
	GDP and population	**Final energy consumption**	**Energy prices variation**	**CO_2 Prices**
High Electrification	OECD Projections [20]	Trend Extrapolation [3]	IEA – ETP2016 2DS [19]	IEA-ETP2016 2DS [19]
Beyond High Electrification	OECD Projections [20]	Trend Extrapolation [3]	Cumulative advantage[3]	IEA-ETP2016 2DS [19]

Table 4
Main model macro-scale assumptions.

	2015	2022	2030	2050
High Electrification Scenario				
Electricity-to-gas price gap	3.9:1	4.2:1	3.6:1	3.4:1
Carbon price (€/tCO_2)	16	45.5	81.8	140.9
Beyond High Electrification Scenario				
Electricity-to-gas price gap	3.9:1	3.8:1	3.5:1	3.2:1
Carbon price (€/tCO_2)	16	45.5	81.8	140.9

Table 5
Main hypothesis of the two scenarios.

6.3 RESULTS

From a purely technological perspective, which considers only availability and technology maturity, electrical appliances could potentially be introduced in all sectors at different temperature levels, with a theoretical potential of 88 TWh thermal energy output by 2030.

Nevertheless, by introducing economic constraints, high temperature electric technologies cannot compete with their traditional counterparts, and it is possible to estimate which fraction of this theoretical potential can be captured, as Figure 7 shows for low-temperature heating appliances in years 2030 and 2050.

3. In this scenario, electricity experiences a progressive reduction of the competitive disadvantage of price. This is achieved by introducing a synthetic yearly growth rate of 0.9 in retail price for electricity, while setting the gas growth rate to 1.1 for the same period.

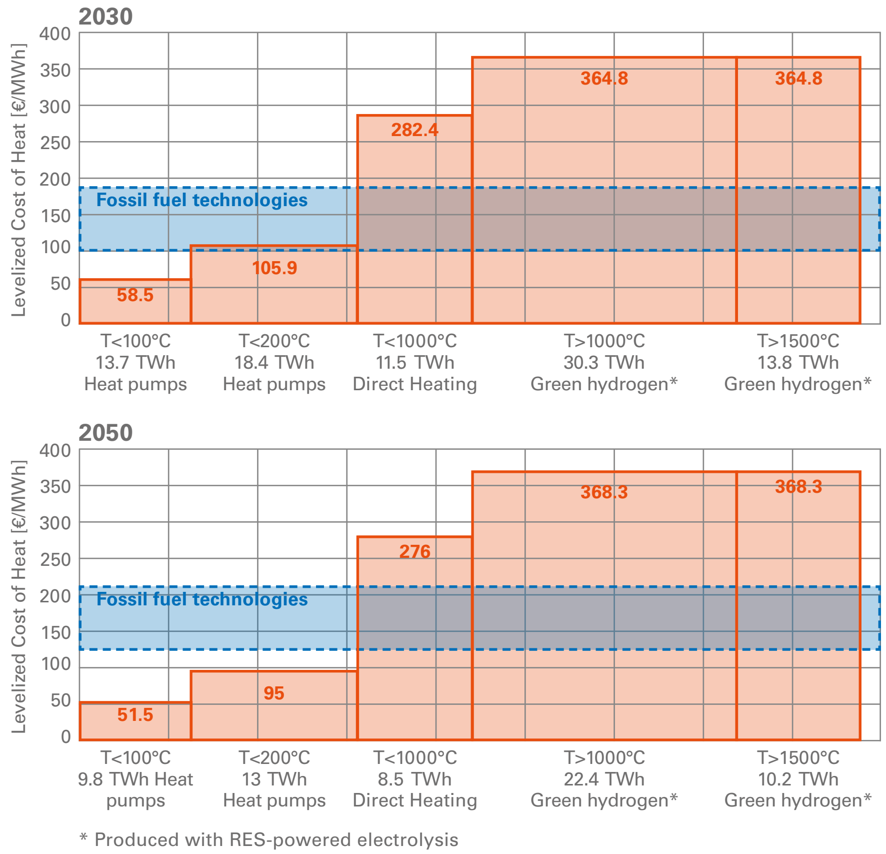

Figure 7
Levelized Cost of Heat for electric appliances in the High Electrification Scenario at 2030 and 2050.

Low temperature (<100°C)

Low temperature heat pumps (<100°C), due to high conversion efficiency (COP range 3.5 - 5.5 for low temperature heat pumps vs. 0.75 - 0.9 of a gas boiler), are already competitive technologies with gas appliances. They capture 43% of the low temperature heat demand potential in 2030 and have potential, in 2050, of 9.8 TWh thermal energy.

Low-to-medium temperature (100°C - 200°C)

Low-to-medium temperature heat pumps, due to high conversion efficiency (COP range 2 - 3 for low-to-medium temperature heat pumps vs. 0.7 - 0.8 of a gas boiler), are competitive technologies with gas appliances after 2030, when electricity-to-gas price gap is below 3.5, and can add a potential of 13 TWh thermal energy through electrification at 2050. They capture 40% of heat production potential by 2050 due to inertial stock substitution.

Medium temperature (200°C - 1000°C)

Despite the slightly higher efficiency of medium temperature electrical appliances than gas appliances (efficiency range 0.75 - 0.95 for low-to-medium temperature heat pumps vs. 0.7 - 0.83 of a gas boiler), high electricity-to-gas price ratios make them not competitive. In 2050 the breakeven would be at a ratio of 1.5 (57% lower than IEA estimates), compared to the present 3.9. The value of providing flexibility services to the power grid and low-cost on-site generation from renewables could improve the competitiveness of electrical appliances.

High temperature (1000°C - 1500°C)

High-temperature solutions (e.g. hydrogen production), characterized by slightly lower efficiencies than their traditional equivalents, are not competitive due to the high capital cost and comparatively high cost of electricity. To be competitive with gas, industrial hydrogen use for high and ultra-high temperature applications would require electricity-to-gas price ratios of 0.7 in 2030 and 1.1 in 2050 (meaning 80% and 70% lower than IEA estimates). Sector coupling, on-site renewable power sources and/or market designs rewarding flexibility and storage could provide those conditions. Sector coupling, i.e. the integration of power and gas infrastructure, could promote high-temperature solutions. Power-to-gas technologies may produce low-cost “green” hydrogen (i.e. produced with electrolysers using mostly renewable energy), as well as providing ancillary services by avoiding power grid congestions and mitigating temporal and geographical mismatches between electricity generation and consumption.

Ultra-high temperature (>1500°C)

Ultra-high temperature electrical technologies (e.g. electric arc furnaces, not represented in Figure 15) are mature and competitive with conventional gas or coal blast furnaces. However, their introduction in the technology mix requires a major change in basic metal processing.

Based on the above considerations, the findings of this study suggest that it is possible to increase electrification in the industrial sector, especially providing high efficiency low and low-to-medium temperature heat, as indicated in Figure 8. Low temperature heat pumps can add 1.3% of electrification in 2030, equivalent to 1.4 TWh of additional yearly electricity demand, corresponding to 43% of the low temperature heat demand. Low and low-to-medium temperature heat pumps can add 3.4% of electrification in 2050 equivalent to 3.1 TWh of additional yearly electricity demand and corresponding to 76% of the low and low-to-medium temperature heat demand. Medium and high-temperature electrical appliances do not add electrification potential due to high electricity-to-gas price gap.

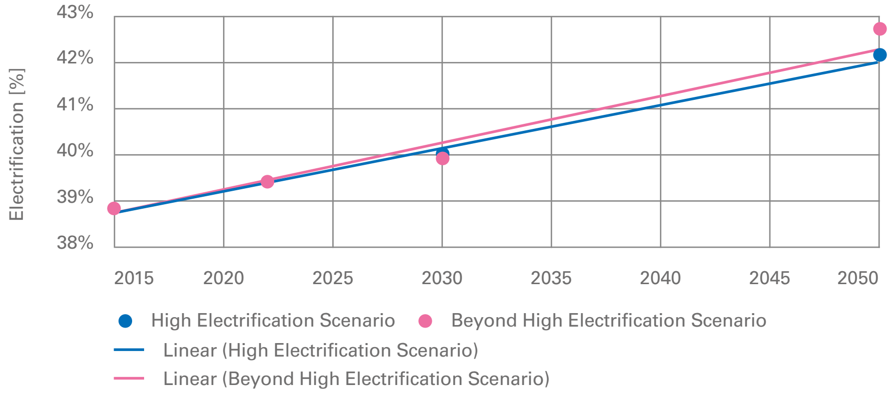

Figure 8
Outlook of the Italian industry electrification potential up to 2050.

6.4 SENSITIVITY ANALYSES

Sensitivity analyses are carried out to investigate the effect of input parameters on the electrification potential of the Italian industry. Results are shown in Figure 9.

Electricity-to-gas prices, conversion efficiencies, carbon price and CAPEX are the main parameters affecting electrification in industry, with electricity-to-gas prices and conversion efficiencies giving the highest sensitivity. Reducing electricity-to-gas price ratios by 50% with respect to International Energy Agency 2050 estimates, could add up to 3% more electrification. Almost 2% of higher electrification can be achieved with 50% higher COP of low and low-to-medium temperature heat pumps. Variations of investigated parameters do not enable the penetration of medium, high, and ultra-high electrical appliances. In 2050, the electricity-to-gas breakeven cost ratio that enables the penetration of induction oven is about 1.4, meaning about 60% lower than IEA baseline estimates. Industrial hydrogen utilization can be profitable with electricity-to-gas price ratios lower than 1.1 meaning about 70% lower than IEA baseline estimates.

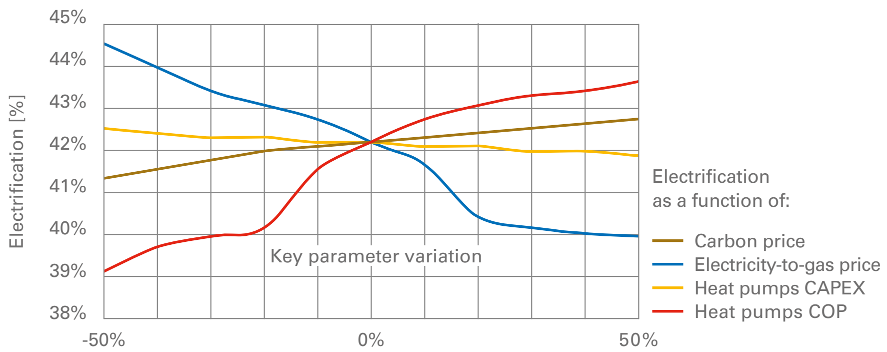

Figure 9
Sensitivity analysis: electrification of industry in 2050 as a function of key parameters variation vs. High Electrification Scenario assumptions.

The effect of two parameters, carbon price and electricity-to-gas price ratio, was investigated with further detail, as shown in Figures 10 and 11 respectively.

Figure 10 shows the rate of electrification in the industrial sector as a function of carbon prices. Sensitivity to CO_2 prices is calculated with -50% to +50% variation with respect to the High Electrification Scenario assumption of 140.9 €/tCO_2 by 2050. Carbon prices have the potential to change -1% to +1% electrification at 2050 due to the change in the cost of heat production from fossil-fed heating appliances. A high share of RES in the power sector would bring an emission factor of electricity generation lower than 51 kgCO_2/MWh_e, thus including a low contribution from environmental externalities to the electricity prices.

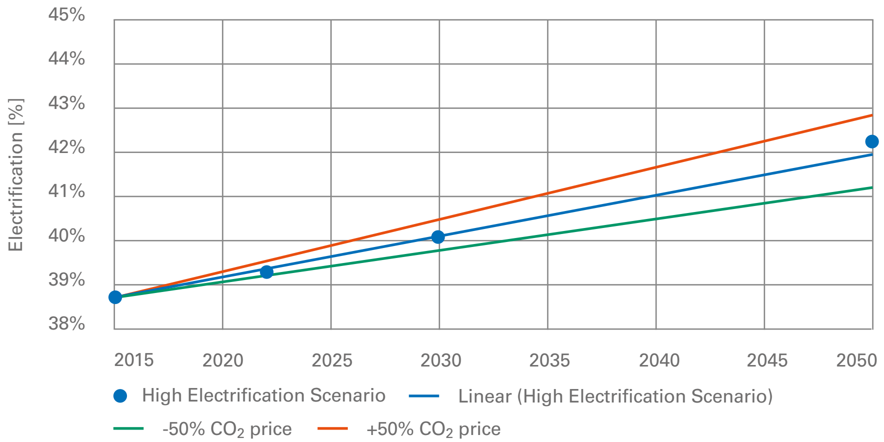

Figure 10
Sensitivity analysis: electrification of industry as a function of carbon prices vs. High Electrification Scenario assumption.

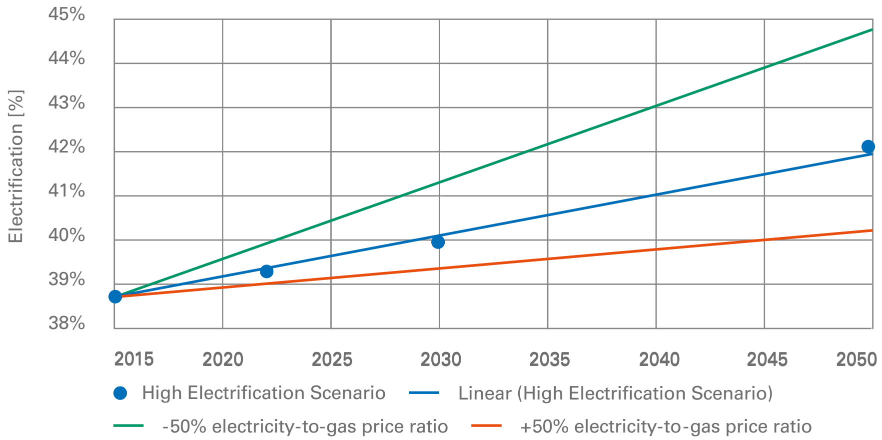

Figure 11
Sensitivity analysis: electrification of industry as a function of electricity-to-gas price ratios vs. High Electrification Scenario assumption.

Figure 11 shows the share of electrification in the industrial sector as a function of electricity-to-gas price ratios. Sensitivity to electricity-to-gas price ratios is considered with -50% to +50% variation with respect to the High Electrification Scenario baseline value of 3.4 of 2050. Electricity-to-gas price ratio variations have the potential to change -2% to +3% electrification in 2050. Variations affect the year when low and low-to-medium temperature electrical heating appliances become less/more profitable with respect to gas technologies, thus promoting a delayed/early adoption by industrial users.

Besides the price of CO_2, gas and electricity, other factors can enhance the penetration of electrical technologies. Efficiency and emission targets, demand response, on-site generation, low electricity cost for power-to-gas applications, and sector coupling could promote these technologies and spread hydrogen use in industry. In particular, a demand to participate in flexibility markets could change the economics of electrical appliances not yet convenient with current electricity-to-gas price ratios and conversion efficiencies. Thus, flexibility requirements in the power sector could support the penetration of low-to-medium and medium temperature electrical appliances. On the other hand, sector coupling of power and gas sectors through power-to-gas technologies could support the indirect electrification of the industrial sector, producing low-cost hydrogen as an energy carrier for high and ultra-high temperature applications. Some of these factors depend on the specific regulation and market design adopted, thus confirming the key role of regulation in the electrification process.

Energy efficiency targets that promote the adoption of technologies enabling the reduction of primary energy consumption per unit of physical output, can enhance penetration of electrical technologies, typically characterized by higher efficiencies. Environmental regulations aimed at reducing both GHG and pollutant emissions may also change the pace of industrial electrification, bolstering the adoption of electrical appliances that avoid environmental costs. Electrification may be an enabler for the entry of industrial stakeholders into the energy market who can combine both capacity and flexibility opportunities from new electricity market designs that appropriately value these services. Demand Response (DR) is an alternative and cost effective way to balance the grid by adjusting the load according to generation capacity. It has multiple sources of value:

- By avoiding investments in peak generation – capacity value.
- By providing reserves for TSOs – flexibility value.
- By balancing supply and demand locally and avoiding congestions – network value.

Commercial and industrial consumers can respond to market variations by increasing or reducing their energy consumption with the aim of responding to peaks in electricity supply and demand, resulting in greater grid flexibility and stability, as well as more efficient use of energy infrastructures and resources. If electrified, certain industrial processes can be stopped on demand, in response to a price signal or a communication (remotely controlled devices, etc.) that usually corresponds to specific grid emergencies (e.g. extreme events, price spikes, unexpected system issues). Aggregation may provide further potential for flexibility and capacity, enabling the participation of industries to new electricity markets as virtual aggregated units. Thanks to digitalization, DR aggregators are able to create values both for the customers and for the utilities/TSOs: their role is to connect energy users to market opportunities in order to balance supply and demand.

Practical examples of energy reduction strategies to implement DR include:

- For cement manufacturing: stop primary and secondary crushers or stop proportioning and grinding mill.
- For industrial gas production: shut down air separation units and associated pumps.

Participation in capacity markets may be further enhanced by adopting dispatchable on-site generation solutions, such as CHP systems or RES and storage configurations.

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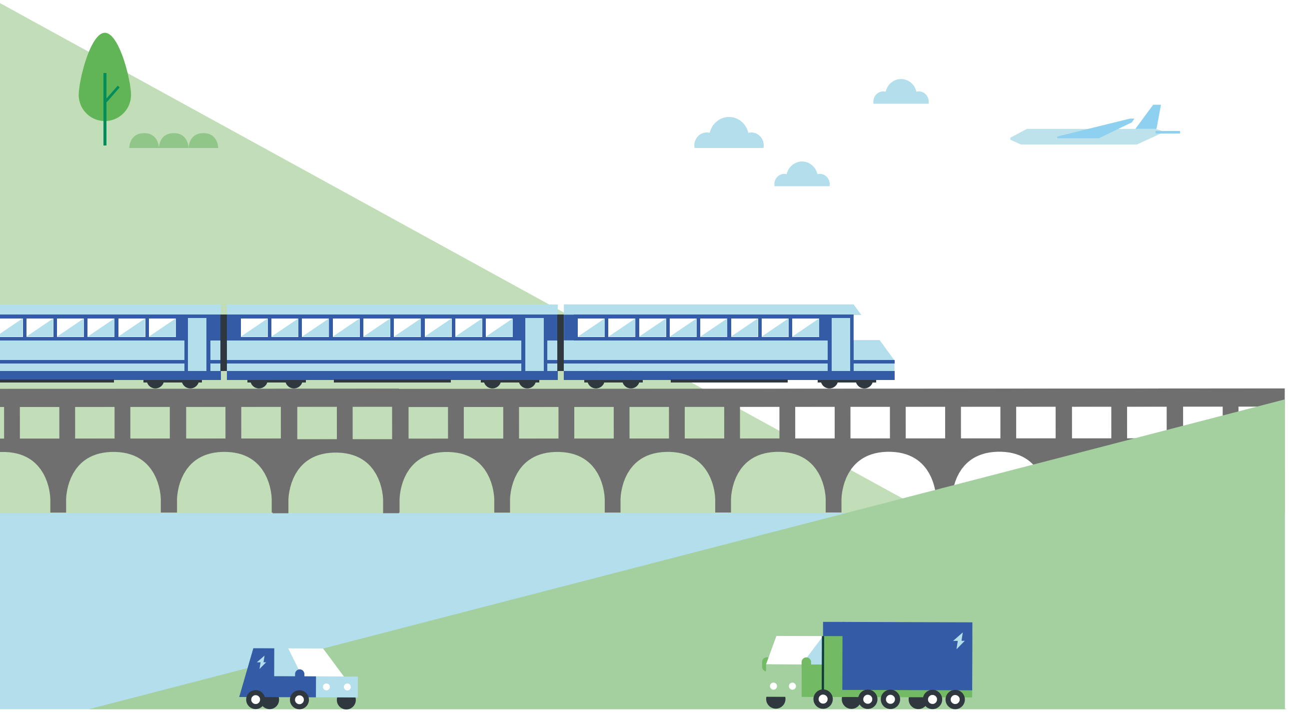
Chapter 7

ELECTRIFICATION OF TRANSPORT SECTOR



7.1 OVERVIEW

Electrification is going to play a major role in the field of transports under the action of three main drivers: reduction in the emission of pollutants and greenhouse gases, reduction in total transport cost, and increase in reliability and system availability [1].

The substitution of internal combustion engines (ICE) with electric motors can provide a valuable response to all this. Electric drives typically show high reliability due to their structure, which is much simpler than that of ICE [2]. The efficiency in conversion of electric power into mechanical is much higher than in the case of conversion of chemical energy stored in fuel into mechanical power [3]. The use of electric drives decouples the location where energy is used and where combustion gases are released to produce electric power. Moreover, the option of producing electric power from renewable sources allows the design of transport systems where no combustion gas is emitted at any level.

The actual possibility of increasing the electrification of transport systems is related with technological advances both in the field of batteries, and energy storage in general, and in that of electric motor construction and control [4]. At the same time evolution in the safety of these components, and especially for energy storage systems, is among the most relevant points for a wide spread of electric technologies in the transport field [5].

The analysis of the penetration of electrification in transports is extended to 2050 and includes all the possible transport modes (road, rail, air and water) and considers both passengers and freight.

The figures show that the main impact is expected on road transports, which are going to benefit from the technological evolutions described above. The impact will be relevant on the complete fleet of road vehicles, including private and public passengers transport, as well as freight transport.

Rail transport is the sector in which electrification already has the largest penetration, and diesel locomotives are used just on minor lines and for maneuver. Therefore, only a reduced area for further development is left, and it is strictly related to the investment choices of RFI[1]. A possible contribution could be provided by hydrogen-powered locomotives, but their introduction in Italy is still at experimental level, and worldwide only UK and Germany seem to be going to introduce a first group of hydrogen trains by 2022 and 2021 respectively [6], [7]. The UK intends to substitute all its diesel locomotives with hydrogen ones by 2040.

1. *Italian railway network operator.*

On the contrary, air transport is not likely to see a switch to electricity in the near future; in this area attention of researchers and manufacturers is focused on the substitution of hydraulic drive with electric ones for flight control mechanism, but the use of electric batteries as main energy sources for thrust generation is far away from development scenarios [8].

Water transports use electric propulsion to increase ship maneuverability, but the architecture of ships includes fossil fuel generators coupled to electric motors [9]. The sector is not likely, at least in the short-mid term, to be subject to a deep penetration of full electrification, because of both the problems caused by the relatively low energy density of the batteries [10] and the slow substitution rate of ships and boats. An interest actually exists for ferries, urban transports in Amsterdam and Venezia and for speedboats for lake navigation, but in general the sector considers a switch to natural gas a more realistic answer to the request for lower emissions [11].

In the following the general assumptions and hypotheses considered for the analysis are described and the results for each sector are shown. The road transport sector is split into its main subsectors: passenger cars, light commercial vehicles (LCV), public transport and trucks. Finally, the general results, obtained as the sum of all sectors, are described.

