Models and scenarios for energy planning

Analysis of the Italian energy mix evolution under various constraints

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Introduction

In its Sixth assessment report, the Intergovernmental Panel on Climate Change (IPCC) states that the global net anthropogenic Greenhouse Gas (GHG) emissions during the decade between 2010 and 2019 were higher than any previous time in human history [1]. Globally, GHG emissions continued across all sectors and subsectors, and in 2019, 34% of global GHG emissions came from the energy sector, considering also the indirect emissions from energy use [1]. In this situation, some new technologies are developed to reduce the GHG emissions on the energy sector and ensure the supply for all the energy demand. For example, the average annual growth in GHG emissions from energy supply decreased from 2.3% to 1.0% between 2000–2009 and 2010–2019 [1]. This can be explained by improvements in energy efficiency and reduction in the carbon intensity, by switching from coal to gas or increasing the use of renewables.

Moreover, the Ukrainian War have highlighted an already existing relationship between political conflict and energy crisis, energy and fuels are political tools. For example, in this case, one of the possible responses to the crisis is to focus on ensuring the continuity of fuel and energy supplies, as well as the economic and political security of domestic energy resources [2]. So, the concept of energy security focus on the issue of ensuring energy supplies for a given country and can be considered as a part of national security [3]. In more general terms, the energy policy must defend geopolitical, economic, and military interests of the country [2]. The replacement of oil, gas, and coal supplies from Russia in a short time will certainly not only change the geopolitics of energy but will also increase costs for business and individual energy consumers in societies in which raw materials from Russia play a significant role (such as Germany, Poland, or Italy) [2].

On the other hand, numerous contemporary analyses have shown that, in addition to the technological and economic aspects, the social and political dimensions have a significant impact on the development of renewable energy [4]. Moreover, electricity systems powered predominantly by renewables will be increasingly viable over the coming decades, but it will be challenging to supply the entire energy system with renewable energy [1].

In this context, this report will study the case of the Italian energy mix evolution. Italy, as said before, is dependent of fossil fuels from Russia and must comply with the European targets for the GHG emissions. So, using the Tools for Energy Model Optimization and Analysis (TEMOA) we will analyse the possible changes in the energy mix of Italy, regarding penetration of new technologies, as hydrogen, emissions limits and energy security.

Scenario definition

The scenario under investigation mainly relies on the double urgency to end EU's dependence on Russian fossil fuels and tackle the climate crisis. In this paragraph a brief overview of the main documents inspiring our scenario is provided.

On 18th May 2022, the European Commission has presented the 'REPowerEU' Plan, as a response to this unprecedented energy crisis. The plan aims at making Europe independent from Russian fossil fuels well before 2030, through energy savings, diversification of energy supplies, and accelerated roll-out of renewable energy to replace fossil fuels in homes, industry, and power generation [5]. As for energy savings, the Commission proposes to enhance long-term energy efficiency measures, including an increase from 9% to 13% of the binding energy efficiency target under the 'Fit for 55' package of European Green Deal legislation [5]. Since the beginning of the war, European politics have been stressing on the fact that saving energy can help Europe to prepare for the potential challenges of next winter. Indeed, according to the 'EU Save Energy Communication', short-term behavioural changes could cut gas and oil demand by 5%. Regarding the diversification of supplies, the 'EU External Energy Strategy' will facilitate energy diversification and building long-term partnerships with suppliers, including cooperation on hydrogen or other green technologies [5]. Furthermore, for the needed massive speeding-up of renewable energy in power generation, industry, buildings and transport sectors, the Commission proposes to increase the headline 2030 target for renewables from 40% to 45% under the 'Fit for 55' package. Some initiatives recently proposed are doubling solar photovoltaic capacity by 2025 and install 600 GW by 2030, doubling of the rate of deployment of heat pumps, or setting a target of 10 million tonnes of domestic renewable hydrogen production and 10 million tonnes of imports by 2030, to replace natural gas, coal and oil in hard-to-decarbonise industries and transport sectors [5].

In this perspective, the National Energy and Climate Plans (NECPs) have a crucial role in enhancing investor confidence and investment predictability. Moreover, they provide a good framework for planning and encouraging the reduction of use of fossil fuels [6].

As for the Italian framework, the NECP released in 2019 set the goal of 30% of renewable energy sources in energy final consumption share by 2030, a reduction of GHGs emissions with respect to 2005 level for all non ETS sectors of 33% by 2030, and a reduction of primary energy consumption of 43% by 2030. All these targets have been revised upwards to make them compliant with 'Fit for 55' package, which aims at reducing GHGs emissions of 55% with respect to 1990 level by 2030. In the meanwhile, the COVID-19 pandemic has suddenly hit the European economy, making financial support for EU countries urgent. Consequently, the Next Generation EU fund has been instituted, allowing Italy to be supported by € 68.9 billion in grants and €122.6 billion in loans [7] in its recovery phase. 37.5% of the plan will support climate objectives, aiming at promoting a green transition by means of investments in energy efficiency in residential and public buildings, sustainable mobility, development of renewable energies and improvement in waste and water management. All these targets have been defined in the 'National Recovery and Resilience Plan' (NRRP), where a certain relevance has been reserved for hydrogen, with a focus on the supply chain, the technologies to be introduced both in the electricity and end-use sectors.