7.2 ASSUMPTIONS AND SCENARIO BUILDING

The aim of this work is to analyze the effect of electrification on the energy demand for transport, together with the probable impact of development of current technologies in the electrification of the sector itself. The results found in Fuelling Italy's Future 2018 [12] and "Low-carbon cars in Italy: A socio-economic assessment" [13] were considered as a basis. These documents analyze the development of the passenger cars market and stock in the next decades as a consequence of the technology evolution of all types of powertrains: internal combustion engines, battery-powered full electric vehicles, hydrogen fueled cars, and hybrid cars. The analysis takes into account evolutions in both the technological and regulation fields and provides estimates about the vehicle stock composition until 2050, the expected energy consumption per kilometer, and the expected yearly mileage for every kind of vehicle in each year. Combining this data, the total energy consumption per year is computed together with the share of the energy sources: petrol, diesel, natural gas, hydrogen and electric batteries.

This study extends the analysis to the sectors of light commercial vehicles, urban and long distance buses and heavy trucks.
These sectors are analyzed considering the following hypotheses:

- Costs of batteries and electric powertrain decrease by 60% and 25% respectively from 2015 to 2050 [12].

- Efficiency of energy conversion and powertrain in electric vehicle increases 3 points from 2015 to 2050 [3].

- LCVs will be subject to an evolution similar to that of passenger cars. However, for this last class of vehicles a relevant impact in the reduction of energy demand will be provided by weight reduction. On the contrary, for commercial vehicles the reduction in the weight of the vehicle is expected to be balanced by an increase in the maximum load, which will keep the total weight constant, thus obtaining a reduction in terms of energy per transported kilogram per kilometer.

- City buses will be subject to a strong electrification campaign as a result of public policies devoted to the reduction of pollution in urban areas. New coming European regulation in fact forces public transport companies to ensure a share of 45% of electric buses in the new vehicle procurement, and this share is going to rise to 65% in 2026 [14], [15]. As a result, city buses are assumed to be 100% electric by 2050, assuming that Milan, according to its public plan, is going to have a fully electric fleet by 2030, while other cities will be slower in the substitution of ICE buses.

- Electric long distance buses are under development, but the requirements for high battery capacity and fast charging infrastructure makes their introduction harder in the next decade, while, starting from 2030, their stock share will rise. These hypotheses are developed considering a delayed penetration with respect to the market of passenger cars. The stock share of electric long-distance buses in 2050 is estimated to be 20%.

- Electrification in the field of heavy trucks[2] is considered similar to what is expected for long distance coaches, with a stock share beginning to be relevant (5%) in 2030 and rising up to 25% in 2050.

The analysis extends then to all other transport modes, rail, air and water. Figure 1, obtained from Eurostat data, shows the yearly energy consumption for transport, split by modes and type of road vehicle in 2015. Road transports, which include cars, buses, LCV and trucks, is responsible for 93% of the total of over 1,500 PJ.

2. In this study the overall structure of transportation system is assumed to remain the same. It is worth noticing that changing the structure of transportation system may favor sectors' electrification. For example, the long haul services could be provided by railways connecting intermodal nodes where goods are handled to short and medium range (below 150 km/day and 150-400 km/day respectively) van and trucks that could be more easily electrified in the next years.

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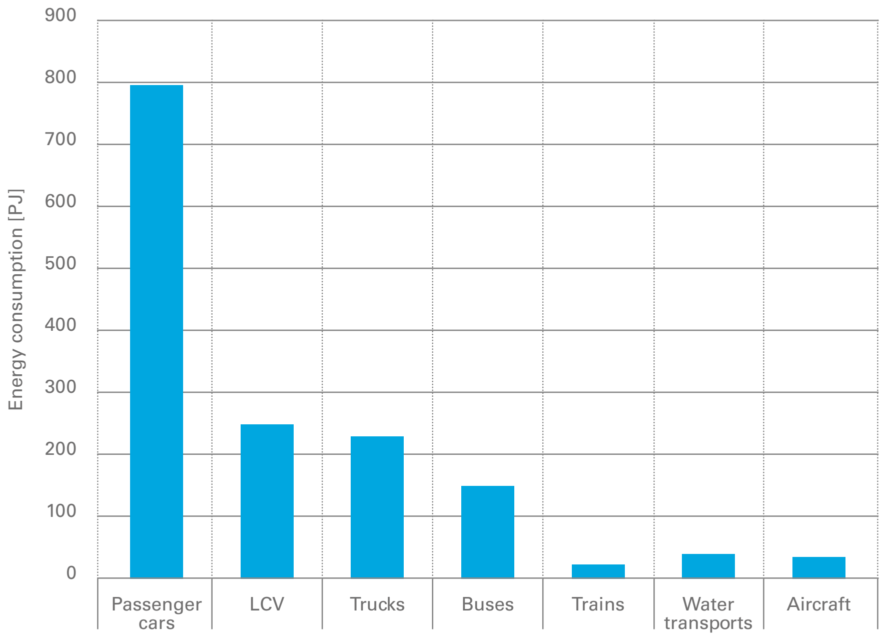

Figure 1
Energy consumption for transport sector in 2015.

Most of the energy comes directly from fossil fuel, and electricity provides only 2.56% of it, and it is exploited mainly by trains.

Today, electricity is the main energy source for railways in Italy, with the exception of some minor lines. RFI is planning the electrification of a few of the latter, but no data are actually available to evaluate the total effect of these actions on the total energy mix. Considering that most of the rail traffic is running on electrified lines, which are the ones which show a larger growth potential, it is assumed that traffic along electrified lines will grow double than that along non-electrified lines. This assumption absorbs the effect of the electrification of new lines too.

As far as air transport is concerned, the current technological trends do not show opportunities for a massive electrification of the thrust engines, even if many researches are under development worldwide. In Europe, Airbus is studying a single seater flying vehicle called Vahana, while in the US Nasa is considering electric flight with its X57 project. About twenty programs for the development of electric aircraft were developed after 2000, all of them considering small aircraft with one or two seats and endurance up to 90 minutes [16]. In this sector the impact of electrification in the next decades will concern mainly the flight control actuators, which at present are mainly hydraulic and are going to become largely electric [17]. This changeover will have an impact on aircraft reliability, maintenance and energy efficiency, however the most relevant impact on energy consumption in the next decades is connected with improvement in engines, aerodynamics and structure lightness [18]. Nevertheless electrification of thrust engines shows a number of advantages: a significant benefit for airport surroundings would come from noise and emissions reduction, and some reduction in total energy consumption could be obtained. Electric aircraft could make possible a reduction in the take-off and landing run, making it possible to exploit minor local airports for commercial flights. Some research in the field is considering full-electric aircrafts, where all propulsion engines and control motors are electric and power is provided by a fossil fuel generator, and all-electric aircrafts which are battery powered [18]. The commercial viability of these technologies is expected not earlier than the second half of XXI century [19].

About water transport, full electric power systems look promising for electrification of a limited portion of recreational boats. In particular electrification of boats is suitable mainly for speedboats [20], [21] for use in internal waters or in short range ships and recreational boats. Electric boats penetration may be encouraged by environmental regulation prohibiting ICE boating in specific areas. As an example, in 2013 Amsterdam issued a new policy, aimed at regulating the emissions of commercial vessels navigating its canals, which can help reducing local emissions and improving air[3] quality.

Especially in the Baltic Region, rich of short and fixed routes for ferries, electrification/hybridization may have good opportunities. Globally there are about 1,200 ferries. More than 70% are in the EU plus Norway, making the European continent the main opportunity area for ferries electrification.

Norway represents a very interesting case. Its government is planning to reach 2/3 electric ferries fleet by 2030, i.e. about 130 ferries. The number of short routes make this target reasonably achievable. Out of a total of about 180 ferries in Norway, 84 have a transit time shorter than 25' and more than 20 crossing per day, making those routes suitable for hybrid or full electric ferries [22]. The first Norwegian full electric ferry (Ampere) has been in service in the Sognefjord since 2015. Other routes already covered by hybrid ferries are the Rødby (DK) – Puttgarden (DE) and the Rostok (DE) – Gedser (DK). Since 2019 a full electric ferry has been linking Fynshav to Soby, in Denmark, running 22 nautical miles with a payload of 200 cars [23].

On the contrary, the use of batteries to power large full-electric freight ships does not appear feasible with the currently available technologies. Due to limits imposed by the energy/mass ratio of the batteries, the Yara Birkeland, the only existing full-electric container ship has a payload of 120 TEU[4], 100

3. Of the about 120 of these boats in Amsterdam, to date, about 20 have been retrofitted with electric propulsion. It has been estimated that the electrification of cruise fleet will reduce GHG emissions by 70% compared to emission of the old diesel fueled fleet and considering the use of electricity with the current energy mix. Further reduction will be possible simply by improving the fuel mix.

4. 1 TEU (Twenty Foot Equivalent) corresponds to the volume of one standard ISO container.

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times less than the 12,000 TEU of a standard one, and an operating range of just 30 miles, against thousands of miles of a diesel powered ship [24]. It is therefore reasonable to expect a very low impact of electric technologies in heavy duty, long-range freight in the next decades.

All of the above considered, it is reasonable to expect a relatively low penetration of electric technologies in water transport in the next decades, especially if compared to the levels of penetration expected in the road transport sector. In conclusion, the impact of electrification of Italian water transports on overall transport sector electrification looks very small, because of the current absence of a suitable technology for heavy duty, large scale commercial operations and of the low speed of fleet renewal, should technology become available.

7.3 PASSENGER CARS

The evolution of passenger cars stock and share of energy commodities is the same as in Fuelling Italy's Future Tech scenario [12].

Figure 2 shows the evolution of the stock of passengers' cars from 2015 until 2050[5]. It is divided by powertrain architecture (ICE – internal combustion engine, HEV – hybrid electric vehicle, PHEV – plug in hybrid electric vehicle, BEV – battery electric vehicle, FCEV – fuel cell electric vehicle) and, when applicable, by kind of fossil fuel consumed.

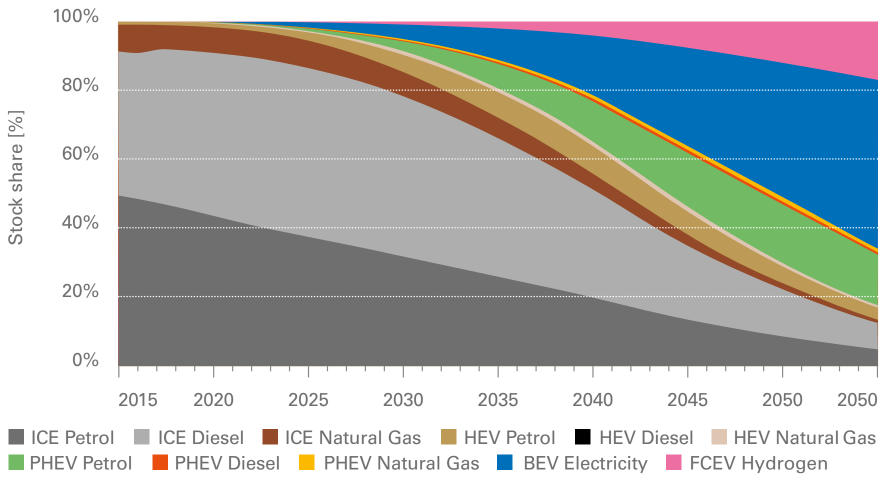

Figure 2
Evolution of stock share by kind of powertrain and fuel.

5. This study makes reference to FIF study, published before the issuing of the PNIEC, which sets more ambitious targets for EV penetration, thus confirming the conservative approach of the present analysis.

The data can be rearranged to underline the penetration of electrification considering the sum of electric vehicle rechargeable architecture, BEV and PHEV, and hydrogen powered vehicles. The data are shown in Figure 3, both in absolute and relative values. In 2050, about 30 million electric cars on a total of 36 million are expected to run on Italian roads.

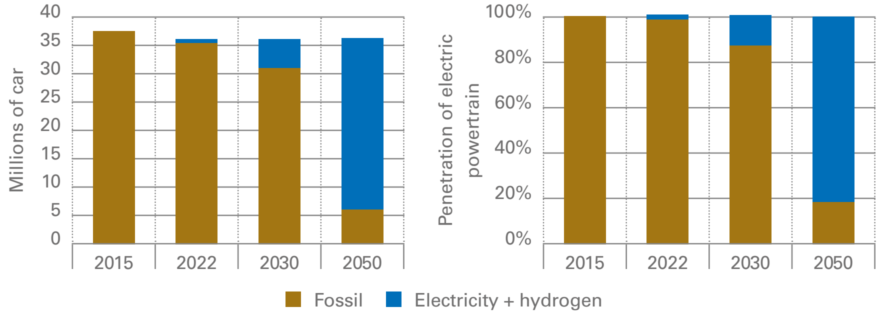

Figure 3
Evolution of electrification in passenger cars: a) number of cars b) relative values.

The evolution of the stock strongly affects total energy consumption and its commodity share. Electrification leads to a strong reduction in total consumption because of the higher efficiency of electric powertrains with respect to internal combustion engines. At the same time, a relevant effect is expected from weight reduction, common to the entire sector, ICE efficiency increase, which is probably reaching its limits, and energy consumption reduction for internal friction and auxiliary systems.

Figure 4 shows the expected evolution of total energy consumption for passenger cars, divided by electrical and non-electrical vehicles [12]. The figure shows a reduction of 587 PJ in 2050, 73% with respect to 2015. In 2050, 70.2% of energy for passenger cars will come from electric power or hydrogen produced by electrolysis.

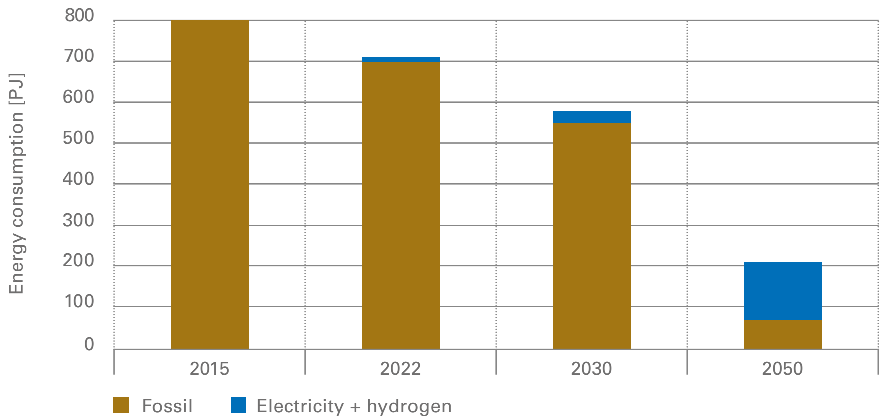

Figure 4
Energy consumption of passenger cars.

7.4 ROAD PUBLIC TRANSPORT

Road public transport is analyzed considering large size buses, which are used both for urban and medium-long range transports. Different outlooks should be considered for these two cases.

As far as urban buses are concerned, several regulatory actions and sectoral initiatives are setting out the foundations for a deep penetration of electrification in the next years:

- The European Clean Buses deployement Initiative[6] set a 30% target penetration of clean buses by 2025.
- The directive 2009/33/EC on the promotion of clean and energy efficient road transport vehicles set the regulatory requirement of considering energy efficiency, CO_2 emissions and pollutant emissions as evaluation criteria in all the tenders related to the procurements of road vehicles.
- EU has adopted a Directive (Clean Vehicles Directive[7]) setting minimum targets in public procurement for clean vehicles, differentiated by Member State and by category of vehicle application. For Italy, public fleet clean buses procurement objectives are 45% from 24 months following the date of entry into force of the Directive to Aug 2nd 2019, and 65% from Jan 1st 2026 to Dec 31st 2030.

Public transport operators are also starting to increase the share of electric vehicles in their fleet.

ATM (Milan municipal public transport agency) has already committed to transform its fleet by 2030, with 1,200 extra electric buses [25]. Dutch provinces will purchase only zero emission vehicles from 2025. Several cities and regions have announced plans to stop purchasing conventionally fuelled buses, including Copenhagen (in place since 2014), London (2018), Berlin (announced for 2020) and Oslo (announced for 2020). In Italy, considering the leading effect of Milan, it is reasonable to believe that no city will procure non-electric buses after 2035, so the complete fleet of local public transport buses could be electrical by 2050. Figure 5 shows the plan of Milan Municipality for the complete changeover of its fleet.

6. https://ec.europa.eu/transport/themes/urban/cleanbus_en

7. Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019 amending Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles.

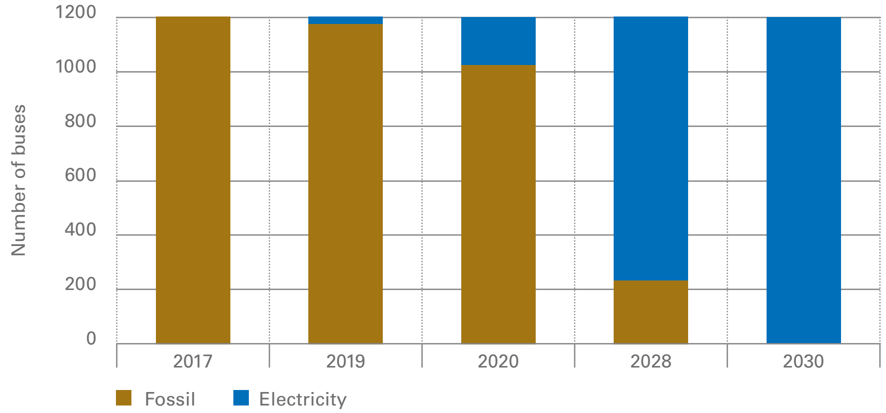

Figure 5
Penetration of electric urban buses, plan of Comune di Milano.

The consequences of a complete electrification of the urban buses fleet involve a reduction of the emissions of pollutant and greenhouse gases together with a strong reduction in energy consumption. Figure 6 shows the expected evolution of energy mix and consumption in the next decades.

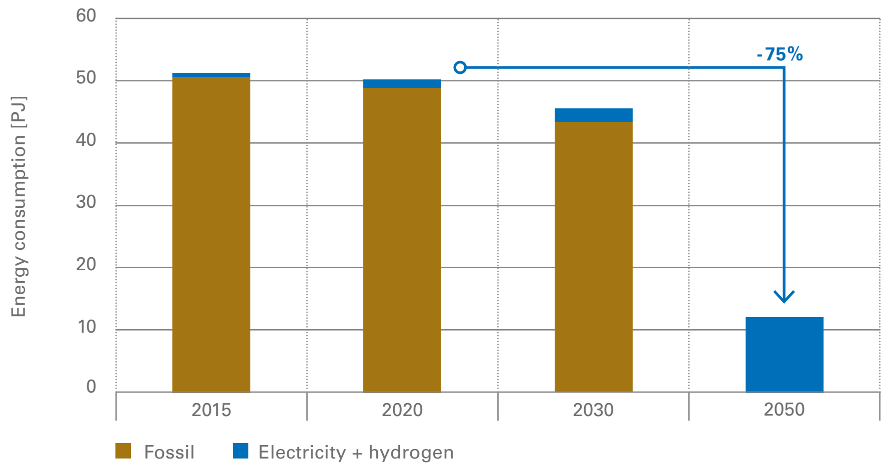

Figure 6
Energy consumption of buses for local public transport.

As for medium and long-distance buses, the electrification of this sector would obviously benefit from the reduction of the cost of batteries and requires the construction of a suitable network of charging station where large capacity battery packs can be charged quickly enough to fit with schedule requirements.

From a technological point of view, the construction of long-range coaches is already at hand, as electric buses with a range up to 400 km are already available on the market. Moreover, in 2017, a prototype built by Proterra set, under optimal conditions, a world record with 1,102 miles (1,763 km) on a single charge [26].

The cost of batteries is expected to drop from 237 €/kWh in 2016 to 70 €/kWh in 2050 [13][8]. This would enable a penetration of 20% of electric coaches in 2050, and bring to a reduction of consumption for long-range coaches up to 22 PJ, 21% of 2015 value. The following table compares the energy consumption of a diesel and an electric bus when running long distances.

DISTANCE [km]	200	500	800
Diesel bus consumption [MJ]	2348	5869	9391
Electric bus consumption [MJ]	840	2099	3358

Table 1
Energy consumption for mid- and long-range buses.

7.5 LIGHT FREIGHT TRANSPORT

Light freight transportation is carried out by vehicles grouped under the Light Commercial Vehicles (LCV) category, which includes all the commercial vehicles defined as category N1 according to the Italian Road regulation, which represent the vehicles for the transport of freight with a full load up to 3.5 tons. According to data from ANFIA (Italian Association of Automotive Industry), 3.5 million of vehicles belonging to this category existed in Italy in 2015.

In order to develop a scenario to analyze the impact of electrification in this field the following assumptions are considered:

- Most of these vehicles, especially when payload is below 1 ton, are often built with the same powertrain of passengers cars; the technological and infrastructural development of the passenger cars sector will therefore have similar influence on the LCV sector.
- Market evidence shows that the development of hybrid, plug-in hybrid and electric LCV is late with respect to passenger cars. In 2017 only 4,500 electric or hybrid LCV were registered, most of them with a payload lower than 1 ton [27].
- Vehicles in commercial fleets run 36,000 km/year on average [28]. However, a large number of vehicles are not part of commercial fleets, but are used for other businesses different from freights transport, suggesting shorter average yearly mileage. Moreover, more than half of the circulating vehicles were manufactured before 2002 (according to ANFIA), again suggesting shorter average mileage. In the absence of precise data and in light of the above-mentioned facts, an estimation of an average year mileage of 25,000 km was done for LCVs.
- The growth rate of the number of circulating vehicles is assumed as half the GDP growth rate, i.e. 0.5% per year.
- The energy consumption of LCV with internal combustion engine decreases in time because of an increase in the efficiency of the engines, as it is expected for passenger cars, while no reduction in weight is considered, as any reduction in the vehicle weight will be used to increase the payload. Figure 7 shows the reference scenario for the evolution of the share of the LCV stock.

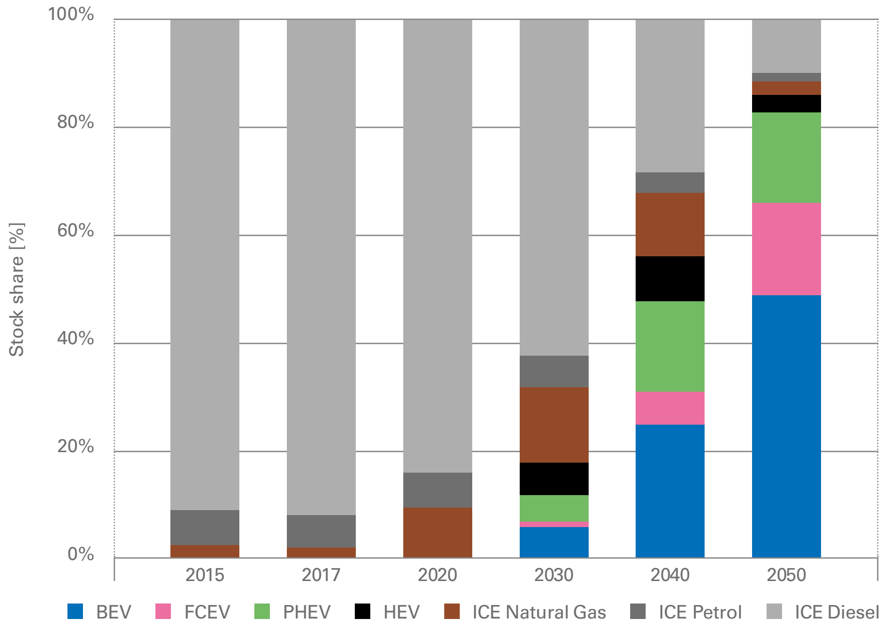

Figure 7
Scenario for the evolution of the LCV stock.

The increasing penetration of electric powertrain in LCVs, which is expected to reach 66% of the stock by 2050, will once again be the cause of a strong reduction in the total energy demand of the sector. The forecast is shown in Figure 8, which shows a drop from 250 PJ in 2015 to 100 PJ in 2050.

8. Other projections foresee a more optimistic trend. For example, Bloomberg 2019 Battery price Survey foresees that the 100 $/kWh wall will be broken in 2024 and that the value of kWh in 2030 could be around 60-65 $/kWh.

ELECTRIFY ITALY / 7. ELECTRIFICATION OF TRANSPORT SECTOR

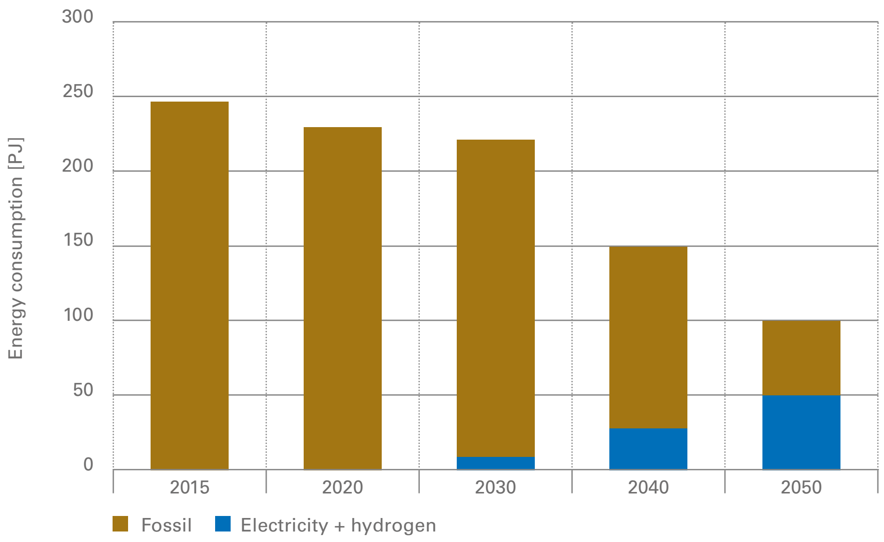

Figure 8
Energy demand from LCVs.

The reduction in energy consumption is going to be achieved while the total number of vehicles is growing, and so the total mileage is growing too as the average mileage per vehicle is assumed constant; at the same time, the average cost of energy for freight transport will decrease due to the switch from fossil fuels to electricity. Figure 9 shows the outlook for the average cost of energy for freight transportation. In the same figure the corresponding outlook for the electrification rate is reported.

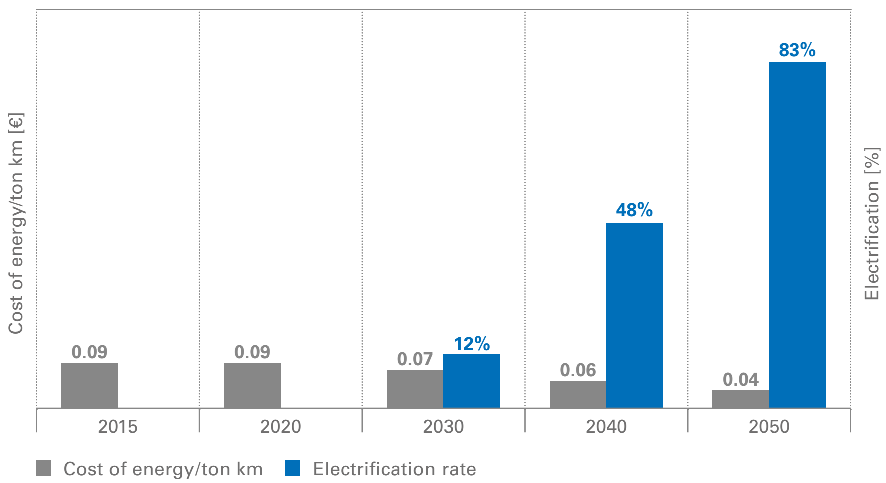

Figure 9
Cost of energy for freight transport, related to electrification rate for LCVs.

7.6 HEAVY COMMERCIAL VEHICLES

Heavy commercial vehicles include all commercial vehicles with a payload larger than 9 tons, including, according to data from ANFIA, 290,000 vehicles in 2017, 130,000 of which were road tractors. It must be pointed out that road tractors usually travel across all Europe, and that a large number of tractors from other UE countries drive on Italian roads. As detailed data about the number of tractors effectively running yearly on Italian roads are not available, only road tractors registered in Italy are considered, and they are assumed to travel only inside national borders to balance the effect of foreign vehicles, which are not computed.

A deep penetration of electrification in this sector cannot be foreseen today, because of the limits imposed by the mass to capacity ratio of the batteries and by the availability of fast recharge infrastructure.

In order to justify this, it is possible to consider the analysis of the energy consumption of a road tractor with a trailer, which is on average 3.36 MJ/km. It is possible to assemble an electric road tractor with a range up to 600 km using currently available technologies, and Tesla and Daimler are announcing some prototypes [29], [30]. However, by considering 8 hours travel at an average speed of 60 km/h (a reasonable duty for industrial use of this kind of vehicle), the night recharge would require 1.6 GJ (i.e. 444 kWh). To charge that amount of energy in an 8 hours stop, a charging station with power of at least 56 kW is needed. Considering that most of the vehicles should be charged during the night, a deep diffusion of heavy electric trucks would require the construction of several thousand high power charging stations in the next years, but such a plan is not under design.

In order to fully evaluate the cost of energy for a battery-operated truck, it is essential to consider the duration of batteries, as daily charging cycles could cause the need to frequently substitute them, with a subsequent relevant impact on the total ownership cost. The target cost for the batteries of 70 €/kWh in 2050 involves a total cost of a battery pack of 450 kWh for a road tractor starting from 123,000 € in 2016 and decreasing to 31,000 € in 2050. To carry out a comparison between the total yearly energy cost in 2015 and 2050, the following assumptions can be considered:

- Batteries have a duration up to 1,000 full charging/discharging cycles.
- One cycle is completed per each of the 220 working days in a year.
- Cost of electricity and diesel projected according to IEA (International Energy Agency), Energy Technology Perspectives 2016 – Towards sustainable urban energy systems [31]. It must be underlined that according to this scenario the evolution of energy prices is disadvantageous for electricity, which price is expected to grow, while

in the same period the price of energy from gasoil is expected to slightly decrease.

With these assumptions, the analysis shows a total yearly cost of energy of 46 k€/year for the electric truck with respect to a cost of 66 k€/year for the diesel one in 2015, that become 37 k€/year and 52 k€/year in 2050, respectively. The cost of energy for an electric truck is steadily lower than that of a diesel one, even in a scenario where the evolution of the unitary cost of electricity is unfavourable in comparison to diesel fuel, because the higher efficiency of the electric truck guarantees a better yearly performance. Conversely, in the case a scenario where the evolution of unitary costs are more favourable to electricity is considered, assuming in 2050 a price of 60 €/MJ for electric power (10% less than IEA projections) and 46 €/MJ for energy from gasoil (10% more than IEA projections), the total yearly energy cost for an electric truck would be 34 k€/year, and 57 k€/year for a diesel one. Naturally in this case the advantage of electrification is stronger.

In the next decade the actual duration of batteries will strongly affect the total energy cost, and a large uncertainty in its forecast can constitute a limit to the diffusion of heavy duty electric trucks. In fact, by doing the same calculation with a battery duration of 750 cycles only, considering IEA projections, the total cost for energy would be about 55 k€ for BEV truck in 2015 (instead of 46 k€) and about 39 k€ in 2050 (instead of 37 k€). On the opposite side, new technology developments seem to promise extended battery duration well beyond 1.000 cycles, thus allowing a situation in which the total energy cost will further favour electric choices.

The analysis also shows that in present days the cost for keeping batteries efficient (replacement cost) is the most relevant term in the definition of total energy cost for a BEV, as it is 60% of the total energy cost. This incidence is expected to decrease to 20% in 2050.

An alternative solution considers the construction of a wide network of electric highways. This technology involves the construction of an overhead contact line along the motorway and the use of special trucks equipped with a trolley and a hybrid powertrain: electric-, to be used where the contact line is available, and ICE-based, to be used outside the equipped road. Full electric vehicles based on contact line technology and batteries could be manufactured in the future, but today no example is known. Electric motorways are under test in Germany [32] where a few kilometers were set up, but no plan exists yet for the development of a European network nor for the massive manufacturing of compatible trucks.

Finally, fuel cell technology for heavy trucks is a research topic [33], but there are no indications of perspective availability of commercial heavy-duty fuel-cell powered powertrain in the next future.

According to the above considerations, it is reasonable to expect a delayed penetration of electric powertrain in this sector, starting to be relevant in 2030 with a penetration of 5% and rising slowly up to 20% in 2050. This scenario corresponds to the intermediate scenario considered in the Electrify 2030 report [34].

Figure 10 shows the expected evolution of the trucks stock from 2015 to 2050 according to the considered scenario.

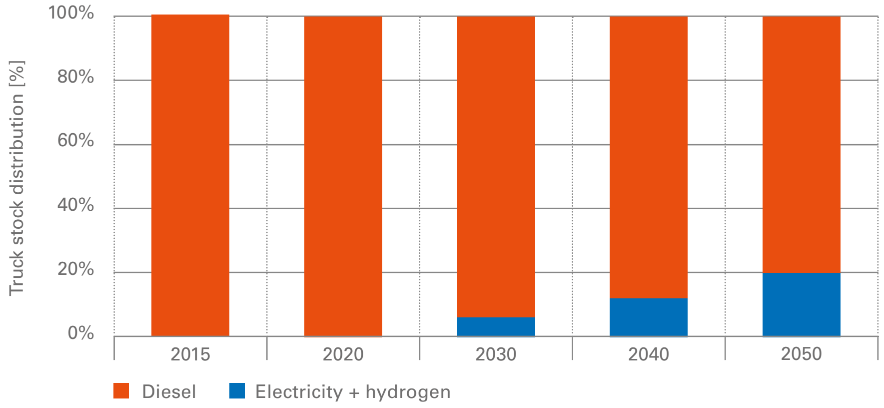

Figure 10
Penetration of electrification in the heavy duty truck sector.

Considering an average mileage of 144,000 km/year for road tractors (300 days/year, 8 hours per day at average speed of 60 km/h) and 33,000 km/year for other trucks [35], the estimated total consumption for heavy trucks is shown in Figure 11.

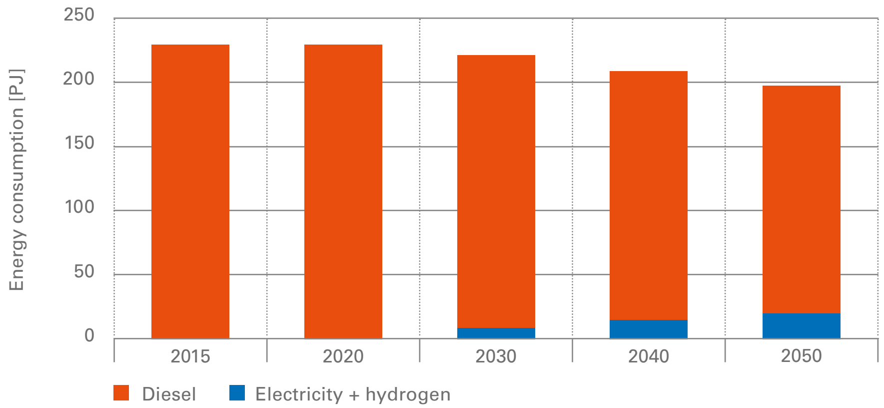

Figure 11
Energy consumption for heavy commercial vehicles.

The results show that, despite an expected 14% increase of the total annual mileage carried out by heavy trucks, a reduction of energy consumption will be obtained thanks to electrification.

7.7 AIR TRANSPORT

Air transports have a large impact on the total energy consumption in Italy. According to Eurostat, in 2015 the total consumption for domestic flights[9] was 32 PJ and for international flights it was 137 PJ, corresponding to about 10% of the total [36].

The field is not yet mature for electrification. Despite few examples of single or two seaters all electric aircraft (e.g. [37]), no opportunity is visible for large passengers' aircraft. Some research programs in the field of the so-called "more electric aircraft" as well as in the field of "full electric aircraft", where electric power is provided by a fuel generator and all the actuators and motors are electric, are running. The closest target is the electrification of flight controls, which are currently hydraulic. Nevertheless, a number of problems related with reliability and resilience in the case of a motor breakdown and lock still prevent for the application of electric drive in critical controls, such as primary flight controls or landing gear actuators.

Other research programs are running to develop full electric or hybrid architectures for passenger aircrafts, but their current target for technology readiness level is just 3 (experimental proof of concept) for enabling technologies and design methodologies and instruments [38], [39].

The possibility of flying a full electric passenger aircraft is strictly related with the energy to mass ratio of the batteries, which actually is not larger than 0.3 kWh/kg for the most advanced batteries, and it stops at 0.15 kWh/kg for standard commercial units, while standard jet fuel has an energy density of 11.9 kWh/kg. The forecast for a reduction of this ratio, together with the evolution of light structural materials and low drag aircraft shape, contemplates the possibility of manufacturing an all-electric mid-range two seats airplane in 2030 and mid-range passengers aircrafts only after 2040. Considering this scenario, this study assumes that the electrification of air transport will be negligible up to 2050.

The sector is going to be subject to strict environmental regulation starting from 2021 [40], with a target of a 75% reduction of CO_2 emissions per passenger*km by 2050 with respect to the standard of 2000 (Flightpath 2050). To reduce the energy consumption and satisfy this constraint, the aeronautic industry is following a path which considers mainly aerodynamic efficiency, aircraft lightening, trajectory planning, engine optimization and new configurations. However, in the same period, a strong increase of air traffic is expected. According to the International Civil Aviation Organization (ICAO) [41], an average growth of passengers and freight of at least 4.3% per year is expected in the next 20 years, that means that in 2040 the total air traffic will be 4 times larger than in 2020.

9. Flights originated in Italy with foreign destination are accounted.

According to this data, the yearly growth in total consumption for aviation could be in the 0 – 2% range, depending on the speed with which the targets for consumption reduction are reached. An average value of 1% of yearly growth is assumed. Figure 12 shows the expected evolution of fossil fuel consumption for air transports.

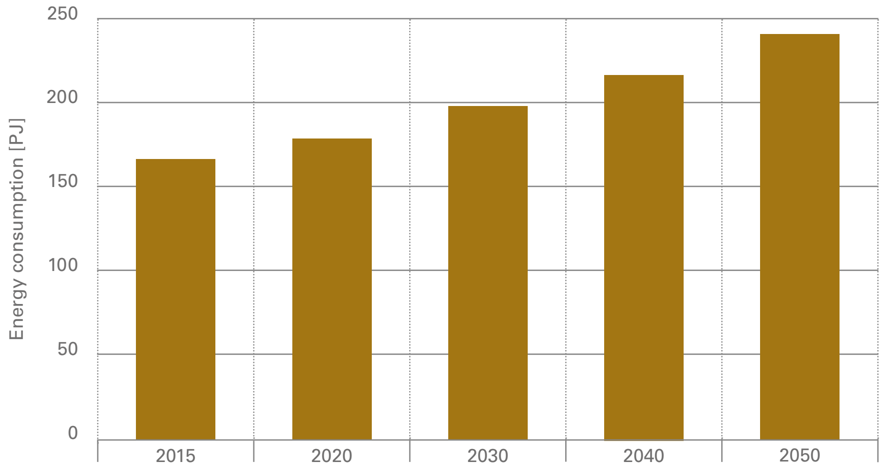

Figure 12
Fossil fuel consumption for air transports.

7.8 RAILWAYS

Electric power is a standard for railways, and only some minor lines are not yet electrified. According to RFI (Rete Ferroviaria Italiana), the Italian railway network is 16,781 km long, 12,018 km of which are electrified, while 4,763 km are operated by diesel locomotives [42]. Data on energy consumption, provided by Eurostat, show a total energy consumption of 19.8 PJ for electrified lines and 1.4 PJ for diesel lines [35], proving that diesel technology is used for low traffic lines only.

Plans for further electrification are ongoing on the Ionic line, in Molise and are planned in Veneto. However, they involve just a small fraction of the non-electrified railways.

In order to reduce the environmental impact of non-electrified lines, hydrogen powered trains look like a feasible option. Experimental projects for their development were carried out in the last years in Germany and the UK, and a first fleet of 27 trains is due to be on the rails in Germany by 2021 [43], while 100 locomotives should be running on UK railways starting in 2021 [44]. In Italy, Toscana and Trentino are considering the introduction of hydrogen trains, and some experimental tests should be carried out soon [45]. It is important to remember that the introduction of this kind of locomotives requires the construction of a suitable infrastructure for hydrogen supply, and that testing involves both the vehicles and the infrastructure. No projections about the diffusion of hydrogen trains before 2050 can be done, as several causes are going to affect it, most of all the success of the experimentation, the renovation policy of the existing fleet, and the policy for the electrification of existing lines.

To evaluate the evolution of energy demand for the rail sector it was considered the scenario provided by the International Energy Agency (IEA) in [46], which involves a growth of energy employed for railways transport by an average yearly rate of 1.6%. In order to consider the increase of electrification due to the electrification of new lines and to the possible introduction of hydrogen trains, and considering that electrified lines are used by most of the traffic and then they will show the larger traffic increase, yearly growth rate of 1.7% was assumed for electric lines and 0.85% for non-electrified lines. Figure 13 shows the results of the projection up to 2050.

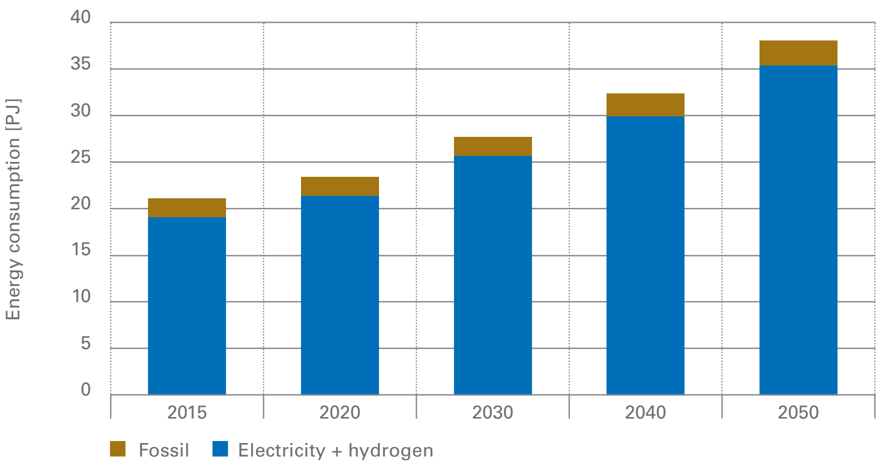

Figure 13
Energy consumption for railways, evolution to 2050.

7.9 WATER TRANSPORT

Water transport, like air transport, is not likely to shift significantly toward electric propulsion in the next decades. Once again, electrification is made hard by the low energy density of batteries, which is not compatible with the need of long-range autonomy typical of large freight ships. Today the maximum energy density of batteries is 0.3 kWh/kg, and most applications use batteries storing 0.15 kWh/kg, to be compared with 11.8 kWh/kg of gasoil. As an example, the only existing electric container ship has a payload of 120 TEU, against 12,000 TEU of a standard one, and an operating range of 30 miles, against thousands of miles of an oil powered one.

In Northern Europe a strong interest exists for the electrification of ferries, as they generally run short and repetitive distances, making possible frequent battery charging, for instance during overnight stops. For the same reason, a large interest for electric propulsion is shown by companies involved in touristic water transport [47] on the lakes (Lago Maggiore, Lago di Garda, Lago di Como) and in Venice. At the same time some manufacturers are beginning to propose electric speedboats. However, there is no evidence that full electric powered ships and boats are going to become popular, while the introduction of hybrid propulsion is considered a plausible option and several programs are running in this direction. Finally, the typical life of a vessel is of some decades, and therefore the substitution ratio is low: even in the case of a strong technological evolution in the next decade a fast diffusion of electric ships is unlikely.

As a consequence, electrification of water transport in Italy is expected to be negligible in the timeframe of this study. As per the evolution of overall consumption, it should reasonably be strictly coupled with the evolution of GDP, with an average yearly growth rate of 1%.

Data from Eurostat [36] show that energy consumption for domestic water transport in 2015 was 36 PJ. Consumption for international water transport is not considered in this report as data about its actual use are not available; however, this value is mainly related to oil used to refuel large cargo and passengers ships, which will spend most of their navigation time in international waters and on international routes, likely with stops in several countries.

According to these data and assumptions, the projection for energy consumption for water transports is shown in Figure 14, considering that the contribution of electricity is negligible.

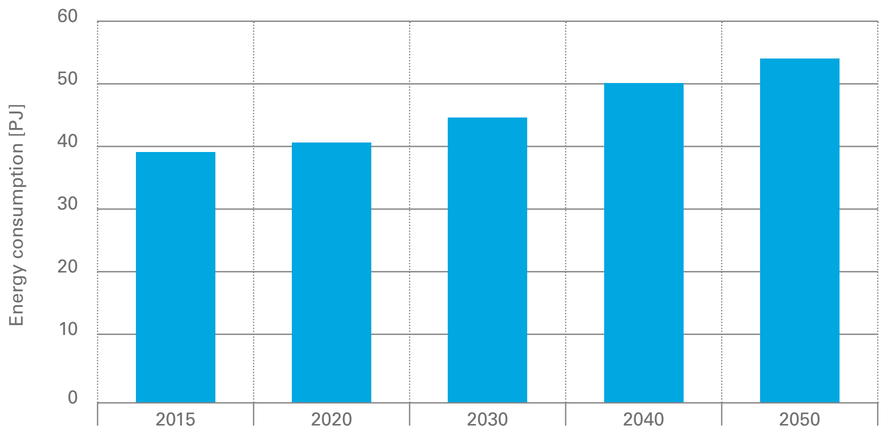

Figure 14
Energy consumption for domestic water transports.

ELECTRIFY ITALY / 7. ELECTRIFICATION OF TRANSPORT SECTOR

7.10 FINAL FINDINGS

The analysis shows that road transports will be the sector where the impact of new technologies for electric traction is going to be the deepest. In particular, it is going to be most relevant for passengers and short to medium range freight transport. Technological limits, on the contrary, still prevent from a large diffusion of electric traction for long-range transport carried out by heavy commercial vehicles and coaches.

These results are summarized in Figure 15, which shows the total electrification share in transports. The graph underlines that, in 2050, 38% of the energy consumed by vehicles will be from batteries, supply electric lines or hydrogen, against the current 2%, half of which used for railways. All the land transport modalities will increase their electrification rate, but the most relevant growth is expected in the field of passenger cars. Electric cars, indeed, will consume a share of 21% of the total energy consumed for transports.