Assumed policies

First, a business-as-usual (BAU) scenario is considered to investigate the effects of the current policies and to get a benchmark useful for comparison with the impact of new alternative policies. There, the technological shift occurs only whether a new technology is more convenient than the old ones and, moreover, this scenario neither plans to achieve policy targets expected by 2030 nor to provide with information about long-term strategies. Therefore, the model is not compelled to reach NECP targets for renewable energies but, instead, they are set as maximum constraints in terms of capacity (see variables *MinCapacity/MaxCapacity* for technologies or *MinGenGroupTarget/MaxGenGroupLimit* for technology groups). Regarding demand side, the drivers in the industrial sector have been adjusted, considering the effects due to the pandemic. As for GHGs emissions, no constraints in terms of reductions are applied, and they are left free to evolve.

The scenario developed in this work, instead, reaches the NECP targets for renewable energies and further increases them, in compliance with more recent and ambitious strategies. In fact, according to the European Commission, in Italy solar power is going to become the main source of renewable electricity, reaching 52 GW of installed capacity by 2030 [8], while wind power capacity will be roughly doubled by 2030 compared to 2017, reaching 19.3 GW, of which 0.9 GW offshore [8]. According to SolarPowerEurope, for the EU to remain on track to deliver on a 1.5 °C Paris Agreement scenario, ambition on renewable energy deployment must be raised [9] and Italy should raise its target for solar technologies up to 71 GW by 2030. Although we strongly agree with this perspective, in our opinion this target may not be likely to be reached in the short run as it is just a recommendation, but we have set it as a value to be reached by 2050. In this perspective, innovative energy storage solutions will play an important role in ensuring the integration of renewable energy sources into the grid [10]. Therefore, the introduction of new storage technology within the market is modelled, including technologies such as Li-ion batteries, lead acid batteries and compressed air energy storage (CAES). The parameters involved for this purpose will be widely discussed in the next chapter.

As stated previously, the latest Italian government plans include strategies for hydrogen introduction within the energy production, discussed in [11]. The goal is to install 5 GW of electrolysers by 2030 to cover the increasing demand of hydrogen in transport and industry sector, combined with the possibility to blend it with natural gas within the national grid. This great ambition has given to us the inspiration to develop a scenario in which hydrogen technologies are introduced in the market starting from 2022 and the curiosity to investigate their impact in the energy mix both in short and long term. It is a breakthrough commodity, in fact, according to 'RePowerEU', renewable hydrogen can be a strong ally in helping Europe to get rid of Russian natural gas, allowing to save an equivalent of 27 bcm by 2030 [12]. Several hydrogen technologies are going to be introduced in the database, focusing on those involved in power sector (e.g., fuel cells, electrolysers, chemical looping-based technologies, compressed hydrogen storages). Regarding the end-use sectors, as reported in [11], for the next decade, the government aims at introducing hydrogen in road transport, especially in medium and long trucks, in railway transport and in industrial sector, focusing on chemistry and iron and steel. Due to the lack of data, we decided to characterize only long trucks and on introduction of hydrogen in iron and steel sector, where it can substitute natural gas in the production of DRI (Direct Reduced Iron). For what concerns hydrogen blending in the natural gas grid, it is assumed that the maximum percentage of hydrogen allowed will be 5% by 2030.

Technical constraints

All the targets previously stated have been applied to group of technologies instead of a single technology to let the optimization process free to choose the most convenient one. This procedure has been applied for several groups: solar technologies, wind onshore, wind offshore and electrolysers. Indeed, by means of *MinGenGroupTarget* parameter, the targets have been set as minimum threshold to be reached by the group providing values in different years useful for the successive interpolation performed in the pre-processing phase by database_preprocessing.py script itself. For the electrolysers' group, the values are set not only for years of interest such as 2030 or 2050, but also for other milestone years, with a sort of calibration for future years aiming at avoiding too sudden and unrealistic changes in the first future years of our scenario. For instance, since the present installed capacity is 0 GW, it would be very unfeasible to set and reach a target of 3 GW by 2022.

In particular, even if the targets should be expressed in terms of installed capacity, in order to avoid that the model decides to install these technologies whenever they are convenient, but it does not use it at all in the future, the following constraints have been set for activity. The conversion from capacity to activity has been performed considering the capacity factor of the technology under investigation according to the relationship:

$$CF = \frac{Activity\ [PJ] \cdot \frac{1}{3600}\left[\frac{h}{s}\right] \cdot 10^6 \left[\frac{GJ}{PJ}\right]}{Capacity\ [GW] \cdot 8760\ h}$$

- For solar group (“ELC_SOL_GRP”) an average value for CF is assumed equal to 16%, which is an average value of the *CapacityFactorTech* values of a solar technology already present in the TEMOA-Italy database
- For wind onshore group (“ELC_WIN_ON_GRP”) an average value for CF is assumed equal to 32.5% [13], while for wind offshore group (“ELC_WIN_OFF_GRP”) CF is 45% [13]
- For electrolysers group (“ELC_ELK_GRP”) an average value for CF is assumed equal to 98% as it will be discussed in the next chapter

The following table resumes the values assigned for each group. For wind offshore technologies the technical constraints already present in TEMOA-Italy database and expressed using *MaxActivity* parameter were removed. However, to be sure that the optimization process will not install a capacity higher than the one allowed in compliance with environmental limits, specifying a value for *MaxGenGroupLimit* parameter around 14 PJ. As for electrolysers group, the values set for 2022 and 2025 correspond roughly to 100 MW and 1 GW which seemed for us to be consistent.

Group	2022	2025	2030	2050
ELC_SOL_GRP			262.2	358.0
ELC_WIN_ON			170.0	
ELC_WIN_OFF			12.8	
ELC_ELK_GRP	3.1	31	154.4	154.4

Table 1: Values for MinGenGroupTarget parameter expressed in PJ

For what concerns hydrogen blending, its modelling will be deeply analysed later since it has involved several parameters, groups and fuel technologies that need an accurate description. All the other technical constraints already present in TEMOA-Italy database in terms of *MinCapacity/MaxCapacity* or *MinGenGroupTarget/MaxGenGroupLimit* have not been modified.