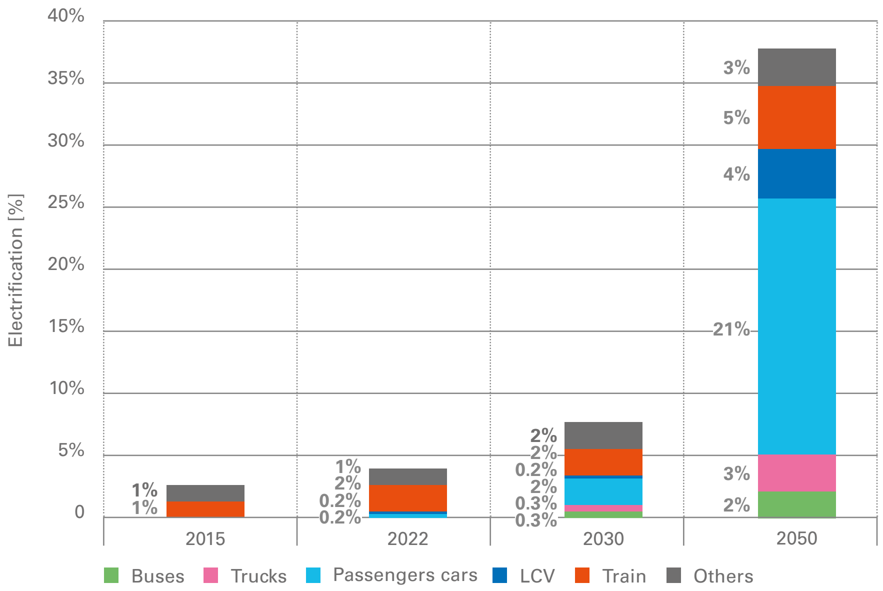

Figure 15
Penetration of electrification in transport sector.

Electrification allows a strong increase in the energy efficiency of transports, so, despite the increase of the transport demand is expected to be in average proportional to GDP increase, the total energy consumption is going to drop from 1,523 PJ in 2015 to 748 PJ in 2050, as shown in Figure 16. This fact suggests a full decoupling between energy consumption for transportation and GDP up to 2050, as shown in Figure 17.

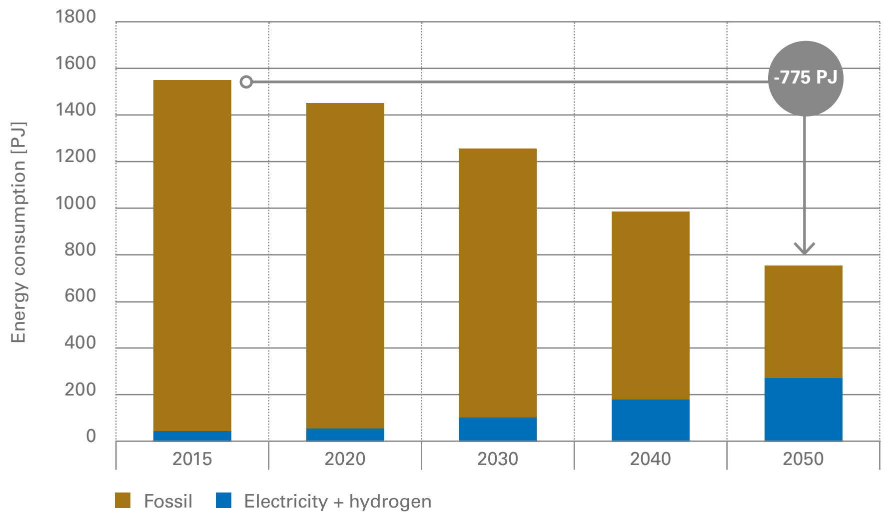

Figure 16
Energy consumption for transports, all modes.

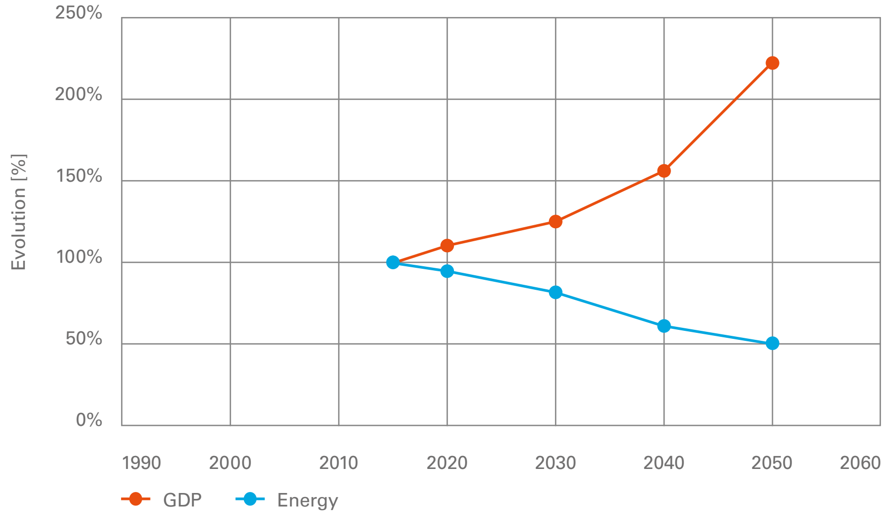

Figure 17
Evolution of GDP and energy consumption for transports.

The consumption of energy from fossil fuels in the transport sector is going to drop even more dramatically, falling from 1,487 PJ in 2015 to 464 PJ in 2050, as visible in Figure 18. This involves a corresponding reduction of the CO_2 emissions, which are going to decrease from 106 Mton in 2015 to 26 Mton in 2050.

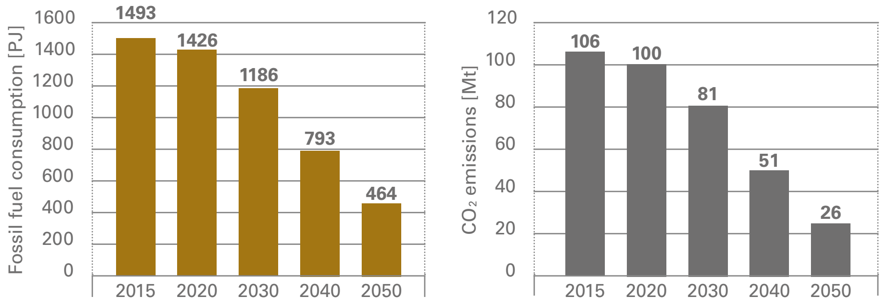

Figure 18
Effect of electrification: outlook of fossil fuel consumption (left) and CO_2 emissions (right) in transport sector.

The findings summarized above, together with the sectoral outlooks shown before, underline that the shift to electric power will involve all the land transports, with a very strong impact on road transports. Citizens and consumers will have large benefits from this process due to the reduction in the emissions of polluting gases, with a relevant impact on health, as well as to the reduction in the direct cost for transportation. The reduction in emissions will reduce also the indirect costs of transportations. Figure 19 shows the outlook on the total emissions of air pollutants from road vehicles.

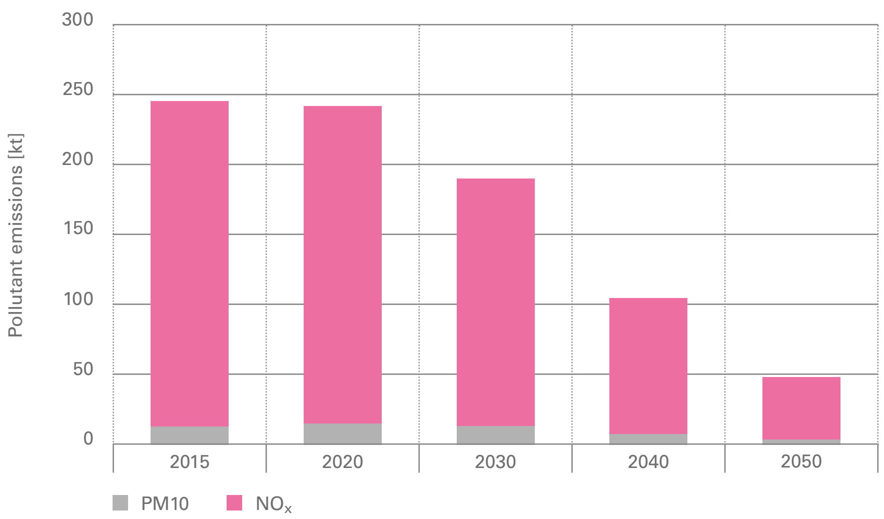

Figure 19
Outlook of emissions of air pollutants from road vehicles.

Even the energy cost for the use of private vehicles is going to drop dramatically thanks to the increase in efficiency. Figure 20 shows an overview of the impact that the energy cost for a car has on the average family net income.

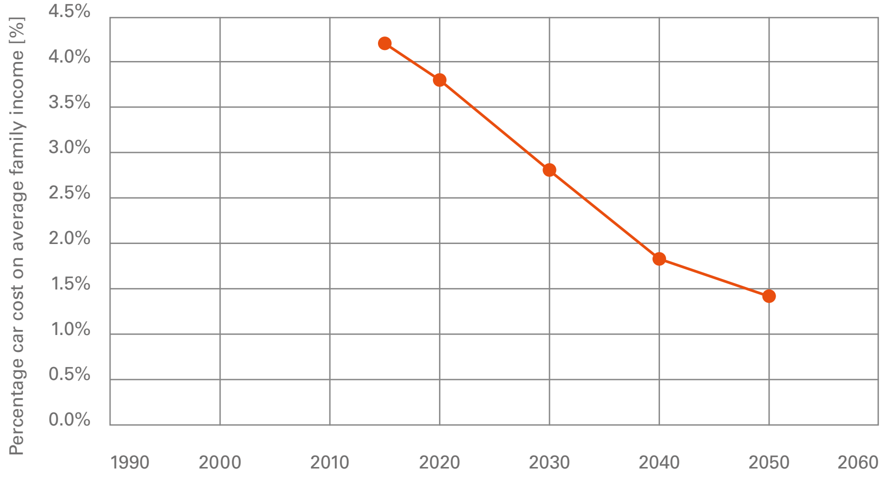

Figure 20
Cost of energy for car use referred to average family income.

From the point of view of electric power producers and distributors, the transformation of the transport sector provides several opportunities and challenges. The national electric system must evolve to adapt to the new demand from vehicles holders, making available both power and recharging points.

Power demand for electric vehicles is going to grow from 39 PJ in 2015, most of them for railways, to 280 PJ (78 TWh) in 2050, with a need for a diffused distribution infrastructure. Figure 21 shows the increase of electricity demand for transportation. The electric power demand for transport with respect to total electric power demand should increase from 6% in 2015 to 25% in 2050.

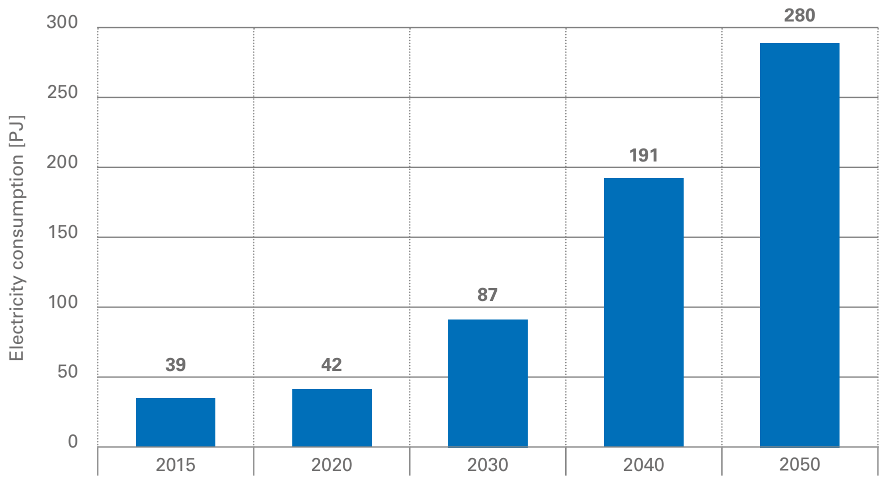

Figure 21
Outlook of electric power demand for transports.

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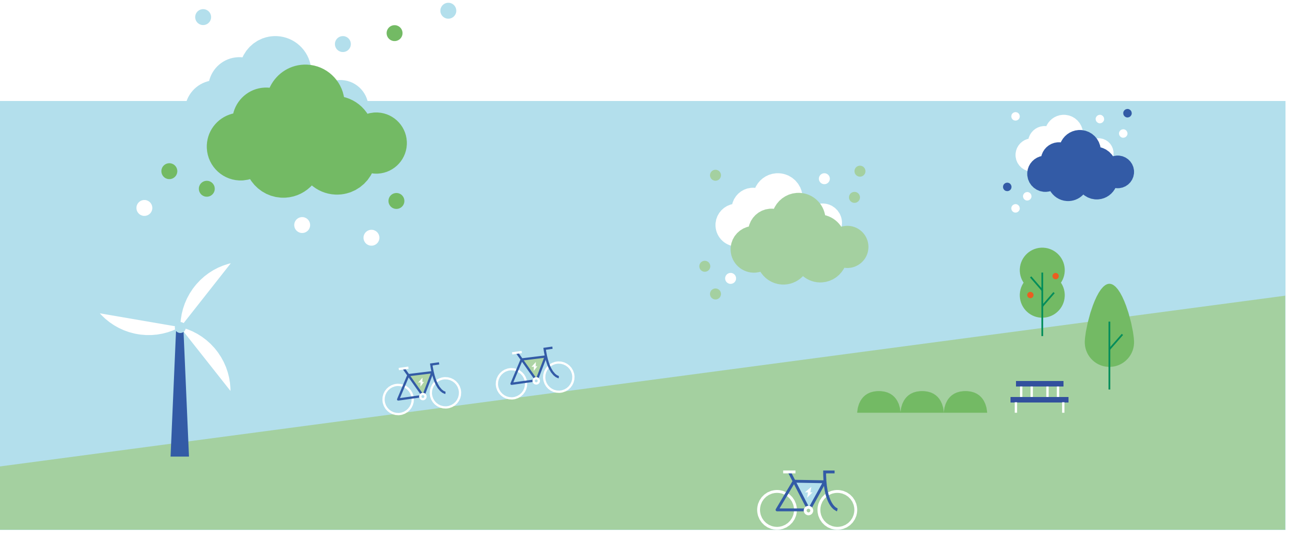
Chapter 8

INTEGRATED SCENARIO AND KPIs ASSESSMENT



8.1 ITELEC2050 SCENARIO

As presented in Chapter 2, the outputs of the four sectoral analyses described in the previous sections are used as inputs to assemble the overall integrated ITELEC2050 scenario, outlining a possible evolution of the Italian energy system up to 2050. In particular, as represented in Figure 1, to build the ITELEC2050 scenario, specific sub-scenarios of supply and demand sides are considered: “Current Policies” scenario for power generation, “Scenario FB” for the residential sector, “High Electrification” scenario for industry, “TECH scenario” for transport. The reasons for these choices are detailed afterwords.

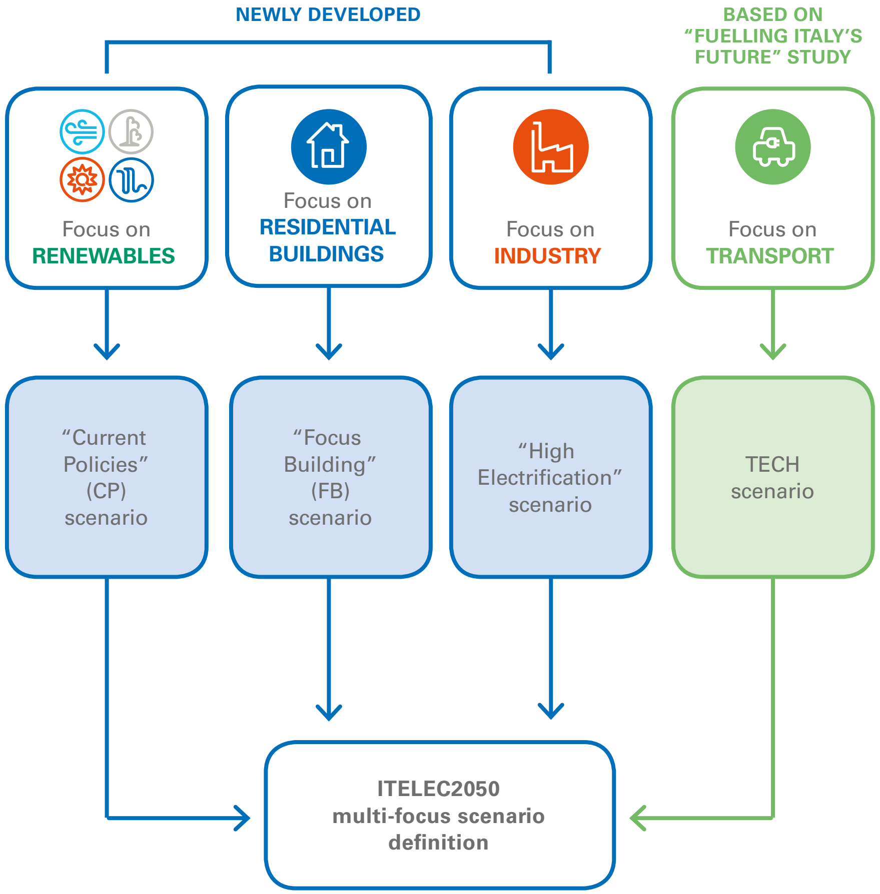


Figure 1
Methodological steps for the definition of the integrated ITELEC2050 scenario.

Power generation

Focusing on the power generation sector, the "Current Policies" scenario is selected as it represents an intermediate option among the ones elaborated considering different assumptions on CO_2 prices (respectively zero CO_2 prices and CO_2 prices as per IEA WEO 2017 "Current Policies" (CP) and "Sustainable Development" (SD) scenarios [1]). This choice is based on the consideration that the impact of higher CO_2 prices is relatively limited in terms of CO_2 emissions and electricity production mix. In particular, the CP scenario (based on a CO_2 price equal to 46 €/t in 2050) leads to a power generation from RES equal to 85.6%, while the SD scenario requires to assume a CO_2 price equal to 169.3 €/t in 2050 to reach a renewable share in the electricity production of 90.2%. These results highlight that the current national strategy of a coal phase-out coupled to the expected future technological advancement for RES and energy storage systems will go a long way in supporting the energy transition towards renewables and in obtaining a significant reduction in carbon emissions from the power sector.

Residential buildings

Referring to the residential building sector, the "FB scenario" is selected because it better reflects the current market regulation and business models in terms of incentives, tariffs and energy prices in comparison with the alternative scenarios, which instead were developed to assess the impacts of some key variables on the electrification of the sector. The use of the GCCA indicator (the ratio between the global costs of the technological options and the related CO_{2eq} emissions avoided) is consistent with this choice, representing compliance with current policy targets, which are mainly focused on GHG emissions reduction.

The analysis is focused on the residential sector, with an in-depth study on not fully electrified services (space heating, water heating and cooking), based on stock distribution, and more aggregated evaluations for full-electric final uses (space cooling, lighting and appliances), relying on projections of historical data. Non-residential buildings are not included in the scenario. Indeed, they represent only 10% of Italian building stock [2] and they are already highly electrified (51% [3]), due to the high use of electric equipment and air conditioning requirements.

Industry

Considering the industrial sector, the "High Electrification" scenario is selected, being the one that better reflects the major international trends in commodity cost variation, learning curves, efficiency gains, and carbon pricing. The energy price evolution consistent with IEA [4] forecasts the fact that a CO_2 price is taken into consideration in the analysis and the projections of the energy demand evaluated through extrapolation and close to other national and international studies forecasts make the "High Electrification" scenario realistic. It must be underlined that the quantitative scenario analyses of the industrial sector do not include agriculture and services subsectors.

Transport

Finally, regarding the transport sector, "TECH scenario" is built based on the "Fuelling Italy's Future" (FIF) study [5], related to passengers' cars. Moreover, an analysis on public transportation (urban and long-range buses), air and water transport, trains and light commercial vehicles (LCV), is added to depict the evolution of the entire Italian transport sector up to 2050.

8.2 KPIs ASSESSMENT

Starting from the quantitative information provided by the single sectoral analyses, the whole set of KPIs, previously described in Chapter 2, is calculated for the ITELEC2050 scenario. Table 1 summarises the obtained values, classified according to the four dimensions: energy, environment, economy and society.

As pointed out in the methodological section, major attention is devoted to the investigation of the contribution of electrification in the four dimensions identified. Furthermore, given the objective of the study, namely to address the potential further electrification of the Italian energy system, the contribution of electrification to the variation of some of the above-mentioned KPIs is calculated. In particular, the contribution of electrification, expressed in percentage terms, is calculated, when possible, for the variation of the total final consumption (TFC) and then translated into the other KPIs (e.g. variation of CO_2 emissions, variation of PM emissions, variation of NO_x emissions, variation of energy intensity, etc.) using appropriate transformation indexes (e.g. emission factors, GDP, etc.). The calculation is performed developing three scenarios: "Business as Usual", which represents the Italian TFC in the case of absence of any technology improvement and null incremental electrification; "Increased efficiency" scenario, which represents the Italian TFC, considering the future technology improvement, but still null incremental electrification; and the "ITELEC2050" scenario, which represents the total final consumption, accounting for both technology improvement and commodity shift, and including electrification. The definition of the scenarios allows to extrapolate the contribution of electrification to the total variation of TFC. Further details are presented in the focus box.

ELECTRIFY ITALY / 8. INTEGRATED SCENARIO AND KPIs ASSESSMENT

DIMENSION	SUB-DIMENSION	UNIT	2015	2022	2030	2050
ENERGY	**Overall energy use**					
	Total primary energy supply (TPES)[1] variation	% w.r.t. 2015	-	-7%	-19%	-45%
	Final energy consumption (TFC)[2] variation	% w.r.t. 2015	-	-7%	-15%	-42%
	Electrification rate	%	17%	19%	24%	46%
	Per capita final energy consumption (TFC) variation	% w.r.t. 2015	-	-6%	-13%	-38%
	Diversification					
	Renewable share in electricity production	%	39%	48%	59%	86%
	National energy dependence variation	% w.r.t. 2015	-	0%	-8%	-37%
ENVIRONMENT	**Decarbonization**					
	CO_2 emission reduction	% w.r.t. 2015	-	-9%	-30%	-68%
	Decarbonization of the power sector	% w.r.t. 2015	-	-3%	-43%	-74%
	Air quality					
	Particulate Matter (PM) pollution variation	% w.r.t. 2015	-	-41%	-63%	-76%
	Nitrogen Oxides (NO_x) pollution variation	% w.r.t. 2015	-	-3%	-28%	-69%
ECONOMY	Energy intensity variation	% w.r.t. 2015	-	-18%	-40%	-71%
	Final energy consumption intensity variation	% w.r.t. 2015	-	-18%	-37%	-69%
	Carbon intensity of GDP variation	$ktCO_2$/Billion €	0.20	0.16	0.10	0.03
	Weighted LCOE variation	% w.r.t. 2015	-	-17%	-38%	-46%
SOCIETY	Healthcare savings related to air pollution variation	Billion € (cumulative w.r.t. 2015)	-	10.3	42.0	192.7
	Productivity savings related to air pollution variation	Billion € (cumulative w.r.t. 2015)	-	8.9	36.3	163.1
	Life savings related to air pollution variation	Billion € (cumulative w.r.t. 2015)	-	24.1	98.2	440.4
	Total health benefits related to air pollution variation	Billion € (cumulative w.r.t. 2015)	-	43.3	176.5	796.2
	Affordability variation[3]	% w.r.t. 2015	-	-28%	-32%	-58%

Table 1
KPIs for the ITELEC2050 scenario, according to the four main dimensions.