Emission limits

According to the Paris Agreement, Italy must try to limit the global warming to 2°C or 1.5°C. This cannot be achieved without rapid and deep reductions in energy system CO_2 and GHG emissions, over the next years, as reduction of fossil fuel consumption, increase of the production from low- and zero- carbon energy sources, and increase use of electricity and alternative energy carriers. In the Sixth assessment report, the IPCC purposes some scenarios. In scenarios likely limiting warming to 1.5°C with no or limited overshoot (likely below 2°C), net energy system CO_2 emissions fall by 87% to 97%% (60% to 79%) in 2050. In 2030, in scenarios limiting warming to 1.5°C with no or limited 18 overshoot, net CO_2 and GHG emissions fall by 35-51% and 38-52% respectively. In scenarios limiting warming to 1.5°C with no or limited overshoot (likely below 2°C), net electricity sector CO_2 emissions reach zero globally between 2045 and 2055 (2050 and 2080) [1]. In the same report, the IPCC states that if investments in coal and other fossil infrastructure continue, energy systems will be locked-in to higher emissions, making it harder to limit warming to 2°C or 1.5°C [1].

Based on these scenarios, the European Union has made some packages to control the emissions in the Member States. The 2020 package (set in 2007, enacted in 2009) imposes a 20% of EU energy from renewable, a 20% improvement in energy efficiency and no cut in GHG emissions (from 1990 levels). These targets vary according to national wealth. EU member countries have also taken on binding national targets for raising the share of renewable energy in their energy consumption by 2020 under the Renewable Energy Directive. These targets also vary, to reflect countries' different starting points for renewable energy production and their ability to increase it [14]. The 2030 package (period from 2021 to 2030) fix the targets of at least 40% cuts in GHG emissions (from 1990 levels). All sectors will contribute to the achievement of the 40% target by both reducing emissions and increasing removals [15]. In the 2050 package, the EU aims to be climate-neutral by 2050 – an economy with net-zero GHG emissions. EU Member States are required to develop national long-term strategies on how they plan to achieve the GHG emissions reductions needed to meet their commitments under the Paris Agreement and EU objectives [16]. The European Union also created the European Green Deal to reach the goal of no net emissions of GHG by 2050, with an economic growth decoupled from resource use and no person or place left behind [17].

Globally, Italy follows the European targets (climate neutrality by 2050), and in most of the cases, is above them. Italy generates 11.4 % of the EU's total GHG emissions and has reduced emissions at a faster pace than the EU average since 2005 [18]. Italy reduced its emissions by 13 % by 2020 relative to 2005 and achieved an 18 % share of renewable energy sources (RES) in 2019 [19]. The country expects to reach the 2030 target of 33 % by focusing on wind and solar power, tripling its production of solar energy and double its production of energy from wind. The phasing out of coal in electricity production will be a main driver behind this development, with projections of 55 % of final electricity consumption to come from RES by 2030 [20]. Its Long-Term Strategy (LTS) is shared between two scenarios: the "Reference Scenario" 2031–2050 which extends the Integrated National Energy and Climate Plan (NECP) up to 2050 and the "Decarbonisation Scenario" 2031–2050 achieving net-zero emissions [21]. Considering that in our model we do not include any Carbon Capture, Utilization and

Storage (CCUS) technologies which can represent a huge artificial sink for CO_2 emissions, the goal of net zero emissions by 2050 is not likely to be reached in the scenario under investigation, in the "Decarbonisation Scenario". So, we will just focus on a reduction of 33% in the GHG emissions in 2030.

In particular, for this purpose, the *EmissionLimit* parameter has been involved. For 2030, we forced the code to stay within 295 Mt of CO_2 emissions, corresponding to a reduction of 33% with respect to the 1990 value, equal to 440 Mt [19]. For 2050, we set an initial value of 100 Mt to be reached (implying roughly a reduction of 80% of CO_2 emissions with respect to 1990 level) but, as it will be discussed later, this solution did not reveal to be feasible under the technology equipment given. Another remark regards *EmissionLimit* parameter: since in pre-processing phase no linear interpolation is performed for it, we set an intermediate and reliable value also for the other milestone year in between that is 2040, equal to 242 Mt, corresponding to a reduction of 45% with respect to 1990 level.

Reference energy system

Description of the TEMOA-Italy database

TEMOA is a technology explicit energy system optimization model (ESOM). It is an algebraic network of linked processes – where each process is defined by a set of engineering characteristics (e.g., capital cost, efficiency, capacity factor, emission rates) – that transform raw energy sources into end-use demands. The model objective function minimizes the present-value cost of energy supply by optimizing installed capacity and its utilization over time [22].

Starting from the base year – which is a past year whose data about supply and demand sides are already known – ESOMs provide the optimal evolution of the reference energy system (RES) of a country along a certain time horizon, covering both past and future years. Indeed, for base year modelling, statistics data are needed to describe base year technologies from the supply side to the demand one, passing through transformation technologies. Therefore, building a RES means building a database. After the base year, new technologies are involved in the model to substitute the retired capacity of existing technologies or to introduce more efficient and innovative technologies not available in the base year. Regarding past RES evolution, a calibration is performed to make it follow the historical evolution while, for future RES evolution, a realistic scenario analysis is performed.