1 The Total Primary Energy Supply (TPES) corresponds to the overall energy needs of a country and, on the basis of the definition provided by Eurostat [2], can be defined as: TPES=local production of energy commodities+recovered products + net imports + variations of stocks – bunkers.

2. The TFC is the amount of energy consumed for fulfilling the so-called "services demand" (space heating and cooling, lighting, industrial production, mobility of passengers and goods, etc.) in the different end-use sectors (agriculture, industry, residential, commerce and services and transport).

3 It includes the effect of the increase of household average income and of commodity shift.

ELECTRIFY ITALY / 8. INTEGRATED SCENARIO AND KPIs ASSESSMENT

FOCUS BOX: CALCULATION OF THE CONTRIBUTION OF ELECTRIFICATION

In order to calculate the contribution of electrification to the total final consumption (TFC), which is the base for calculating all the other KPIs, the following calculations are carried out. The ITELEC2050 scenario is defined based on the outputs of the demand and supply sectoral studies. These outputs are used to calculate the total services needed by each focus resorting to the efficiency of the commodity. With these inputs, a "Business as Usual" (BAU) scenario is defined assuming no changes in the technology (energy mix) and concerning efficiency for the single commodities with respect to the baseline year, assuming that the needed total service in each milestone year must be satisfied. Thus, the adjusted services provided by each commodity can be defined. Based on that, the corresponding energy consumption of each commodity per sector in each milestone year is calculated. In this way, the BAU scenario represents the total Italian final energy consumption, in the case of absence of any technology improvement and of null incremental electrification.

Then, the "Increased efficiency" (IE) scenario is built starting from the services provided by each commodity in the BAU scenario, by considering the real energy efficiencies, for each commodity, sectoral study, and milestone year. Compared with the BAU, this scenario represents the total Italian final consumption, considering the future technology improvement, but still null incremental electrification.

Finally, the ITELEC2050 represents the scenario for which the total final consumption accounts for both technology improvement and commodity shift, including electrification. Based on the 3 above scenarios (BAU, IE and ITELEC2050), it is possible to calculate the contribution of electrification to the TFC variation for each milestone year and subsector in the following way:

- The contribution of energy efficiency (ΔF) is calculated as the TFC difference between IE and BAU scenarios per each commodity.
- The contribution of commodity shift (ΔC), including the contribution of electrification (ΔE) is calculated as the TFC difference between ITELEC2050 and IE scenarios per each commodity. In this step it is important to note that, in the commodity shift, the final consumptions of some commodities will increase, as in the case of electricity (due to the shifts from fossil fuels to electricity), while others will decrease; therefore, it is possible to identify the shifts toward electricity.
- The total contribution of energy efficiency and commodity shift (ΔT) is calculated as the TFC difference between ITELEC2050 and BAU scenarios per each commodity.

Through this, it is possible to isolate the contribution of electrification to the TFC reduction (ΔE) and the total TFC reduction (ΔT) compared to the BAU for each milestone year. Further, the contribution of the electrification of each milestone year with respect to the base year is calculated in the following way, using 2050 as an example:

$$\frac{\Delta E^{2050} - \Delta E^{2015}}{TFC^{2050} - TFC^{2015}} = \frac{\Delta E^{2050} - 0}{TFC^{2050} - TFC^{2015}}$$

After getting the TFC related quantities calculated, such as ΔF, ΔT, ΔE, ΔC, and ΔNE (ΔNE is the quota of TFC not shifted to electricity), it is possible to use these deltas to multiply relevant indexes representative of the other KPIs. For example, the CO_2 emission factors per non-electrical commodity can be used to multiply the variations of the shifted energy of other non-electrical commodities to consider the contribution of the electrification to the reduction of CO_2 emissions at the demand side. Similar approaches are used for the other KPIs.

The calculated percentages of the contribution of electrification to the main KPIs variations, with respect to 2015, are summarized in Table 2.

DIMENSION	CONTRIBUTION OF ELECTRIFICATION TO	2022	2030	2050
ENERGY	TPES variation w.r.t. 2015	17%	43%	76%
	TFC variation w.r.t. 2015	31%	52%	80%
	Per capita TFC w.r.t. 2015	31%	56%	83%
	National energy dependence variation w.r.t. 2015	31%	59%	89%
ENVIRONMENT	CO_2 emission variation w.r.t. 2015	58%	60%	85%
	Particulate Matter pollution variation w.r.t. 2015	32%	27%	52%
	Nitrogen Oxides pollution variation w.r.t. 2015	58%	46%	80%
ECONOMY	Energy intensity variation w.r.t. 2015	10%	23%	35%
	Carbon intensity variation w.r.t. 2015	61%	49%	89%
SOCIETY	Total health benefits related to air pollution variation	37%	41%	87%
	Affordability variation w.r.t. 2015	13%	31%	29%

Table 2
Contribution of electrification to the main KPIs.

Table 2 highlights how the contribution of electrification increases over the timespan, reaching the highest percentage values in 2050, thanks to the combined effect of higher penetration of renewables into the energy mix and higher electrification rates of the end-use sectors. A different behaviour is noticeable for the environmental dimension, and specifically for the variation with respect to 2015 of the PM and NO_x emissions. For both KPIs, it is possible to see how the contribution of electrification presents a low peak in 2030. The explanation of this behaviour lies in the evolution of the electricity generation mix, and especially in the peak reached by generation from coal power plants in 2022 and in its later phase out. As a consequence, a relevant contribution to the variation of PM and NO_x emissions is attributable to the phase out of coal in the period 2022-2030, making the contribution of electrification looking lower in 2030, compared to the other milestone years. In 2050, instead, electricity consumption in final uses significantly increase, causing a considerable reduction of TFC, as well as an important reduction of air pollutants emissions, and thus making the percentage contribution of electrification increasing again.

ELECTRIFY ITALY / 8. INTEGRATED SCENARIO AND KPIs ASSESSMENT

Energy

The impact analysis based on the outcomes of the ITELEC2050 scenario allows to point out the benefits that the coupling between electrification of final uses and high renewables penetration in the power generation sector could determine.

Figure 2 shows, for the baseline of the study (2015) and for all the milestone years (2022, 2030 and 2050), the energy balances forecasted by the ITELEC2050 scenario for both the Italian electricity generation and demand sides. On the left, the total electricity production forecasted by the focus on power sector is shown, underlining the contribution of renewables. On the right side, the total final consumption estimated by the three sectoral analyses (residential building, industry and transport) is reported, highlighting the portion fulfilled by electricity and the one satisfied through other fuels.

The graphs highlight the significant change that is expected in the end-use sectors and the key importance that electricity can assume in the fulfilment of the final demands. While the overall energy consumption is estimated to decrease (from 4188.1 PJ in 2015 to 2438.5 PJ in 2050), thanks to an overall energy efficiency improvement, the share of electricity in the energy mix grows, leading to a consequent increase in the electricity demand.

Furthermore, this electrification process is accompanied by the increase in the contribution of RES to the electricity generation. Indeed, as an outcome of the study of power generation, it appears that renewables will be a key element to reach a sustainable energy system. Their penetration in the power mix will steadily increase up to 85.6% in 2050 (45% in 2022, 59% in 2030), almost 120% more than the current level. This penetration in the mix could happen even with relatively low CO_2 prices. The hydro resource is almost fully exploited, thus its contribution to net electricity generation will remain almost constant, while solar plants will represent the largest RES contribution (see Figure 3), representing 62% of the total power generation in 2050 (24% in 2022, 34% in 2030), followed by wind plants (9.7%) and bioenergy and waste technologies (1.6%). In order to allow this RES deployment, storage will play an increasingly important role along the years, with a projected installed capacity of about 112 GW.

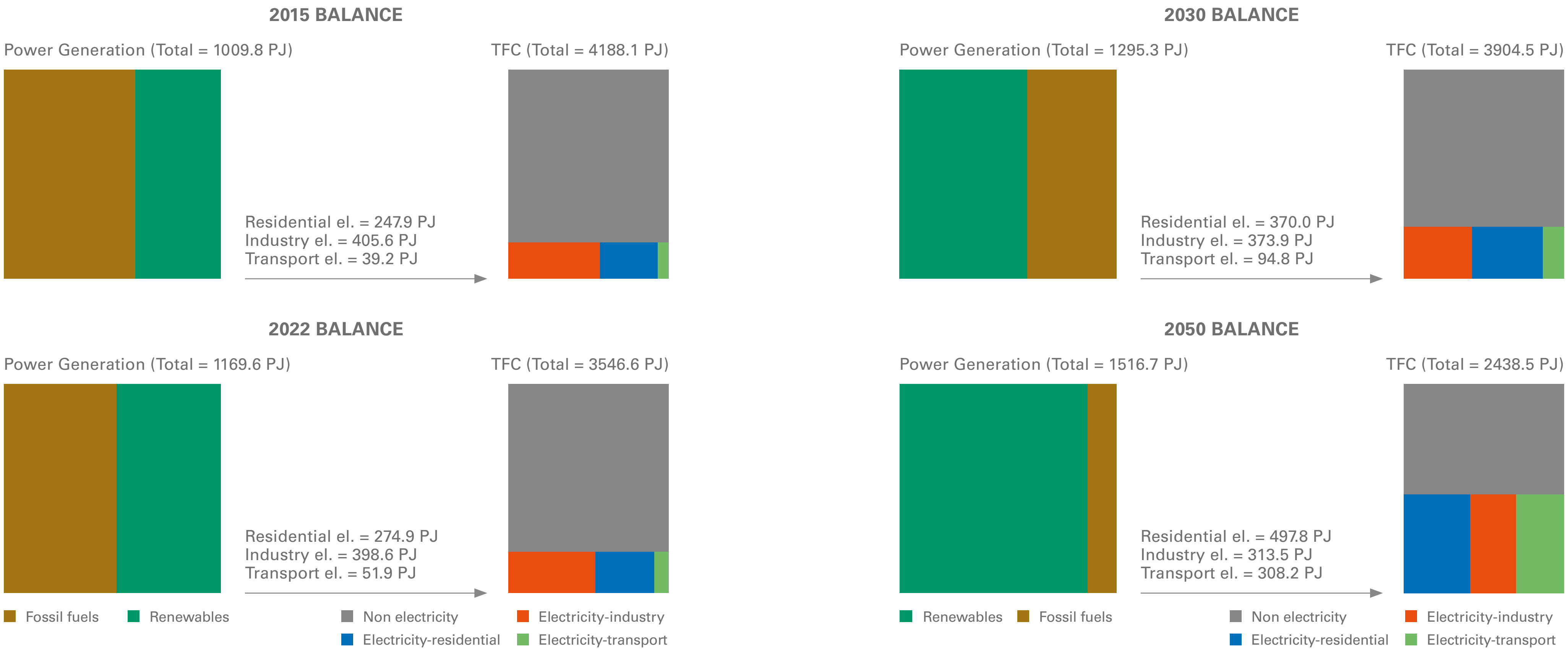


Figure 2
Energy balance in terms of power generation and final energy consumption in 2015, 2022, 2030 and 2050.

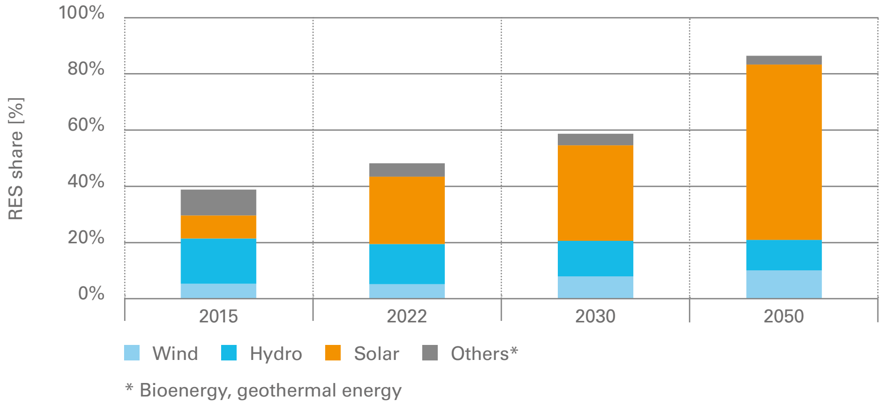


Figure 3
Evolution of RES share in total power generation in Italy.

From the demand point of view, this change in the energy system paradigm – with a transition towards a more and more relevant role played by electricity (which is expected to reach by 2050 a 46% share in the final uses) – could lead to significant savings, reducing the overall final energy consumption by 42% in 2050 in comparison with the 2015 value. Electrification will contribute to more than 3/4 of this reduction, as shown in Figure 4. This contribution is particularly due to higher energy efficiencies of electric technologies with respect to the traditional solutions based on fossil fuels.

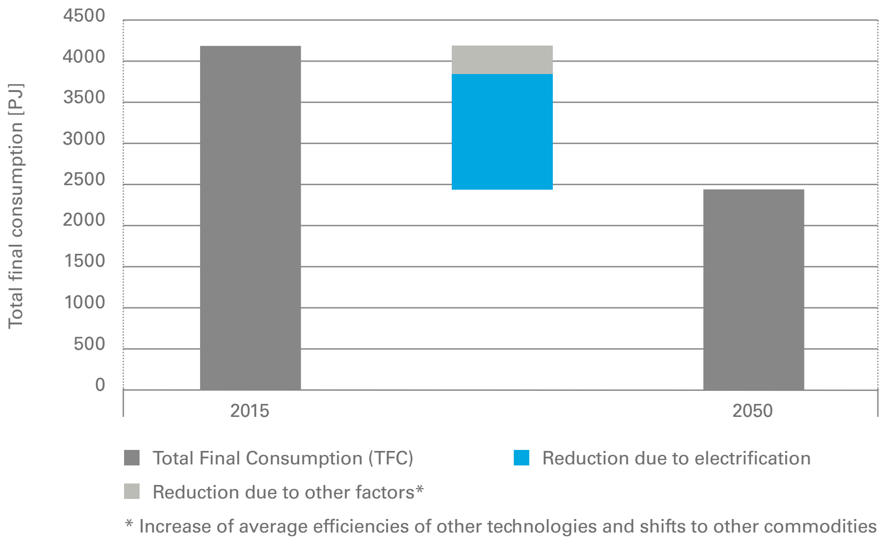


Figure 4
Contribution of electrification to the reduction of total final consumption in 2050.

In order to understand the effects of the different sectors in the TFC reduction, Figure 5 shows the separate contribution of electrification of the three demand sectors analysed in the study. From the graph, it is possible to note that the highest contribution to the reduction of TFC is represented by the electrification of transport sector, contributing for 42% of TFC reduction, followed by buildings (31%) and industry (8%).

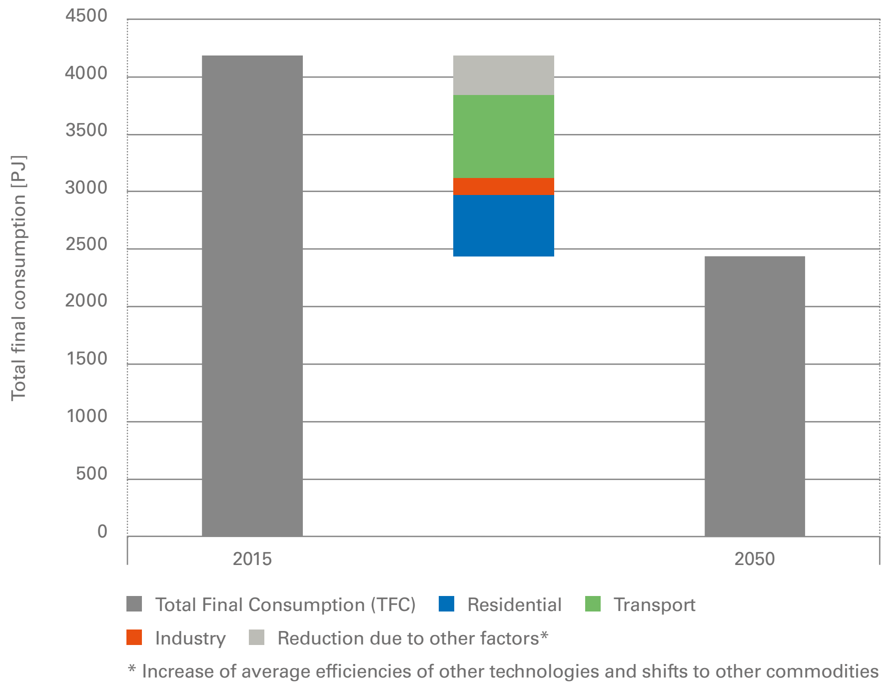


Figure 5
Contribution of electrification to the reduction of total final consumption in 2050 by end-use sector (residential, industry, transport).

Detailing the electrification rate of the demand side, intended as the share of electricity in the final energy consumption, this is expected to increase from the current 17% to almost 46%, as shown in Figure 6. In particular, it can be observed that the major increases in electrification are expected between 2030 and 2050, when both technical maturity of available technological options and policy actions will effectively support a rapid growth in the penetration of electricity-based solutions.

Out of the 46% electrification rate in 2050, 20% is due to the residential building sector, 13% to industry and 13% to transport (Figure 7).

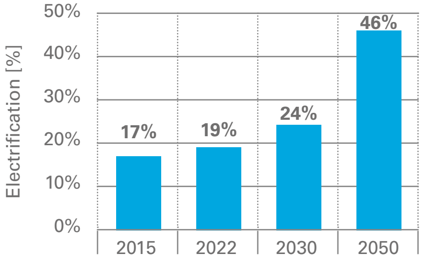


Figure 6
Electricity share in final energy consumption up to 2050.

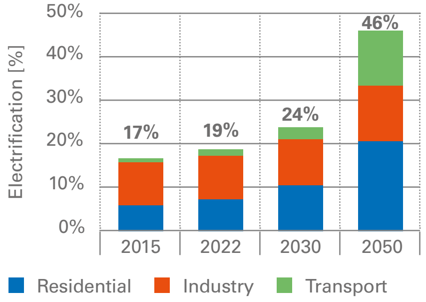


Figure 7
End-use sectors contribution to total electrification up to 2050.

Among the analysed end-uses, residential building and transport sectors seem to have the largest electrification growth potentials, while industry sector can slightly improve its efficiency through electrification. Figure 8 shows the evolution of the electrification rate in the studied end-use sectors, compared to the expected RES penetration in power generation at the baseline (2015) and in the three milestone years (2022, 2030 and 2050).

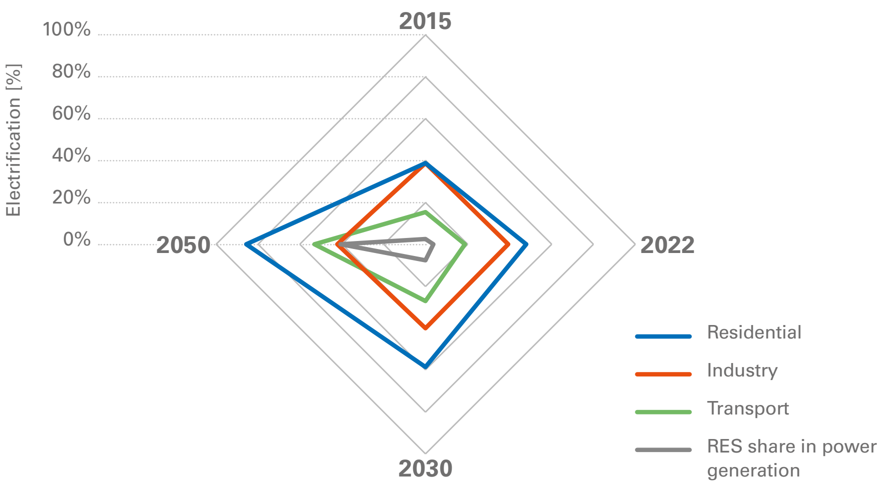


Figure 8
Electrification in the end-use sectors and RES share in power generation sector for the base year (2015) and for the three milestone years (2022, 2030, 2050).

Moreover, as shown in Figure 9, the residential building sector has the potential to become the most electrified sector in Italy, reaching a 53% share of electricity in TFC in 2050, with respect to the initial 16%. Industry will conserve a high electrification rate, which will marginally grow from 39% to 42%. However, the sector that has the largest growth potential is transport, which may grow twelve times (from 3% in 2015, to 41% in 2050).

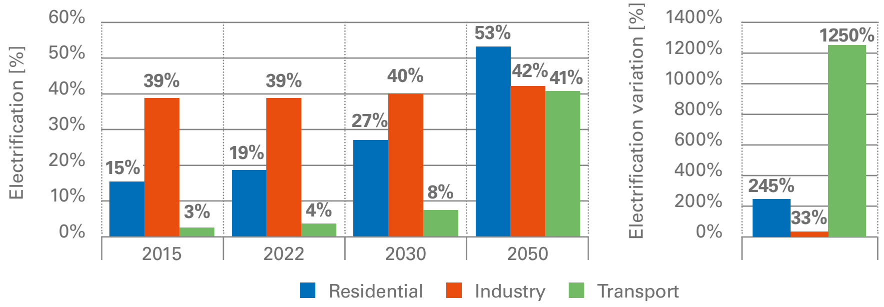


Figure 9
Evolution of electrification rate in end-uses sectors (left) and 2015-2050 electrification variation (right).

Among the benefits that the electrification of the energy system could have, the variation of the national energy dependence is reported. This KPI is strongly correlated to energy security issues; indeed, as pointed out in [6], security issues related to the acquisition of energy commodities are particularly critical in countries, like Italy, whose level of self-sufficiency is low. In this project, the national energy dependence is calculated as the ratio between the net Italian fossil fuels imports and the total primary energy supply in the different milestone years. From the scenario, it appears that the national energy dependence is expected to decrease, up to 37% in 2050. Electrification alone can provide a reduction of 33% in energy dependence, almost 90% of total 37% reduction, showing that an electricity-driven energy transition could clearly enhance national energy security.