As for the TEMOA-Italy model, the time horizon covers the period from 2006 (the base year) to 2050 and the RES is characterized as it follows:

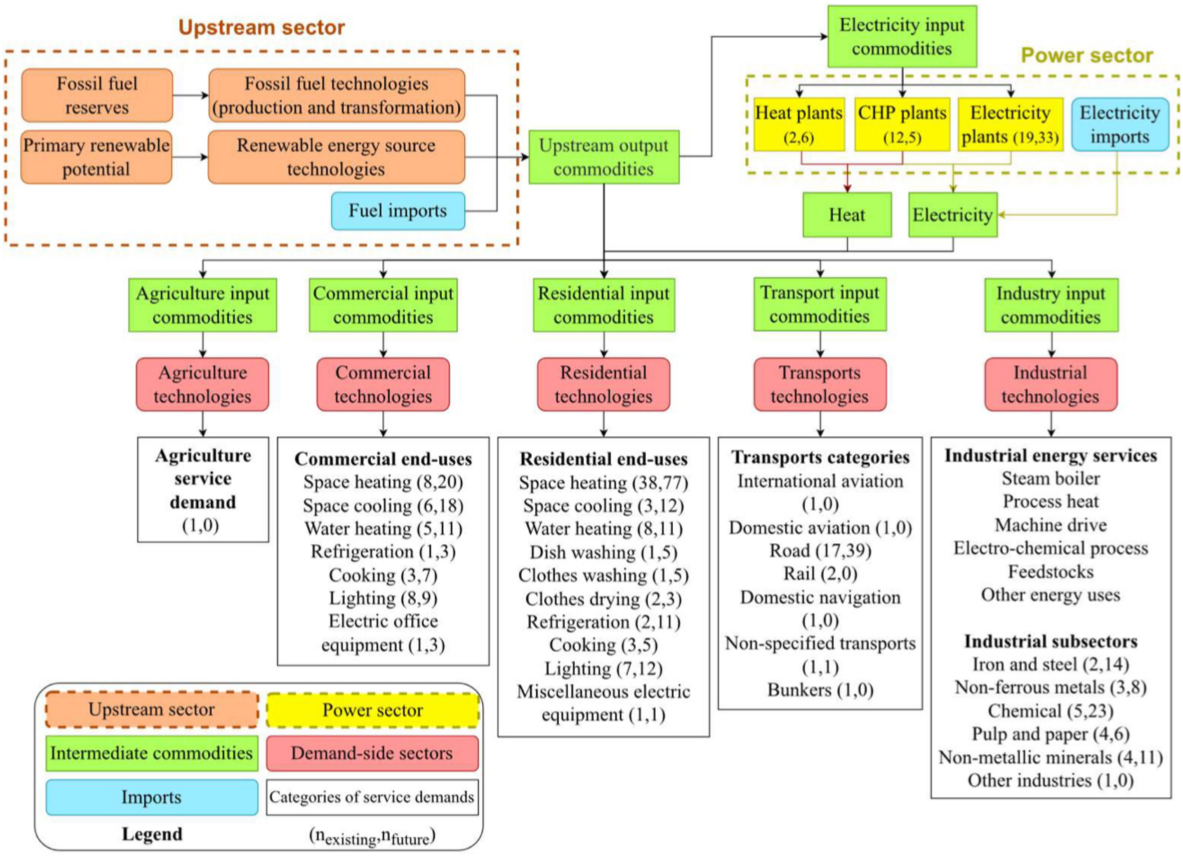

Figure 1. Qualitative scheme of supply-side and demand-side sectors in TEMOA-Italy

Where the supply-side sectors are:

• The *upstream sector*: it is the starting point of the commodity flows within a RES. It includes extraction of raw fossil fuels (e.g., oil reservoirs), fuels primary production (e.g., natural gas refining), fuels secondary transformation (e.g., oil refineries), natural potential of renewable energy sources (e.g., solar energy potential, biogas production). Import commodities are included too, but those exported not. Commercial exchanges with other regions are modelled assigning prices to the commodities produced by the supply sector. Import is modelled with processes with only an actual output but, since TEMOA always needs an input, a fictitious input commodity is considered, called 'ethos'. The same procedure is applied for extraction of raw fossil fuels and for natural potential of renewable energy sources. The main parameters used are extraction costs, lower and upper boundaries to the extraction, production and exploitation of renewable resources, lifetime, fixed and variable operation and maintenance (O&M) costs. The upstream sector evolution is modelled only by using the base year technologies.

- The *power sector*: it includes centralized and decentralized production of heat and electricity. Base year and new technologies are described by means of different techno-economic parameters and constraints, as it happens in other sectors. Base year technologies are mainly characterised in terms of base year installed capacity, minimum and maximum activity after the base year, fixed and variable O&M, while for new technologies data are provided for minimum and maximum capacity installation, lifetime, investment cost and discount rate. Already planned technologies are included, such as CHP plants and wind farms. At this stage, storages, hydrogen technologies and carbon capture, utilization, and storage technologies (CCUS) have not been included yet.

The link between the supply-side and the demand one is modelled through the so-called *fuel technologies* (e.g., the green boxes in Figure 1). They allow the model to track separately the consumption of commodities within the different consumption sectors, since there is one fuel technology for each consumption sector. They receive as input the supply-side commodity and as output they provide sectorial specific commodity. For instance, the fuel technology for natural gas in residential sector (called in TEMOA-Italy "RES_FT_NGA_E" or "RES_FT_NGA_N" whether it is an existing or new technology) receives natural gas from supply-side ("UPS_NGA") and provide as output natural gas for residential sector ("RES_NGA"). They model the average transmission and distribution networks and, as it will be discussed later, they can be very useful in representing the mixing between fuels.

Regarding the demand-side sectors, except for the agricultural one, the other sectors are well characterized in terms of existing, planned, and new technologies involved that use energy to produce final output (e.g., kilometres run in case of transport vehicles, tons of materials produced in case of industries, square meters of house heated or cooled in case of space heating or cooling systems). For all these technologies, techno-economic parameters such as efficiency, base year installed capacity, minimum and maximum activity after the base year, fixed and variable O&M, minimum and maximum capacity installation, lifetime, investment cost and discount rate are provided as previously stated for power sector. Industry is the sector modelled in more detail, since it is divided into sub-sectors (e.g., iron and steel, non-ferrous metals, chemicals, etc.) and it also includes energy services (e.g., steam, machine drive, process heat, etc.) which are inputs for the end-use technologies specific to the sub-sectors and outputs from processes consuming energy. However, not all the final consumptions are assigned to specific sectors and sub-sectors. For these cases, the energy balance statistics for Italy have been aggregated into industry non-specified final energy consumption and other non-energy use.

Implementation of new technologies

As said our model will be strongly focused on the power sector, especially on the electricity production. A major part of implemented technologies deals with hydrogen, in form of new energy vector and also with some specific applications such as the blending in the natural gas network. The other type of technologies that have been implemented are the power storage technologies.

For the technical parameters of the various implemented technologies, due to the lack of specific information about the time evolution of these parameters, they have been assumed constant during the whole simulation period.

For the economical parameters, instead, investment and O&M cost trends are characterized providing values for 2022, 2030 and 2050 and, in absence of specific data, constant trends have been assumed also for the costs. Another assumption done deals with the operational cost related to the activity of the different technologies: in fact, due to the lack of specific knowledge in the field, they have been neglected.

It must be considered that all these simplifications can strongly affect the achieved results. In fact, as it is well known, under the perfect-foresight approach, the significative lack of data may mislead the modeller, who is asked to have a complete knowledge on the whole-time horizon. However, attention has been paid while collecting the following data from literature and other authoritative sources, such as IEA (International Energy Agency) or IRENA (International Renewable Energy Agency).

Hydrogen production technologies

Among all the different hydrogen production technologies, only two main categories have been characterised since they are considered as the most promising to entering the market in the next years.

All these technologies have been set in the power sector and the produced commodity, the Hydrogen, is considered in terms of energy: in all the transformations its lower heating value assumed is equal to 33.33 KWh/Kg.

Methane reforming

The actual worldwide hydrogen consumption is mainly covered by means of the so called "Grey hydrogen", that is the hydrogen obtained from methane with a reforming reaction. Nowadays, this process is responsible for more than 70% of the total produced hydrogen.

The basic concept of the process consists of the chemical reforming of the methane producing a mixture of carbon monoxide and hydrogen; this process is then followed by the water gas shift that produces hydrogen from the carbon monoxide making it react with water vapour, that as by-product produces the carbon dioxide.

In order to implement this technology in the database the technical data reported in Table 1 have been used.

Efficiency	Emission Factor	Lifetime	Capacity factor
70% [23]	8,9 [24]	25 [25]	80%

Table 2. Technical data of Grey Hydrogen technology

It is important to specify that for this technology, and also for all the other with one exception, the capacity factor has been defined exactly as *CapacityFactor* within the code assuming it constant for the whole simulation. Always dealing with the capacity factor of Grey Hydrogen, due to the lack of data found, the value has been assumed similar to other chemical industries.

The emission factor in this case accounts for the CO_2 emitted in the process while the efficiency takes into account the losses during the whole process while transforming the methane, that is not modelled as a proper commodity, is used the natural gas already implemented, in hydrogen.

The other type of parameter that is needed for the code are the economic parameters to find out the optimal configuration that minimizes the total cost of the Reference Energy System. For this technology, data are provided about the Investment cost, assumed as constantly equal to $910\ M€/GW$ [26], and the fixed operation and maintenance costs, assumed constant too and equal to $42{,}8\ M€/GW$[26], equivalent to 5% of the investment cost.

Electrolysers

The second type of modelled production of hydrogen is the so-called green hydrogen, the hydrogen obtained from the exploitation of renewable energy sources, using electrolysers.

The technology basically works making a split of the water molecule, the Redox reaction is performed keeping separated the two half reactions and, in this way, it is possible to harvest the hydrogen. The process is electrically driven, the cost of the electricity is a key element, and it has been assumed to use only electricity produced by renewables. Therefore, no emission factors have been specified for this technology.

In order to better represent the market and to allow the model to make its own choices, three different technologies producing green hydrogen have been included: Proton Exchange Membrane Electrolysers (PEMEC), Alkaline Electrolysers (ALK), and the Solid Oxide Electrolysers (SOEC). To be precise there are some differences among these technologies, but the basic working principle is the one reported.

For all the three types of technologies have been made the same characterization that is reported in Table 3.

	Efficiency	Lifetime [y]	Capacity factor
PEMEC	50,1% [27]	30 (9) [28]	98%
ALK	52,1% [27]	30 (7) [28]	98%
SOEC	74,1% [27]	30 (3) [28]	98%

Table 3. Technical parameters of electrolysers

The efficiency of the electrolysers has been computed making the ratio between the lower heating value of the hydrogen and the specific consumption of electrolysers reported in [27].

From [27] has been also computed the lifetime reported in brackets, it represents the average life of the electrolytic cell, while the other value of lifetime is the one of the total plants. It has been assumed that the change of the cell stack does not represent the end of life of the plant but the additional cost to change the stack has been computed in form of O&M cost, with the 30% of initial CAPEX considered as the expenditure needed to substitute the stack. The value of 30% to represent stack substitution is an assumption based on the modelers experience in the field.

In order to account this cost in a simple way, the choice has been to take the value equal to the 30% of the CAPEX and then split it over the year, for the SOEC the additional yearly OPEX is 10% of the CAPEX while for the PEMEC is equal to 3,33%.