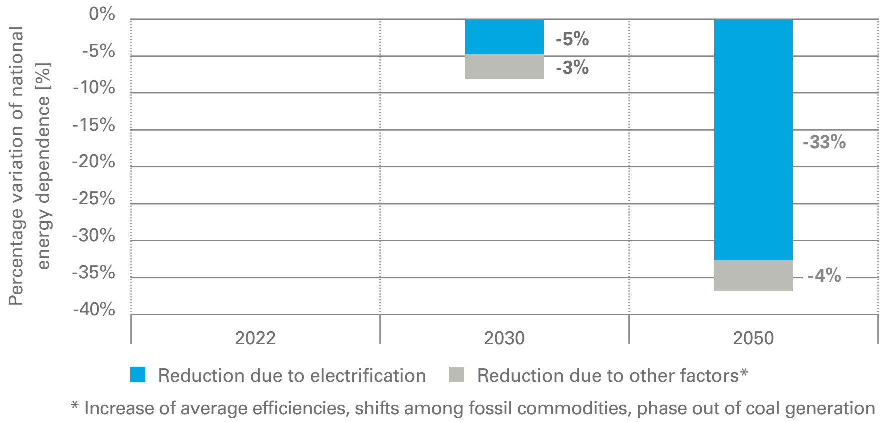


Figure 10
Contribution of electrification to the reduction of national energy dependence.

Environment

The decreasing energy demand and its electrification has positive environmental impacts, reducing the amount of CO_2 emissions by 68% in 2050 compared to 2015 levels, thus highlighting the suitability of this new electricity-based paradigm with the long-term decarbonization targets aiming at counteracting global warming and the related climate change phenomena. In particular, as reported in Figure 11, the contribution of electrification to this reduction reaches 85% in 2050 (58% in 2022, 60% in 2030), while the rest of the variation is attributable to an overall increase of the efficiency in the use of other energy sources.

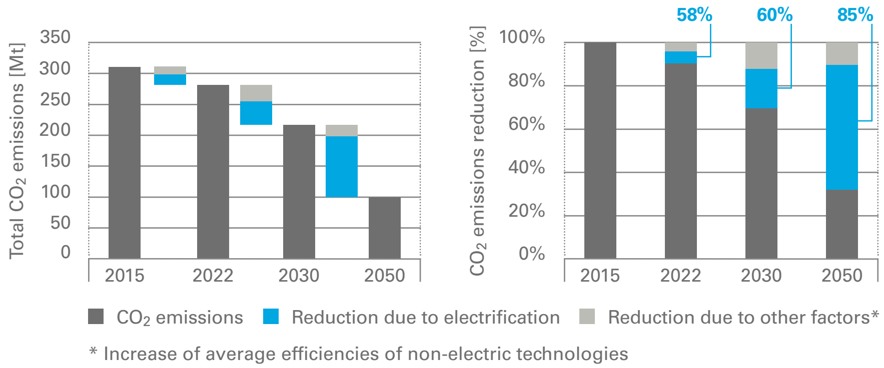


Figure 11
Contribution of electrification to CO_2 emissions reduction: in absolute (a) and percentage (b) values.

Nevertheless, besides the CO_2 emissions reduction, nowadays there is an increasing attention towards the air pollution topic, due to the negative impacts that pollutants (mainly PM and NO_x) have on people health. These effects are particularly perceived in urban areas, where local air pollution is extremely problematic due to traffic and building consumption, especially during the winter season.

Therefore, shifting from the global (CO_2) to the local (PM and NO_x) scale, this study investigates how the increasing electrification of the Italian energy system may also lead to the reduction of air pollutant emissions. In particular, the ITELEC2050 scenario permits to reach a reduction of 76% and 69% of PM and NO_x emissions, respectively, over the period 2015-2050. In particular, regarding PM emissions (Figure 12), the highest reductions occur in the residential sector, due to the shift from fossil and biomass technologies (the latter being the highest PM emitters) to electric technologies, which have null direct PM emissions. Also, the industry sector greatly contributes to the overall reduction of PM emissions. As for the NO_x emissions, it is possible to note from Figure 13 that the highest reduction is achievable in the transport sector, thanks to the shift from fossil-based transport systems to electric ones.

Generally speaking, the contribution of electrification to the overall reduction of air pollutants is 52% and 80% for PM and NO_x emissions, respectively.

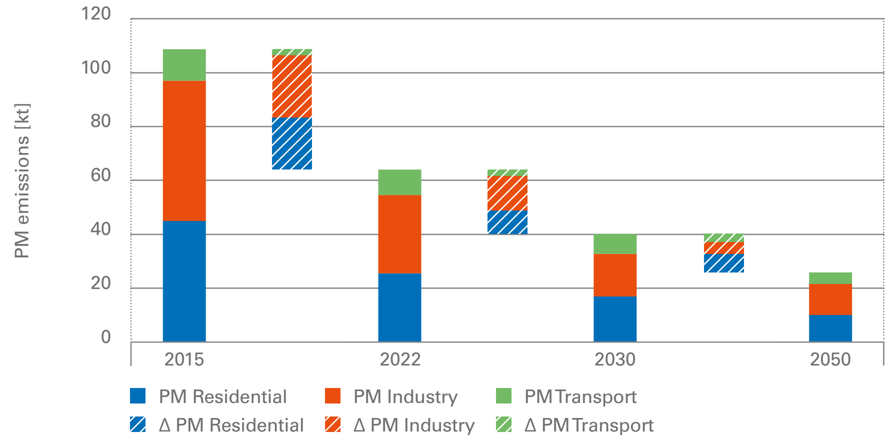


Figure 12
PM emissions reduction by sector.

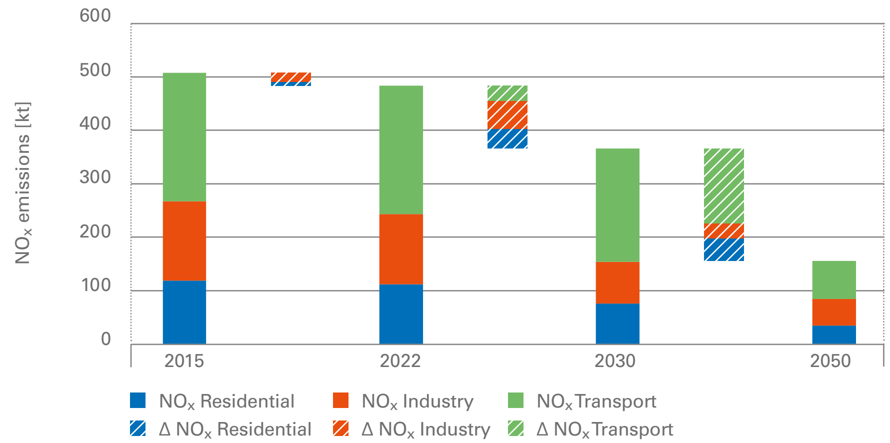


Figure 13
NO_x emissions reduction by sector.

Figure 14 shows the evolution of PM and NO_x emissions (fixing to 100 the values of 2015) compared to the electrification rate from 2015 to 2050. The trend is clearly opposite, justifying how the choice of electricity-fuelled solutions will globally improve the air quality.

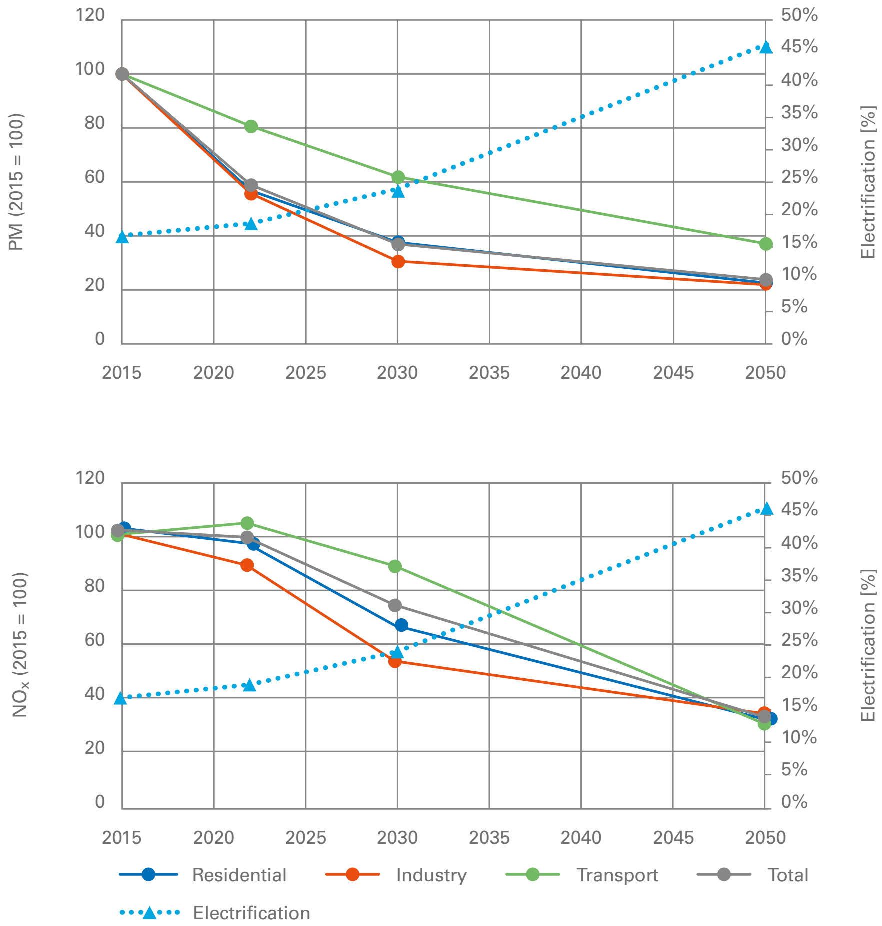


Figure 14
Evolutions of PM (top) and NO_x (bottom) emissions by sector and total, compared to the electrification rate (power sector emissions excluded).

Economy

A consequence of the reduction of energy consumption (-42% in 2050 compared to 2015) is the decrease of the energy intensity, reducing the amount of energy requested for generating a unit of GDP by 71% in 2050 with respect to 2015. Similar effect is noticed in terms of carbon intensity, which achieves a 83% reduction in 2050, compared to 2015 (Figure 15 and Figure 16). It clearly appears that electrification represents the highest contribution to its reduction, representing almost 90% of the overall carbon intensity variation in 2050.

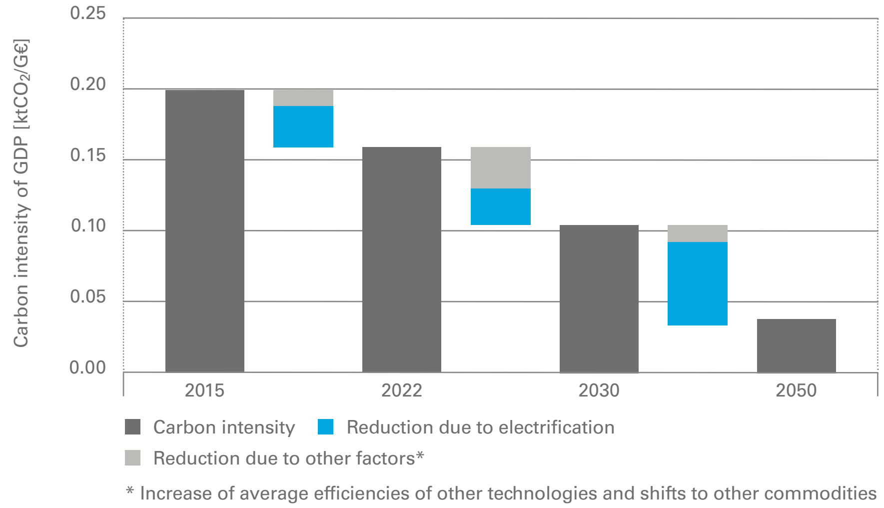


Figure 15
Contribution of electrification to the carbon intensity reduction up to 2050.

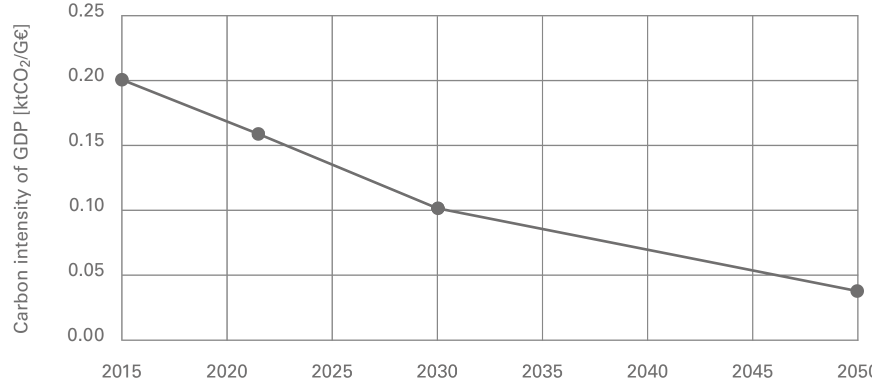


Figure 16
Carbon intensity evolution over the period 2015-2050.

These trends in terms of energy consumption and CO_2 emissions strengthen the decoupling between economic growth and CO_2 emissions (particularly relevant at the end of the considered period, see Figure 17), underlining the possibility of guaranteeing a country's economic development and welfare, and assuring at the same time its environmental sustainability. Particularly, Figure 17 shows the trends of CO_2 emissions for the three end-uses sectors (residential, industry and transport) and for the power generation sector,

ELECTRIFY ITALY / 8. INTEGRATED SCENARIO AND KPIs ASSESSMENT

in comparison with the GDP evolution. It is worth noting that the trend of CO_2 emissions from the generation side is characterized by an increase of emissions, that reach a peak in 2022, and then a decrease until 2050. The trend is related to the electricity generation projections, which forecast a peak of electricity generation from coal power plants in 2022, which thus is responsible of higher CO_2 emissions. The subsequent decrease of CO_2 emissions, from 2022, is strongly related to the joint effect of the progressive coal phase out and the growing penetration of renewable sources.

From the graph, the decoupling effect is evident, especially in the 2030-2050 period, when stronger electrification facilitates higher emissions reduction. Moreover, from an economic perspective, the needed investments for implementing the relevant modifications envisaged by the ITELEC2050 scenario could have positive effects on the productive sectors of the country, allowing the strengthening or the creation of significant value chains.

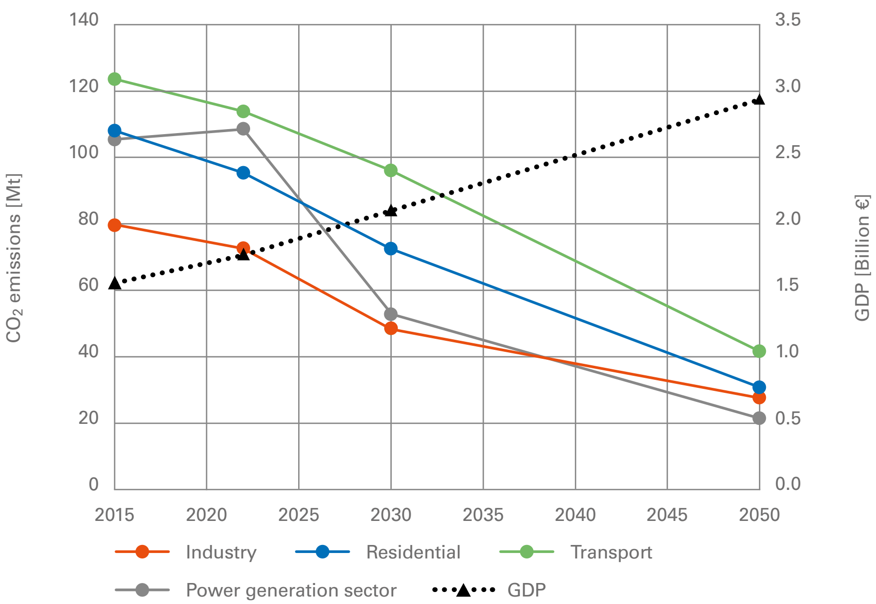


Figure 17
CO_2 emissions and Italian GDP evolutions over the time horizon 2015-2050.

Finally, when dealing with the financial aspect of the energy transition, it is fundamental to explore the dynamics of the renewable technology economics. The criterion usually used is the Levelized Cost of Electricity (LCOE), which is an economic indicator usually implemented for comparing different electricity generation technologies.

As reported in Chapter 4, the technology cost is location dependent and the future RES penetration in Italy will depend on the developments in investment, operation and maintenance (O&M) costs for these technologies. In order to gain some insights on the future of RES in Italy, it is therefore important to explore the future expected costs of RES in the EU. Future cost trajectories to 2050 are reported for hydropower, wind (on-shore and off-shore), solar and other RES (bioenergy and geothermal) in a European Commission report [7]. The International Energy Agency (IEA) reports that the motivation for higher RES capacity installations and the corresponding reductions in CO_2 emissions is the main driver of RES cost reduction in different scenarios [4]. These projections, represented in Figure 18, indicate a promising future for investments in solar and wind technologies. On the other hand, cost trajectories for hydropower and geothermal do not show significant change in the future, in part because they are naturally limited resources with modest opportunity for further expansion.

Coupling the projections for the renewable technologies reported in Figure 18 with the non-renewable ones, it is possible to compute a single LCOE value, weighting the technologies LCOEs with their actual electricity generation for the entire set of generation technologies. The evolution of the weighted LCOE is reported in Figure 19, showing an overall reduction of 46% in the period 2015-2050, mainly due to the forecasted LCOE variations for solar and wind, which mostly contribute to the expected high RES penetration in 2050.

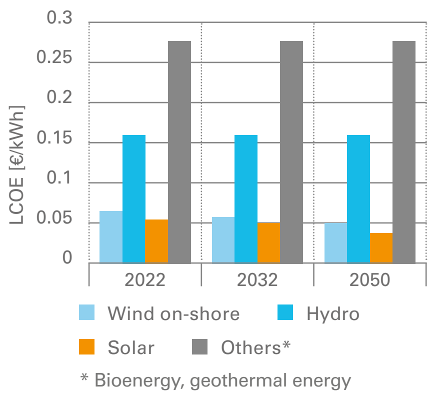


Figure 18
Evolution of LCOE of renewable technologies in Italy.

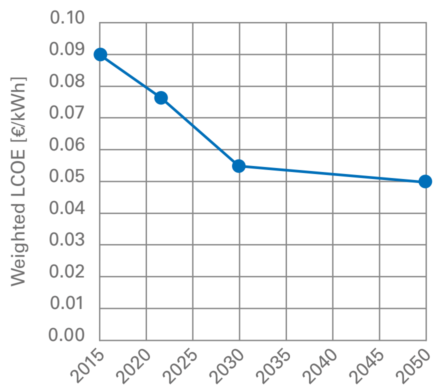
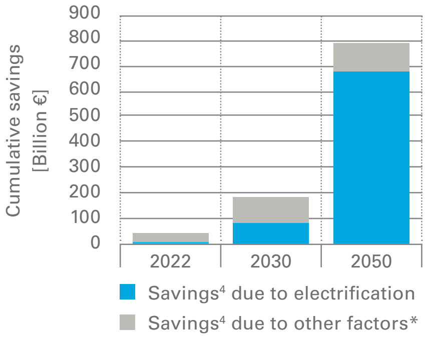


Figure 19
Evolution of LCOE weighted on the forecasted electricity generation.

Society

The social impacts of the electrification of the Italian energy system are assessed with reference to two main aspects: effects on health and impacts on energy affordability for families.

Concerning the former, as previously shown in Figure 12 and Figure 13, ITELEC2050 scenario foresees a key role of the electricity-based transition of energy system in reducing pollutant emissions, reaching a total reduction of 76% and 69% of PM and NO_x emissions, respectively, over the period 2015-2050. Electrification thus improves air quality (especially in urban areas), leading to social benefits in terms of reduction of negative health effects for citizens. This can be translated into cumulated monetary savings of 796 Billion € in 2050, due to the combined reduction of healthcare expenditures, recovery of lost productivity, and avoidance of premature deaths. As shown in Figure 20, electrification will contribute up to 87% of this reduction (equal to 692 Billion € savings in 2050).



* Increase of average efficiencies of other technologies and shifts to other commodities

Figure 20
Contribution of electrification to cumulated health monetary savings up to 2050.

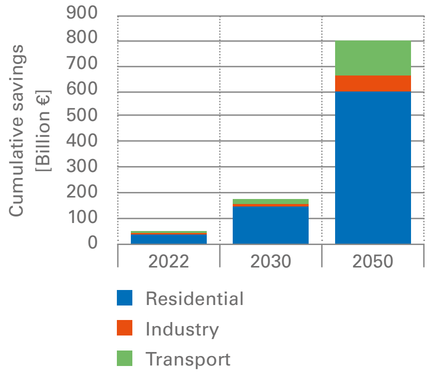


Figure 21
Cumulated health monetary savings up to 2050 by sector.

Figure 21 shows the contribution of the studied end-use sectors to these savings. The building sector will contribute the most to this benefit, followed by transport and industry, mainly due to the substantial decrease of biomass technologies (which are the highest emitters of PM and NO_x) in the residential sector and the reduction of petroleum-based transport systems in 2050.

Furthermore, ITELEC2050 shows that the electrification will boost energy affordability for Italian families, thanks to the improvements in energy efficiency. This process could reduce the energy expenses of households and the related incidence on their income. Indeed, the share of income that each average household will need to devote to energy expenditures will decrease by 17% in 2050 (Figure 22). The impact that electrification can have on family budgets, in terms of decreasing energy expenditures, will presumably also induce a positive feedback supporting further penetration of electric technologies. This effect is not accounted in this study.

4 *Reduction of healthcare expenditures, recovery of productivity, avoidance of premature deaths.*

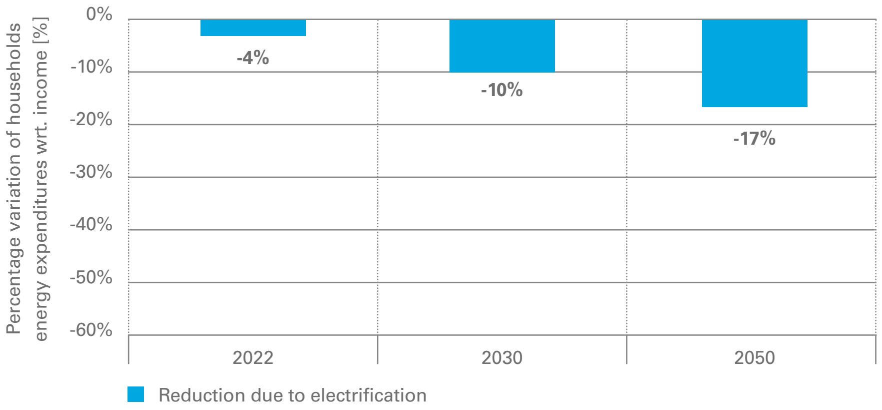


Figure 22
Variation of households energy expenditures with respect to the income.

References

[1] International Energy Agency (IEA), World Energy Outlook, 2017.

[2] ISTAT statistics, http://dati.istat.it/

[3] Enerdata database, http://www.odyssee-mure.eu/

[4] International Energy Agency (IEA), Energy Technology Perspectives 2016 - Towards sustainable urban energy systems, 2016.

[5] Cambridge Econometrics, Fuelling Italy's Future – Come la transizione verso la mobilità a basso contenuto di carbonio rafforza l'economia, from: Low-carbon cars in Italy: A socioeconomic assessment, 2018.

[6] E. Bompard, A. Carpignano, M. Erriquez, D. Grosso, M. Pession, F. Profumo, National energy security assessment in a geopolitical perspective, Energy 130, 1, 2017, pp. 144-154.