Concerning capacity factors, the value has been assumed on the basis of the modelers experience since the electrolysers are machines able to work almost constantly over the year, their high-cost forces the use of them, so it has been supposed to shut them down only when it is strictly needed.

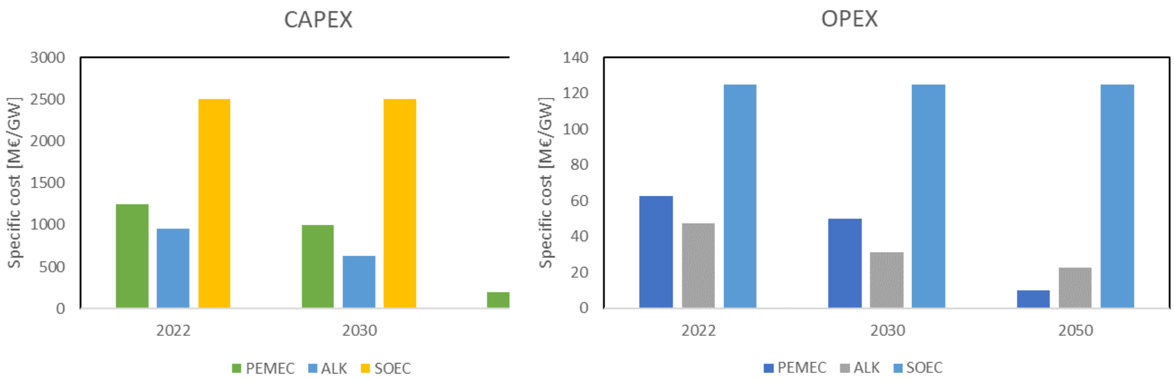

Figure 2. Electrolysers investment, left, and operational and maintenance, right, cost trend

The economic parameters needed for these technologies are the same of the grey hydrogen, we have the investment cost, reported as CAPEX, and the operational and maintenance cost, OPEX.

The data used for the CAPEX values are taken from [30], in which are underlined the trends for ALK and PEMEC, for the SOEC instead the value is assumed constant, while the OPEX is assumed as a fixed percentage of CAPEX, equal to 5%. This value is taken as equal to the one of the fuel cells; this assumption is since the fuel cells and the electrolysers shares the same electrolytic cell.

Fuel cells

The fuel cell technology is the most efficient way to convert hydrogen in electricity. The basic process is exactly the one of the electrolysis reversed, where we have again a separated half reactions of the hydrogen oxidation that allow the harvesting of electrons in this case.

This is the only modelled way of transformation of hydrogen in electricity, even if there are other possible technologies, but has been chosen to represent only the most efficient and cleaner one. Also, in this case have been reported three different type of technologies that are very similar whit respect to the ones of electrolysers: Proton Exchange Membrane Fuel Cell, PEMFC, Molten Carbonate Fuel Cell, MCFC, and Solid Oxide Fuel Cell, SOFC; there are some small differences in the operation of these technologies but have been not considered.

Dealing with the technical parameters needed, they are almost the same as the ones of previous technologies, with added the thermal efficiency since this kind of technology can produce both electricity and heat.

	Electrical Efficiency	Thermal Efficiency	Lifetime [y]	Capacity factor
SOFC	55,0% [32]	30,0%	20 (3) [31]	98%
MCFC	47,0% [32]	23,0%	20 (7) [31]	98%
PEMFC	42,0% [33]	25,0% [33]	20 (9) [31]	98%

Table 4. Technical parameters used for fuel cell technologies

The assumptions behind the values are the same done for the electrolysers, especially the ones regarding the lifetime, in this case the plant lifetime is assumed equal to 20 years in accordance with the modelers experience, and the capacity factor that follows the exact equal reasoning.

The specific values of the lifetime of the single cells are taken from [31] in which are provided some ranges for the different applications, the values are compliant with them and are based on the modelers' knowledge in the field.

The efficiencies have been kept constant over the years. It is important to underline that the thermal efficiency of SOFC and MCFC has been derived from the knowledge of a total efficiency of more than 80% for SOFC and about 70% for MCFC. Since there are no papers providing effective and proved evidence of this, it has been done as an assumption.

From the efficiencies defined in this way as been derived the parameter of *TechOutputSplit* that forces the code to produce both the outputs of the technology, simply representing the relative weight of one efficiency with respect to the total one.

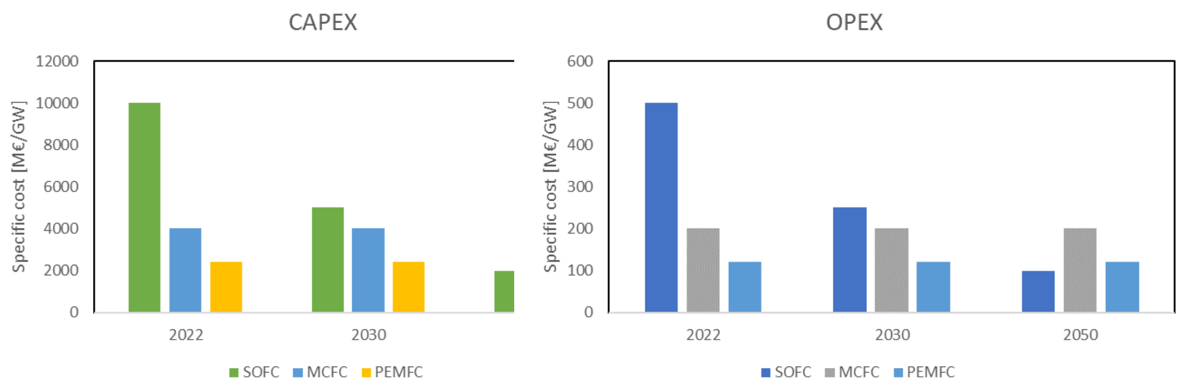

Figure 3. Fuel cells investment, left, and O&M, right, cost trend

The Economic parameters for these technologies are the same of the electrolysers and are reported in the figure behind.