[7] P. Mandatowa et al., "Technology pathways in decarbonisation scenarios," 2018.

Chapter 9

COMPARISON WITH OTHER SCENARIOS

9.1 SELECTION OF NATIONAL AND INTERNATIONAL ENERGY SCENARIOS

The final part of the study aims to compare the results obtained from the multi-focus ITELEC2050 scenario with a set of selected national and international future mid/long-term scenarios (with data specifically related to Italy), to provide a more comprehensive view of the future expectations and forecasts about the electrification of Italy. The comparative analysis is based on the integrated assessment framework of the expected benefits (namely KPIs), reported in Chapter 8.

Several scenarios aiming to capture the possible future evolution of energy systems, in terms of both supply and demand sides, are available in literature. Moreover, a review of the key trends, assumptions and major implications of other existing reference scenarios is developed, aiming to compare them with the developed ITELEC2050 scenario, which main results are introduced in the previous sections.

As reported in the methodological section, the scenarios to be compared with the integrated ITELEC2050 are selected based on:

- Time horizon (minimum up to 2022).
- Geographical coverage (Italy/Europe/World).
- Spatial granularity (national disaggregation).
- Year of release (not older than 2012).
- Sectoral coverage (at least one among building, transport, industry and power sector).
- Numerical data granularity (possibility to get quantitative information for all the needed comparison parameters).

The literature review allowed to select the six scenarios reported in Table 1.

ACRONYM	NAME	ISSUED BY	YEAR	SPATIAL GRANULARITY	GEOGRAPHICAL COVERAGE	BASE YEAR AND TIME HORIZON	MODEL TYPE AND APPROACH
SEN	National Energy Strategy – SEN 2017 [1]	Ministry of Economic Development, Ministry of Ministry of the Environment, Land and Sea	2017	National	Italy	2015 – 2030, perspectives until 2050	Integrated approach: bottom-up scenarios developed with TIMES-Italy plus an emission model by ISPRA
BNEF – NEO	Bloomberg New Energy Outlook 2017 [2]	Bloomberg	2017	Global	World with country details	2016 – 2040	Bottom-up: Least-cost modelling
COM – EU	Energy Roadmap [3]	European Commission	2012	Regional	Europe with country details	2005 – 2050	Integrated modelling framework: top-down, bottom-up and emissions PRIMES, PROMETHEUS, IGAINS, GEM – E3
Eurelectric	Decarbonization pathways, Synthesis of key findings, May 2018 [4]	Eurelectric	2018	Regional	Europe with country details (8 regions)	2015 – 2050	Granular inputs and modelling at country and sub-sector levels
ENTSOs	TYNDP 2018 Scenario Report [5]	ENTSOE – ENTSOG	2018	Regional	Europe	2015 – 2040	Integrated modelling framework: top-down and bottom-up
DDPP – ITA	Pathways to deep decarbonization in Italy [6]	Sustainable Development Solutions Network (SDSN) - Institute for Sustainable Development and International Relations (IDDR)	2015	National	Italy	2010 – 2050	Integrated analysis top-down and bottom-up; TIMES-Italy (bottom-up optimization); GDyn-E and ICES (top down)

Table 1
Selected studies and reference scenarios.

All the analysed studies build a certain number of scenarios. Typically, a "Baseline" scenario is developed in order to be representative of the currently implemented policies and their future progressions; then, one or more alternative scenarios are defined, characterised by long-term targets to be reached and coherent assumptions setting the evolution of key variables, to be compared with the baseline ones. The targets of the alternative scenarios are typically defined in terms of GHG emissions requirements and, for Italy, typically refer to the European targets (-40% and -80% in 2030 and 2050 respectively, compared to the 1990 emission levels) or beyond. In order to better explore the selected studies, Table 2 lists the respective developed scenarios, highlighting their targets and their sectoral coverage. Even though the electrification potential is not the focus of the scenarios, from their analysis it is possible to extract information on how the defined transition strategies towards cleaner energy systems might be also related to the penetration of electricity.

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ACRONYM	TARGETS AND OBJECTIVES	COVERED SECTORS	DEVELOPED SCENARIOS
SEN	Strategy up to 2030 to: 1) Increase the country competitiveness: reducing the energy prices gap (gas and electricity) compared to other EU countries; 2) Reach the EU environmental targets; 3) Increase energy security and the flexibility of energy infrastructures	Industry, Buildings, Transport, Power generation	2 scenarios: - Baseline scenario - Policy scenario
BNEF – NEO	Understanding the: 1) changing fundamentals of RES and conventional energy; 2) the related market risks and opportunities	Electricity system, with a systemic view on coal, gas and oil markets	1 scenario
COM – EU	Examining the impacts, challenges and opportunities of possible ways of modernizing the energy system to reach an 80-95% decarbonization of the European energy system to 2050	Industry, Residential, Tertiary, Transport, Power generation	7 scenarios: - 2 current trends scenarios - 5 decarbonization scenarios
ENTSOs	Providing an overview of possible European energy futures for reducing 80-95% emissions to 2050 (compared to 1990 levels)	Power generation, Transport, Heat, Electrical load, Gas demand and supply	3 scenarios: - 3 Best Estimate Scenarios for 2020 and 2025, coupled with 3 Storylines for 2030 and 2040
Eurelectric	Understanding the role of electrification for accelerating the decarbonization of the economy in a cost-effective way	Power, Transport, Buildings, Industry	3 scenarios: - 3 decarbonization scenarios (2015-2050) compared to the base year (2015)
DDPP – ITA	Understanding how to reach the CO_2 emission reduction (Italy): 40% in 2030 and 80% in 2050, compared to 1990	Industry, Buildings, Transport, Power generation	4 scenarios: - baseline scenario - 3 decarbonization scenarios

Table 2
Selected scenarios: targets, sectoral coverage and number of scenarios.

The development of future scenarios relies on the definition of coherent assumptions and parameters that influence the evolution of some key variables, in turn influencing the results. Generally speaking, in all scenario analyses, the main input data are generally represented by macro-economic parameters (i.e. population and GDP), which evolutions impact on the level of end-uses demands over the analysed time horizon. For the definition of the ITELEC2050 scenario, the population projections are taken from the United Nations World Population Prospects [7], while GDP projections derive from the OECD [8].

Another key assumption affecting the evolution of the energy system (especially in terms of installed capacity, technological substitution and energy mix) is represented by the techno-economic characterisation of the alternative technological options that can compete for satisfying the different sectoral demands, including, for instance, efficiency, availability factors, emission factors, investment costs, and operating and maintenance costs. In this sense, energy prices are parameters strictly related to the forecasted energy system evolutions; usually, energy prices represent input variables in the so-called explorative scenarios (in the ITELEC2050 scenario, energy prices are elaborated from IEA ETP 2016 projections [9]), while for the normative or prescriptive scenarios, they represent an output of the model.

Specific assumptions related to the technological evolutions and ad hoc constraints (for instance, on CO_2 emissions) are imposed in order to simulate different policy contexts and long-term strategies, according to the aims of the various scenarios.

The assumptions adopted in the reference scenarios are listed in Table 3. In scenario analyses, it is important to distinguish between assumptions common to all the developed scenarios (in general, the macro-economic ones) and the ones specifically related to single scenarios, reflecting their policy orientations. Consequently, these assumptions are the most relevant ones for the evaluation of the electrification impacts, involving aspects (i.e. energy prices, environmental targets, support to RES, development and implementation of innovative/breakthrough technologies) that can potentially foster, either directly or indirectly, the electrification in the end-use sectors and the penetration of renewable sources in the power generation sector.

ELECTRIFY ITALY / 9. COMPARISON WITH OTHER SCENARIOS

ACRONYM	SCENARIOS	DESCRIPTION	COMMON ASSUMPTIONS	SCENARIO-RELATED ASSUMPTIONS
SEN	SEN_BASE (2030) (Reference Scenario)	The scenario includes policies in plase until 31/12/ 2014, as in the EU Reference 2016-25	Population increase 0.3%/y until 2040, then 0.1%/y up to 2050. Annual growth rate of GDP between 1.19% and 1.54%/y (2010-2050)	2020 national objectives fixed by 2013 SEN are assumed as reached, yearly emission reductions ETS equal to 1.74% even after 2020
	SEN_POLICY (2030) (Alternative Scenario)	Yearly final consumption reduction of 1.5% in the period 2021-30 (with respect to 2016-2018, excluding transport). 28% RES share on 2030 final consumption, 55% electricity RES, phase out of coal power plants		Energy prices refer to European Commission values. Included policies: mobility infrastructures objectives (Ministero dei Trasporti al DEF 201618), sustainable mobility plan (law 232/2016), infrastructure for alternative fuels (257/2016- 2014/94/UE)
BNEF – NEO	BNEF – NEO (2040) (Alternative Scenario)	Subsidies mechanisms removed once they have run their course (excluding nuclear characterized by long development schedule)	Population and GDP set to shape electricity demand growth. Near term: market projections based on policy drivers and proprietary project database (new build, retrofits and retirements). Medium-long term: forecasts driven by the cost of building different power generation technologies, country by country. LNG liquefaction and regasification capacity continues to proliferate, regional price benchmarks converge	
COM – EU	COM-EU-REF (2050) (Reference Scenario)	Includes current trends, upward trends of import fuel prices, achievement of 2020 targets, but no assumptions for later years. 40% emission reduction 1990-2050	Eurostat EPC/ECFIN long term-projections on population and economic development GDP growth rated 1.7% pa (2010-2050). Oil price: 106 $/barrel (2030) and 127 $/barrel (2050)	Includes the policies adopted by March 2010 (Ecodesign and Labelling, RECAST), 2020 targets for RES, GHG reductions and ETS Directive, regulation on CO_2 from cars and vans. Rising fossil fuels prices
	COM-EU-CPI (2050) (Reference Scenario)	Updates the measures adopted in COM-EU-REF with the 2020 Energy strategy. 40% emission reduction 1990-2050		Includes the actions proposed in the "Energy Efficiency Plan" and the "Energy Taxation Directive", Waste Management Directive, facilitation policies for infrastructure
	COM-EU-HEE (Alternative Scenario)	High Energy Efficiency. Political commitment for energy savings, energy demand decreases of 41% in 2050 compared to 2005 peaks. 85% GHG reduction target	Eurostat EPC/ECFIN long term-projections on population and economic development GDP growth rated 1.7% pa (2010-2050). Carbon prices leading to 85% CO_2 emission reduction. Transport White Paper measures included. Lower demand for fossil fuel prices and subsequently lower prices	Political commitment for energy savings (appliances performance standards, building renovation, smart grids, etc.), stringent implementation of the Energy Efficiency plan
	COM-EU-DST (2050) (Alternative Scenario)	Diversified supply technologies: all energy sources compete on a market basis, no specific support to measures. 85% GHG reduction target		No specific support for energy efficiency, carbon pricing drive decarbonization, public acceptance of CCS and nuclear
	COM-EU-RES (2050) (Alternative Scenario)	High Renewable Energy Sources: RES as 75% in gross final energy consumption to 2050 and 97% in electricity consumption. 85% GHG reduction target		Strong support to RES, very high RES in power generation (mainly relying on domestic supply)
	COM-EU-DCCS (2050) (Alternative Scenario)	Delayed CCS: CCS is delayed, carbon prices drive decarbonization. 85% GHG reduction target		Similar to scenario DST, but with delayed CCS (higher shares for nuclear energy driven by carbon prices)
	COM-EU-LN (2050) (Alternative Scenario)	Low nuclear: No new nuclear, higher penetration in CCS (32% in power generation). 85% GHG reduction target		Similar to DST, but no new nuclear (besides reactors currently under construction)

Table 3 (part 1)
Key assumptions for the reference scenarios.

ACRONYM	SCENARIOS	DESCRIPTION	COMMON ASSUMPTIONS	SCENARIO-RELATED ASSUMPTIONS
ENTSOs	ENTSOs-ST (2040) (Alternative scenario)	80-95% decarbonization, power sector: gas replacing coal and lignite. Mobility: gas displaces some oil in heavy transport/shipping. Electrification: slower pace	Moderate growth of economic conditions, national regulation, ETS and subsidies. EU ETS and direct RES subsidies, on track to 2030 targets, slightly beyond 2050 targets. Transport: moderate growth of electric and hybrid vehicles, very high growth of gas vehicles. Buildings: moderate growth of demand flexibility, stable electricity flexibility, slight reduction in gas demand, low growth of electric heat pumps (HP), moderate growth of hybrid HP, moderate growth of energy efficiency. Industry: stable electricity demand, stable gas demand, low growth CCS and demand flexibility. Power: gas before coal, nuclear reduction, low growth storage, moderate growth wind, solar and bioenergy, not significant CCS, some surplus capacity. Not significant P2G, high growth bio-methane	
	ENTSOs-DG (2040) (Alternative scenario)	80-95% decarbonization, prosumers as central figures, decentralized solutions, smart technologies and dual fuel appliances, high demand side response, PV and EVs	EU ETS, slightly beyond 2030 targets, on track 2050 targets. Transport: very high growth of electric and hybrid vehicles, low growth of gas vehicles. Buildings: very high growth of demand flexibility, moderate growth electricity flexibility, reduction in gas demand, moderate growth of electric HP, very high growth of hybrid HP, high growth of energy efficiency. Industry: moderate growth electricity demand, reduction gas demand, not significant CCS and very high growth demand flexibility. Power: gas before coal, nuclear reduction, very high growth storage, high growth wind, and bioenergy, very high growth solar, not significant CCS, high surplus capacity. High growth P2G, high growth bio-methane	
	ENTSOs-GCA (2040) (Alternative scenario)	80-95% decarbonization with global effort. Emphasis on large scale renewables and nuclear in the power sector. Decline of gas in residential and commercial, EVs and gas vehicles, energy efficiency and renewable gases	Global ETS, beyond 2030 targets, on track 2050 targets. High growth of electric and hybrid vehicles, high growth of gas vehicles. Buildings: high growth of demand flexibility, moderate growth electricity flexibility, reduction in gas demand, high growth of electric HP and hybrid HP, high growth of energy efficiency. Industry: stable electricity demand, stable gas demand, low growth CCS and moderate growth demand flexibility. Power: gas before coal, moderate growth storage, high growth wind and solar, moderate growth bio-energies, not significant CCS, some surplus capacity. High growth P2G and bio-methane. No shale gas	
Eurelectric	Eurelectric – S1 (2050) (Alternative Scenario)	80% decarbonization target w.r.t. 1990, accelerate current technological trends, policies and customers' uptake	Projected annual GDP growth for Italy 2015-2050: 1.3% Projected annual population growth for Italy, 2015-2050: -0.2%	Technology development by accelerating current trends and learning curves, increased market share of existing low carbon technologies, cost/convenience still drive end-user's awareness, taxes and levies support the switch to electrification, policy to drive clean technologies (e.g. carbon taxes)
	Eurelectric – S2 (2050) (Alternative Scenario)	90% decarbonization target w.r.t. 1990, shift policies significantly to remove barriers and promote decarbonization and electrification		Cost reduction of mature technologies to 2030 and of new technologies after 2040, some industrial processes are redesigned, increased competitiveness of clean technologies, electricity as a competitive energy carrier, regulation on CO_2 emissions, fossil fuels and infrastructure tightens, major shift in policies
	Eurelectric – S3 (2050) (Alternative Scenario)	95% decarbonization target w.r.t. 1990, drive early technological breakthrough and deploy-ment at scale through global coordination		Cost reduction of non-mature technologies driven by high adoption of electricity solutions and R&D, breakthrough technologies commercialized at the large scale before 2040, adoption of clean technologies by end-users, high competitiveness of electricity, same policies of Eurelectric-S2 but stronger and early implemented
DDPP – ITA	DDPP_ITA: REF (2050) (Reference Scenario)	Current trends and legislations, consistent with the European Commission 2013 PRIMES scenario	Population increase of 5.3% by 2050. Annual growth rate of GDP: between 1.17% and 1.25% (2010-2050) Costs for grid infrastructures and transportation not included, as well as investments in trains, ships, and aircraft	
	DDPP_ITA: CCS (2050) (Alternative Scenario)	Powering the energy system with a large share of electricity from renewables and with fossil fuel technologies, coupled with CCS. 80% decarbonization target		
	DDPP_ITA: EFF (2050) (Alternative Scenario)	Fewer available options to decarbonize the electricity system: increased reliance on advanced energy-efficiency technologies, and greater use of renewable energy for heat and transportation. 80% decarbonization target		Lower sectoral discount rate to stimulate the penetration of highly efficient technologies
	DDPP_ITA: DEM-RED (2050) (Alternative Scenario)	Limited availability/commercialization of CCS (especially in the industrial sector) and high costs of decarbonization. 80% decarbonization target		Energy prices increase, acting on price elastic demand, the demand drivers of end-use sectors are influenced by the high fuel and energy carrier prices, lower price of electricity, costs reduction for RES, reduction of gas prices

Table 3 (part 2)
Key assumptions for the reference scenarios.

9.2 SCENARIO COMPARISON THROUGH KPIs

To compare the ITELEC2050 and the literature-reviewed scenarios, when possible, the KPIs reported in Chapter 8 are calculated also for the reference scenarios, for the years 2030 and 2050.

2030

Focusing on the energy dimension, in 2030 (i.e. at the end of the time horizon for the Italian national energy strategy SEN [1]), a total final consumption (TFC) reduction between 7% and 16% with respect to 2015 is observed in the reference scenarios (as Figure 1 underlines), achieved through a combination of energy efficiency enhancement, commodity shift and technological innovation in all the sectors. Electrification is expected to reach 22-24%, contributing as well to the TFC reduction, since electric equipment is characterized by higher energy efficiency compared to traditional technologies. The TFC trend is also reflected into the reduction of the total primary energy supply, further enhanced by the higher RES penetration in the energy mix, particularly relevant in the power generation mix (the latter ranging between 38% and 55%). The ITELEC2050 scenario is aligned to the studied reference scenarios for almost all KPIs, with a forecasted RES share for 2030 (equal to 59%) slightly higher with respect to the range. This high share of renewables leads to a growth in the national electricity generation capacity, in turn being beneficial also from the point of view of the energy dependency reduction (improving by 8% in 2030).

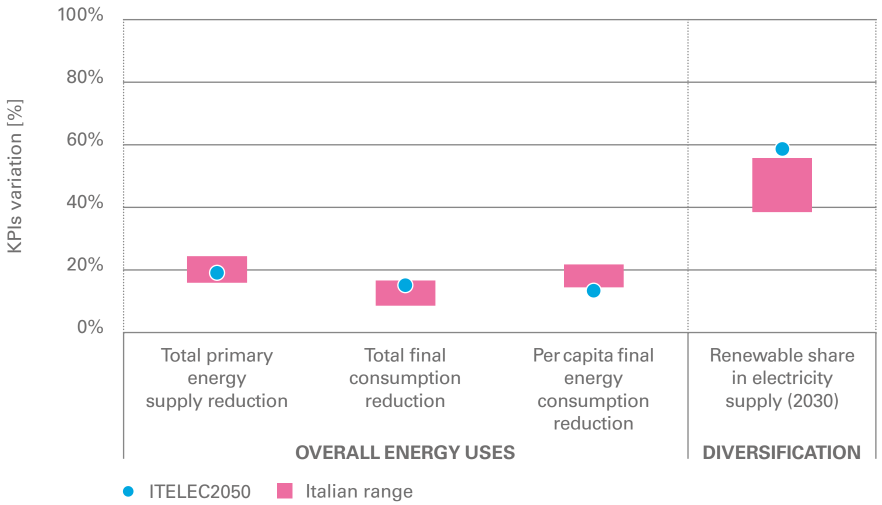

Figure 1
ITELEC2050 vs. other studies at 2030: comparison of energy KPIs.

In 2030, the ITELEC2050 scenario shows a 24% total electrification level. By looking at the sectoral evolution (reported in Figure 2), with respect to the SEN scenario, the electrification appears to be a little faster for industry and transport and slower for residential buildings. The latter in particular accounts for the effect of barriers hindering a quicker penetration of electric technologies, such as high electricity-gas price ratios, limited incentives, tax and levies, low building refurbishment ratios, information asymmetry, reliance to gas supply and equipment for space heating.

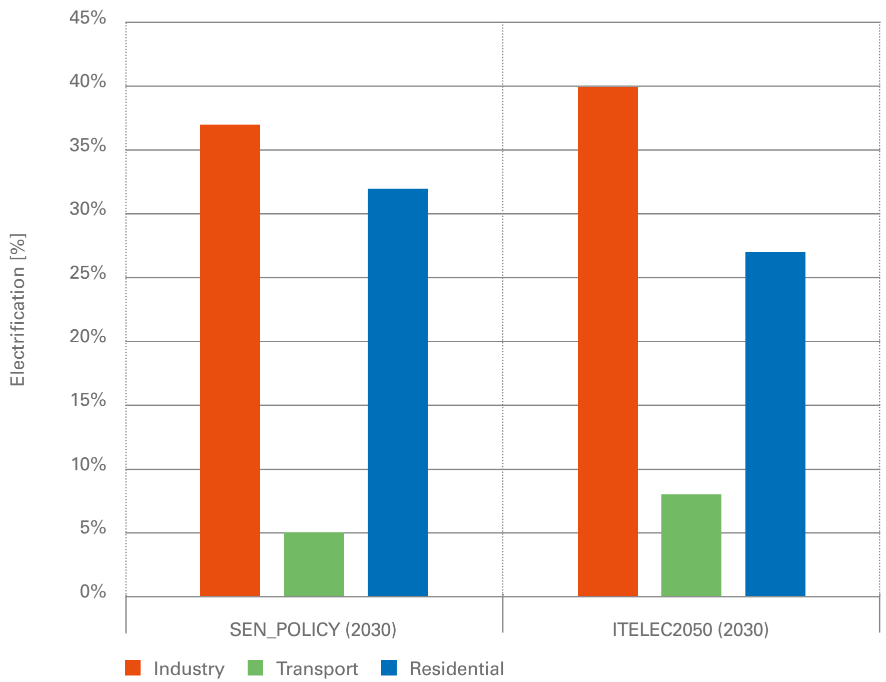

Figure 2
ITELEC2050 vs. SEN at 2030: comparison of the electrification rate by sector[1].

From the economic point of view, the energy intensity (calculated as the ratio between TPES and GDP) is expected to decrease by 40% by 2030, as reported in Figure 3. Moreover, total final consumption intensity reduction is expected to reach a slightly lower level, since final energy consumption variation is lower compared to the TPES one.

1. Note for industry forecasts: SEN scenario is based on the National Energy Balance, which results in a 33.9% electrification in 2015, while ITELEC2050 scenario is based on Eurostat statistics (coherently with other focuses), which results in a 39% electrification in 2015. The discrepancy might depend on different procedures of statistical accounting for energy consumption from renewable energy sources and on the consideration of marine bunker into national consumptions in the National Energy Balance, differently from Eurostat.

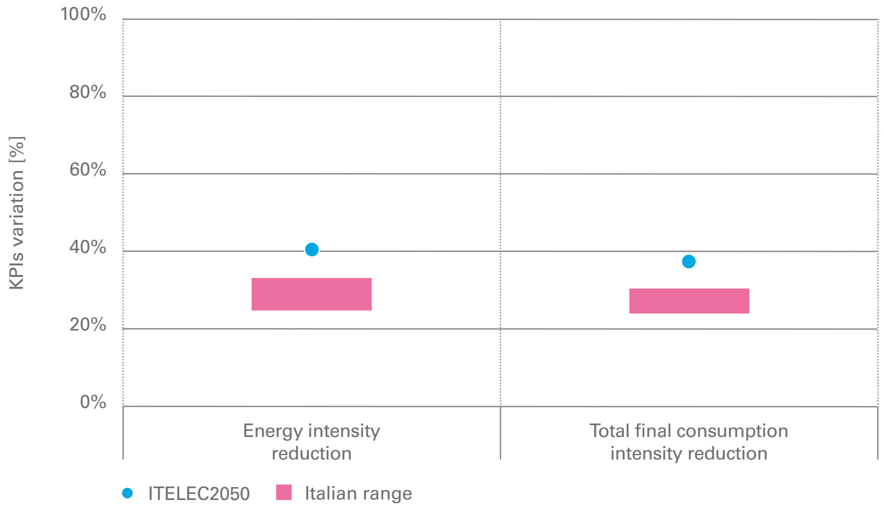

Figure 3
ITELEC2050 vs. other studies at 2030: comparison of the energy intensity.

2050

Also considering 2050, the ITELEC2050 scenario results generally lie within the spectrum of the reference scenarios of the benchmark studies. In particular, Figure 4 represents the comparison in terms of energy KPIs.

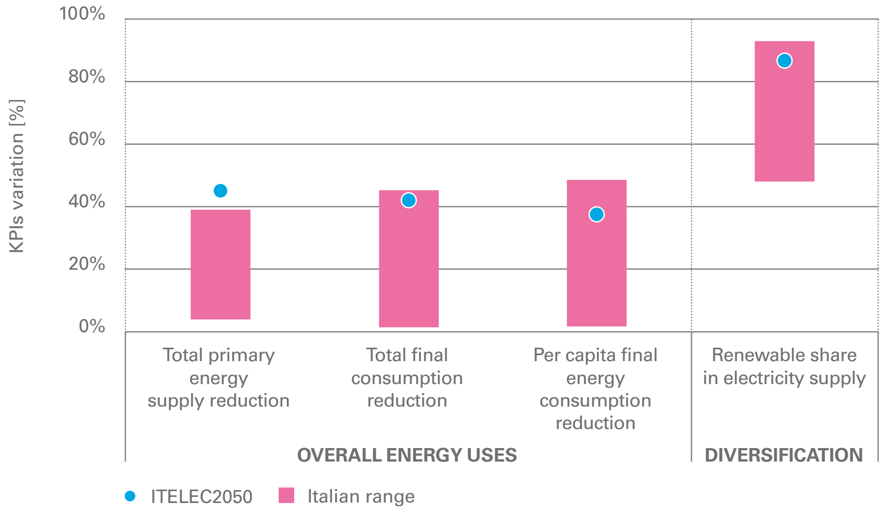

Figure 4
ITELEC2050 vs. other studies at 2050: comparison of energy KPIs.

The Italian reference scenarios define reductions of total final consumptions up to 43% by 2050, due to the accelerated diffusion of high-energy efficient technologies. ITELEC2050 completely lies in this range, forecasting a TFC reduction of 42%, as well as a TPES reduction of 45% by 2050, the latter being slightly higher than that of reference scenarios.

Focusing on electrification, after 2030, transport electrification forecasted by the ITELEC2050 scenario is accelerating, reaching 41% in 2050, i.e. a value slightly higher than the average value emerged from the reference scenarios analysis (see Figure 5). The electrification of residential buildings reaches the highest percentage among the sectors (53%), while the electrification of industry is almost constant in the analysed time horizon, reaching a value equal to 42% in 2050. In the industrial sector electrification is easier in non-energy intensive industries with lower temperature heat demands (especially in terms of equipment costs). This can be beneficial in terms of load management, reducing the stress of the power sector by greater flexibility options. As an effect, even if the higher energy efficiency allows to limit the overall energy demand in the end-use sectors, in 2050 the electricity demand is almost double compared to 2015. Figure 5 shows the electrification levels in 2050 compared to the range of the reference scenarios, confirming the general compliance of the ITELEC2050 scenario with these ones.

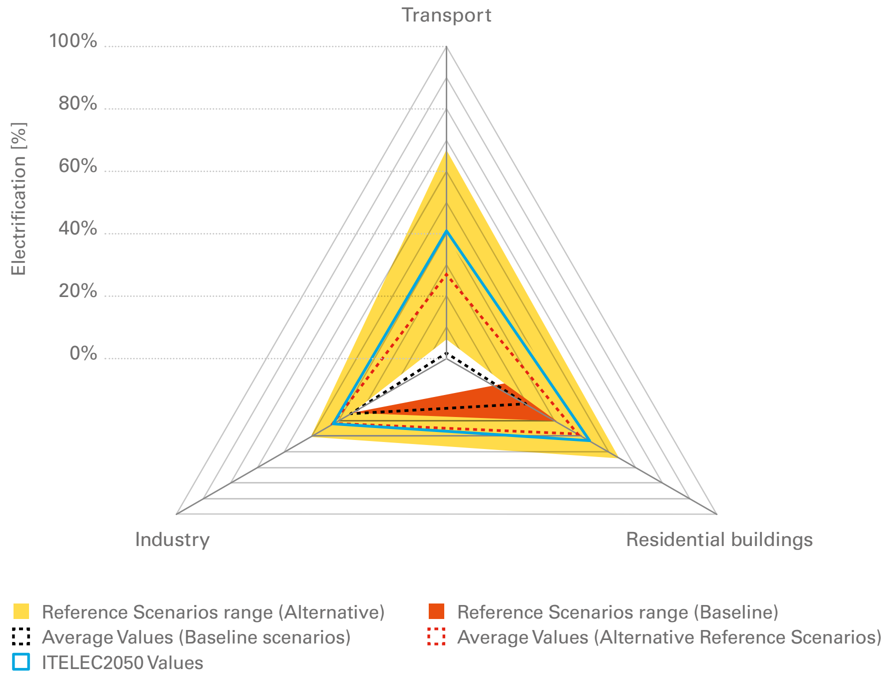

Figure 5
ITELEC2050 vs. other studies at 2050: comparison of the electrification of the analysed end-use sectors.

According to the economic dimension, in the ITELEC2050 view, the energy intensity of GDP decreases by 71% by 2050 compared to 2015 (as reported in Figure 6). This outcome is slightly higher than the expectations from the other national reference scenarios, but in line with the European ones (up to 71%). The energy intensity indicates the decoupling of economic growth from energy consumption, highlighting how the new electricity-based paradigm allows to reduce, through the increase in energy efficiency, the amount of energy required for producing each unit of GDP.

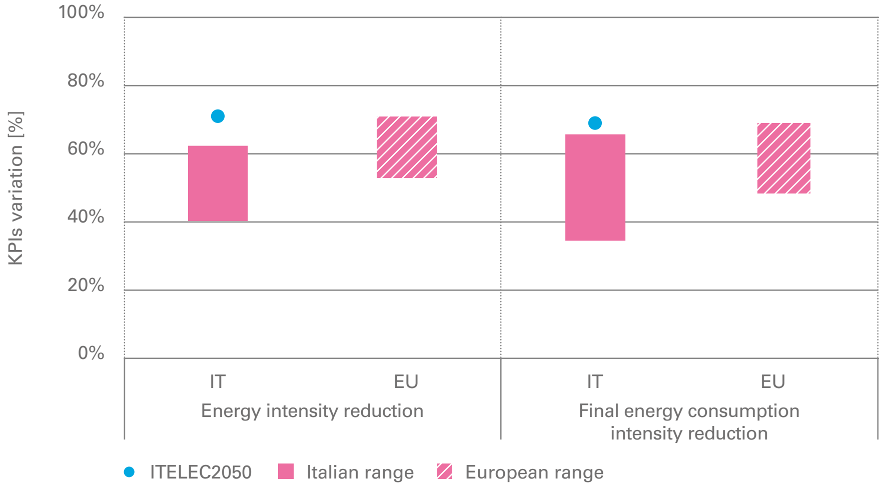

Figure 6
ITELEC2050 vs. other studies at 2050: comparison of the energy intensity indicators.

Furthermore, the energy used, due to the electrification coupled to a power generation increasingly relying on renewables, is expected to be “cleaner” than the current energy mix. For this reason, the economic growth is decoupled also from the CO_2 emissions, as already reported in Chapter 8. This decoupling phenomenon underlines the possible coexistence of economic development and environmental sustainability.

Considering the environmental dimension, the reference scenarios studied suggest that CO_2 emissions need to be dramatically reduced compared to 1990 levels. The ITELEC2050 perspective estimates a 68% reduction by 2050 of the national emissions, with respect to 2015 levels. All end-use sectors contribute to the emission decrease; in particular, residential buildings are characterised by the highest reduction (72%), followed by transport (66%, accelerating after 2030) and industry (65%).

From all the considered reference scenarios, the improvements in decarbonization are related to a significant electrification of end-uses (Figure 7). For instance, in the very aggressive Eurelectric S3 scenario, an almost full decarbonization is reached when electrification levels reach 60%. The ITELEC2050 outcome is not as aggressive, showing for Italy a 74% decarbonization (calculated as the CO_2 emission reduction at the generation side) over the period 2015-2050, with an electrification rate of 46%, which lies between Eurelectric S1 and Eurelectric S2 scenarios. The strong relationship between decarbonization and electrification is also related to the consideration that renewable technologies are relevantly penetrating in the energy mix. In fact, to reach 2050 ambitious targets, renewable energy sources are expected to reach up to 67% of share in primary energy supply in Italy and up to 75% in Europe (historical trends suggest 52% penetration).

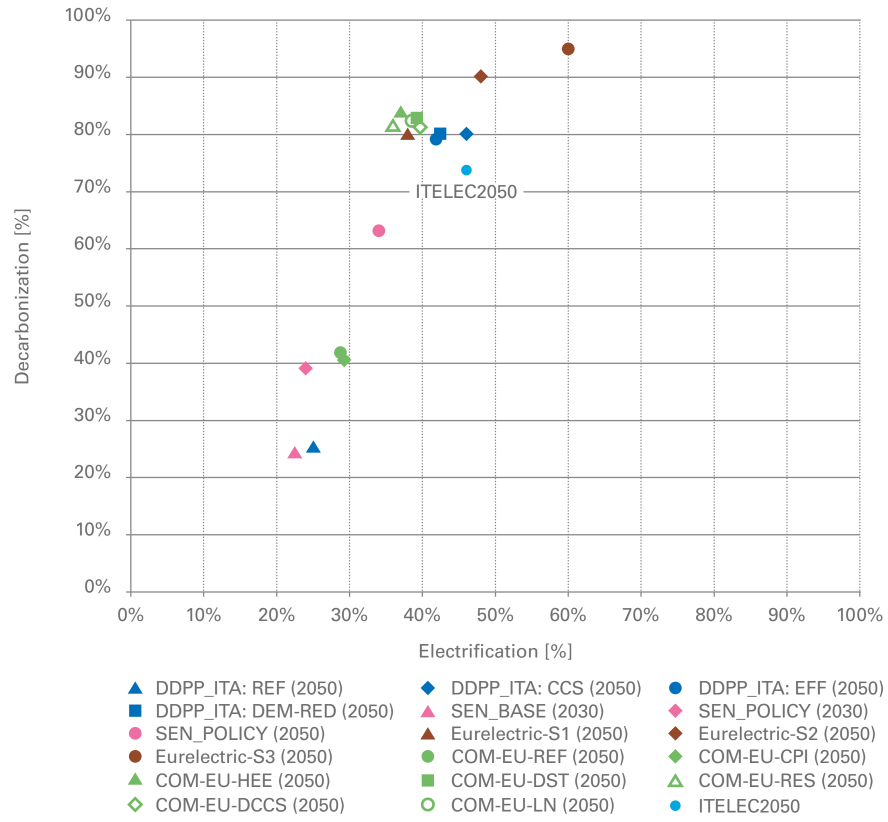

Figure 7
ITELEC2050 vs. other studies at 2050: decarbonization vs. electrification.

Renewables are the largest contributors to the emissions reduction achieved in the power sector. Their share in electricity supply is progressively growing: from 34% in 2015 up to more than 95% in 2050 in the Italian reference scenarios; in 2050, ITELEC2050 scenario foresees instead an 85.6% renewable share in power generation. Moreover, renewables play a key role in the power sector also in terms of diversification of the energy mix and consequently in the reduction of the national energy dependence. In this regard, the analysed reference scenarios aspire to reach a value of energy dependence between 30% and 35% in 2050. The ITELEC2050 is aligned to this vision, reaching a 37% reduction of national energy dependence in 2050, compared to 2015.

Wrapping all up, the ITELEC2050 scenario results are generally in line with the benchmark studies. Figure 8 and Figure 9 summarize some selected energy, environmental and economic KPIs for 2030 and 2050, respectively, calculated based on the system configuration forecasted by the ITELEC2050 scenario (in blue) and compared with the ranges of values obtained from the national and international reference scenarios analysed (yellow areas). The optimistic value for RES penetration in the power mix (85.6%) results in a high reduction of total primary energy supply (-45% with respect to 2015) for the ITELEC2050 scenario. This reduction, coupled with the assumed GDP growth, leads to a decrease in the national final energy intensity of about 73%.

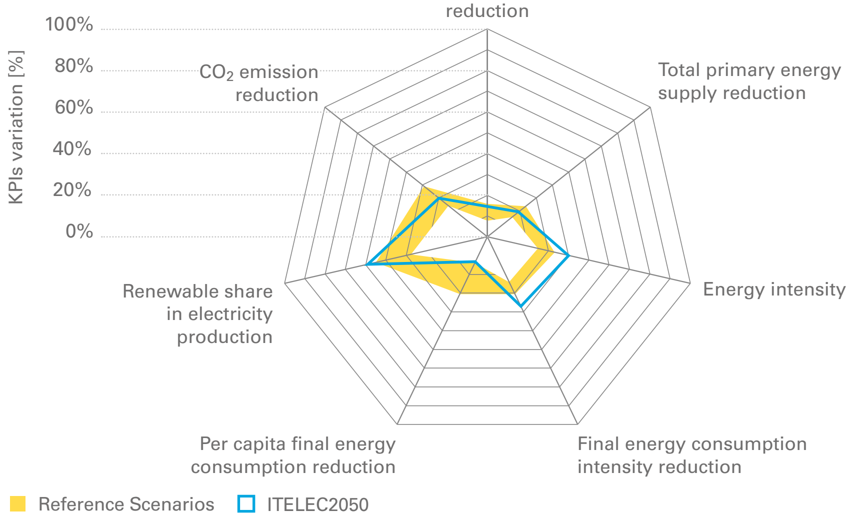

Figure 8
ITELEC2050 vs. other studies in 2030: comparison of energy, economic and environmental KPIs.

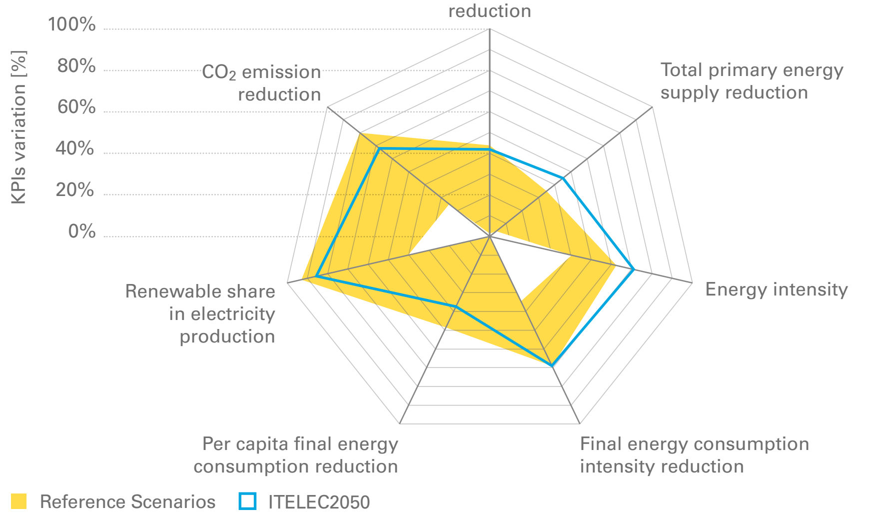

Figure 9
ITELEC2050 vs. other studies in 2050: comparison of energy, economic and environmental KPIs[2].

2. The graph for 2050 is built considering the variations in the period 2015-2050 for the ITELEC2050 scenario and for the reference scenarios that include 2050 results in their analysis. The range of the reference scenarios (yellow) is not directly comparable with the range obtained for 2030, due to the differences in the set of reference scenarios used for the comparison.

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FINAL REMARKS

Carlo Tamburi
Head of Italy
Enel

It is now a shared vision that economic development cannot ignore the principles of environmental and social sustainability.

There is an increasingly urgent need to fight climate change through the decarbonization of our economy. This is a clear objective towards which policy makers and the business world are directing their efforts.

Global, European and National Institutions and industrial players are at the forefront of the transformation of the energy sector from fossil-based to a zero-carbon approach.

These issues have now strategic value in the political agendas of many countries that have signed up to ambitious objectives for the fight against climate change to be pursued through the development of sustainable and innovative tools.

This is the context where the energy transition in our sector is taking place.

We are witnessing at a global level a progressive process of replacing energy production from fossil sources with energy produced from renewable sources, thanks to a new wave of investment based no longer on incentives but on the economic competitiveness of wind and solar energy compared to traditional sources.

Faced with an increasingly clean generation, ***the gradual penetration of electricity into the energy system will allow us not only to decarbonize the historically most polluting sectors of the economy, but also to create value in new ways by offering new services to consumers.***

The electric carrier lends itself to innovative uses in residential construction, industry and transport, bringing numerous benefits in the areas of health, environment and energy efficiency. In order to achieve this outcome, the collaboration between the main actors in the transition is crucial: Institutions, business operators and consumers.

The strategy to tackle climate change, established at ***COP21*** in Paris in 2015, set clear and challenging targets to limit the temperature increase to ***1.5°C*** by providing an update of the 2030 climate protection targets by 2020. Since then, we have witnessed an ever clearer definition of decarbonization objectives in the succession of the various Conferences of the Parties: the COP22 in Marrakech in 2016, the COP23 in Bonn in 2017, and finally - for time being - the COP24 in Katowice in the 2018, which led to the creation of a "Paris Rulebook" which defines the criteria for reporting, monitoring and reviewing the commitments made in 2015.

The global commitments have been reflected in the European context with the development of the "Clean Energy for All European Package", a set of measures aimed at increasing the competitiveness of the European economic system in a view of the energy transition. For the European legislator the 2030 targets are clear and ambitious: a 40% reduction in greenhouse gas emissions (compared to 1990 levels); a 32% share of renewable energy; an improvement of at least 32.5% in ***energy efficiency.***

Italy has responded to the call for the fight against climate change by promptly redefining its energy balance on the basis of global and European decarbonization targets. We are one of the countries most oriented towards the development of a sustainable economy powered by renewable sources. In recent years we have reached about 34% of national electricity production from "green" sources and we aim to reach in 2030 ***a share of renewable energy in the electricity sector of 55.4%***, according to what is established on a preliminary basis by the ***National Integrated Energy Climate Plan (PNIEC)***, the main Italian tool for energy-environmental planning currently being defined. PNIEC sets out objectives and measures to be pursued in order to reach the environmental targets by 2030, setting a target of ***30%*** renewables on all final consumption by 2030 (of which a share of ***21.6%*** in the transport sector compared to 14% in Europe); an improvement in energy efficiency of ***43%*** compared to the Primes 2007 reference scenario[1]; a ***33%*** reduction in

1. *Scenario based on the PRIMES Model, a tool for quantitative analysis tool of the European Union's energy system that simulates energy consumption and the energy supply system.*

greenhouse gas emissions in non-ETS[2] sectors and the phase-out of coal-fired plants by 2025.

The Enel Group is a global leader in the promotion of a sustainable business thanks to a high level of technological diversification and the alignment of the strategic business objectives with environmental targets. Italy is at the heart of the Group's Development Plan, in fact we have planned for the three-year period 2019-2021 an increase in investment over the previous three years to develop projects closely related to the energy transition and the UN Sustainable Development Goals. These projects include: improving the resilience and quality of service of the distribution network; developing renewables, energy efficiency, electric mobility and innovative services to the customer, which plays a central role in our business. Achieving the European target of reducing CO_2 emissions between 80 and 95% by 2050 by focusing on electrification, means ***enabling the electric carrier to new uses strictly connected to the habits of energy end-users***, the main players in a sustainable and inclusive energy transition.

Our Plan for a carbon neutral Italy is based on renewable sources, smart grids, energy storage systems, demand response (mechanisms of aggregation and active management of the demand of commercial and industrial consumers). In this context promoting the use of the electric carrier in the final consumption of the residential, industrial and transport sectors is a priority to generate a virtuous circle that starts from the demand for energy and is reflected in the relative offer, stimulating its production from sources with sustainable environmental impact.

The residential and transport sectors (i.e. efficient air conditioning and water heating systems, public and private electric mobility, maritime transport) have the greatest potential for electrification, estimated to grow from 15% to 53% over the period between 2015 and 2050, while the industrial sector - already highly electrified - has an improvement range that goes from 39% to 42% in the same period. To fully develop these opportunities, it is essential for the Institutions to commit themselves to making the Country System a fertile ground for the growth of investments necessary for economic progress linked to energy efficiency and the reduction of CO_2 emissions.

Institutions play a key role in the energy transition, promoting concrete actions to combat climate change. The new sustainable energy paradigm - based on the strong penetration of the electricity carrier in final consumption - needs to be supported by the streamlining and adaptation of the authorization procedures, in order to optimize the exploitation of the electric commodity by maximizing the production and the diversification of uses, from a timely and accurate planning of infrastructure investments, digitizing the electricity grid and making it intelligent and flexible so as to act as an enabler for new innovative services, new rules and measures to increase the flexibility of the system on both the supply and demand side (such as the acceleration of electric vehicles participation in the dispatching market through the development of the "vehicle to grid", the two-way technology that allows electric vehicles to store and return energy for grid stabilization), and a new enabling framework for the development in the market of new technological solutions and applications.

Therefore, to achieve the challenging decarbonization objectives and at the same time ensuring the reliability of the electricity system, integrated planning of investments in new capacity, new resources (i.e. demand response) and network infrastructure is critical.

Electrification is the fundamental driver to reach the Italian and European decarbonization targets and Enel's projects can contribute to their achievement. In order to fully develop its potential, it is also essential that Institutions, business operators and local communities work together to find the best tools for exploiting the end uses of electricity.

2. Emission Trading System, the European Emissions Trading System to reduce greenhouse gases in energy-intensive sectors, which sets a maximum limit on the overall level of emissions allowed to all the bound subjects, and allows participants to buy and sell on a special market the rights to issue CO_2 quotas according to their needs, within the established limit. It is aimed in particular at industrial plants, the sector of electricity and thermal energy production and air operators.

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