The cost of the CAPEX of SOFC is taken from [34], in which it is underlined the trend over the years, while for MCFC have been used [32] and for PEMFC [33]; since these documents does not report any trend, these costs are assumed constant.

For the evaluation of OPEX cost, it has been assumed equal to 5% of the CAPEX, according to [32], and have been added the cost of the fuel cells stack replacement every x year, where x is the number in brackets reported in Table 4.

Chemical looping

This is one of the more interesting technologies in the energy field that can be used to produce electricity, as it uses the solar heat to drive a closed cycle of redox reactions producing hydrogen and then, electricity.

The technology is quite complex since requires many different steps and has some positive applications if is coupled with a decarbonization cycle that can be used to transform CO_2 in a syngas, at inlet we will have water and carbon dioxide obtaining a mixture of hydrogen and carbon monoxide with oxygen as a by-product.

This process is highly innovative, consequently reliable data are very few, due to this reason has been chosen to do not provide details about the most innovative one but it has been chosen to model the cycle avoiding possible more efficient but complex solutions.

This is the only technology characterized by a not constant Capacity factor, but it is used the variable *CapacityFactorTech* to differentiate the availability of this technology according to the seasonality, since the sun source requires this. The values chosen has been assumed as equal to the ones of an already implemented sun-fed technology.

The other technical parameters are the Efficiency, equal to 25,5% [34], that comprehends all the passages needed to transform the entering sun energy in electricity, neglecting all the intermediate passages, and the Lifetime, equal to 30 years [35].

Concerning economic parameters have been assumed constant values over the years since no other evidence where provided, in detail the values implemented in the code are:

- Investment cost equal to $12.136\ M€/GW$ [35]
- Fixed operation and maintenance cost equal to 10% of the CAPEX [35]

Electricity storage technologies

The second big family of implemented technologies is the one of electricity storage. The electricity storage is one of the key elements in order to allow a bigger penetration of renewables in the energy market, this kind of technologies is characterized a big variability over the seasons and time of the day, only with suitable storage technologies it can be possible to maintain a sufficient level of reliability.

Following this reasoning has been chosen to try to implement this new type of technologies in order to check if the model uses them coupled with a larger number of installed renewables. This is not a trivial issue since this kind of technology where not yet implemented and also, they are mainly seen as a cost by the model since they receive and deliver electricity with an efficiency lower than unity.

Batteries

This is the most common and diffused type of electricity storage technology: in them the electricity is stored in form of chemical potential energy, in different ways according to the type of battery is being analysed and can release this energy in a fast way when needed.

The main issue about this type of well-developed technology is the scalability of the technology, in particular for small sizes the costs are more affordable with respect to bigger ones. This problem is being overcome and the technology is wide spreading also for big plants.

The batteries that can be used coupled with the electricity production are forced to be rechargeable batteries, since they have the need of being charged and discharged multiple times, and the choice has been to go in details about two types of batteries only: Lithium-Ion batteries (LION), and the Lead-Acid batteries (LEA).

Concerning the technical parameters needed for this different type of technology comprehends a parameter not used for the other technologies that is the Storage duration, accounting the necessaire time to totally discharge the energy stored, on the other hand is not required to specify any Capacity factor. The technical parameters implemented are reported in the Table 5.

	Efficiency	Storage duration [h]	Lifetime [y]
LION	87% [36]	1	13 [36]
LEA	76% [36]	1	9 [36]

Table 5. Batteries technical parameters

The Lifetime has been computed on the basis of the number of cycles that can be performed by the battery, relating this to the energy averagely stored in it and with the nominal charging and discharging powers. The Efficiency of storage technologies is related to the amount of electricity that are able to provide back over the total energy stored at the beginning.

For what concerns the Storage duration instead, it has been assumed on the basis of the modelers knowledge, considering that normally an energy applicable battery has a charge and discharge rate close to a unitary value.

The economic parameters needed are exactly the same as the ones used for the other type of technologies, the used projections of the investment cost are reported in the figure below.

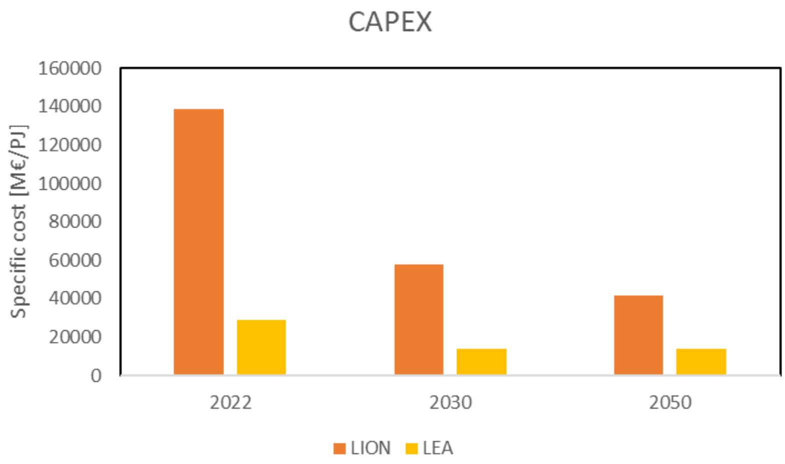

Figure 4. Batteries capital expenditure

The costs are taken from [37] for what concerns the lithium-ion batteries while for the lead acid ones instead has been used [38]; in both cases the reported data has been changed in order to be compliant with the unit of measurement used in the code.

As for the OPEX costs, in this case has been chosen to neglect the one of the LION batteries since according to [39] since are of many orders of magnitude lower than the others, for the LEA instead has been used the value of $2361{,}1$ $[M€/PJ]$ [38]; this value as been assumed constant over the years since the LEA batteries are a mature technology.

Pumped Hydro Energy Storage

This technology is the most diffused for the storage of large quantities of electricity. It consists of two basins linked together by a water duct able to let it flow in both directions. During the electricity excesses, the charging phase consists in the pumping of the water to the upper reservoir and then it is let flow down in the lower reservoir and pass through a turbine to produce electricity when needed.

This technology is highly site dependant and can be installed only in a limited amount, and this aspect would have been considered when dealing with possible constraints only if the first simulations had shown a too large use of this technology, actually this has not happened.

The technical parameters needed for the characterization are the same as the ones needed by the batteries; they are reported in the table below.

Efficiency	Storage duration [h]	Lifetime [y]
80% [40]	8	75 [40]

Table 6. Pumped hydro technology technical parameters

Also, in this case the storage duration values have been assumed based on the modeller's knowledge, as it has been done for batteries.

The costs of this type of technology have been taken from [41], that underlines values of 22.222 $M€/PJ$ for the CAPEX and an OPEX equal to 10% of this value. Since this technology is a very mature one, the costs have been assumed constant over the whole simulation period.

Compressed Air Energy Storage

This technology is one of the other alternatives for a large energy storage. It is based on a concept like the one of Pumped Hydro. During the charging phases air is compressed and stored in a proper site, normally natural storages like empty salt caverns, and then it is made expand in a turbine to produce back electricity.

This technology can be described by the same type of parameters used for other storage technologies; the values used are:

- Efficiency: 55% [40]
- Storage duration: 8 h
- Lifetime: 30 years [40]

The value of the efficiency is an average in the range proposed by [40], while the storage duration is assumed equal to the one the Pumped Hydro technology since it is used for similar purposes.

The economic parameters in this case are:

- CAPEX: 14.700 $M€/PJ$ for the year 2022 while from the 2030 it will be lowered to 12.200 $M€/PJ$ according to [38]
- OPEX: 2500 $M€/PJ$ assumed as the one of a natural gas turbine incremented by 5% in order to account the higher complexity of the system, this assumption has been made due to the lack of specific data.

Hydrogen storage technologies

The storage of hydrogen is one of the more complex issues about this energy vector since it is highly inflammable and volatile. There are different possibilities to store it but are all expensive either in term of energy needs, for liquefaction, space needed, for compressed storage, or technological complexity for the metal hydrates.

As a choice has been decided to model only the compressed storage, in which hydrogen is simply stored as all the compressed gases; the main reason behind this choice is this is the simpler way to store hydrogen. This technology has been implemented to allow the code to perform electricity storage transforming it into hydrogen, using electrolysers, and later exploit it.

Since the hydrogen commodity has been considered as an energy, the parameters needed are exactly the same of electricity storage technologies.

Efficiency	Storage duration [h]	Lifetime [y]
37%	24 [42]	20

Table 7. Hydrogen storage technology technical parameters.

All the parameters used, also the economic ones, comes from [29] in which there is a detailed report about the hydrogen technologies. In this paper are reported the values of $69{,}4\ M€/PJ$ for the CAPEX, it is exactly this value but when changed in the correct unit of measurement is it, and 0 for the OPEX. The null Operation and maintenance cost is not so logic but probably it is such low that can be considered negligible.

Non-power technologies

There have been implemented in the code also some technologies not belonging to the power sector, in particular have been chosen technologies related to hydrogen, even if not always the hydrogen commodity will be explicitly included in the technology characterization.

Hydrogen methanation

This process is used in order to convert the hydrogen in methane and directly use it. This solution can be needed since the hydrogen has some problems if used in the technologies that are actually using the methane (e.g., gas turbines), as a consequence this passage can be necessary until there will be a technological shift. This technology is set in the Upstream sector where we have the fuel production.

This is one of the technologies that have not clearly expressed the presence of the hydrogen since the technology is modelled considering also the electrolyser needed to transform electricity in hydrogen, after it we have a chemical reaction that is the methanation process, it uses CO_2 to produce a syngas. For sake of simplicity the technology has been modelled with electricity in input and natural gas in output, with a null emission factor considering that the used CO_2 compensates the emissions of the whole plant.

Efficiency	Lifetime [y]	Capacity factor
83% [43]	30 (4) [43]	95%

Table 8. Methanation technology technical parameters

The modelled plant is assumed as equipped with a SOEC, as reported in [43], and as a consequence the lifetime comprehends in brackets the lifetime of a single stack after which we have to replace the electrolytic cell stack; the costs are treated as the ones of the electrolysers.

The efficiency in this case is a pure number since also the natural gas is considered in terms of energy, in the calculations have been used the lower heating value as equal to $52\ MJ/kg$.

The capacity factor in this case is assumed, the value is slightly lower than the one used for the electrolysers accounting for the higher complexity of the plant.

The economic analysis is based on [43] and the reported values are:

- CAPEX: $6000\ M€/GW$
- OPEX: $120\ M€/GW$ obtained as 2% of the CAPEX

This technology is still in its early stages and, as a consequence, the information about it is not well proved and characterized, looking at Figure 2, it is evident that the OPEX cost od a simple SOEC plant is higher than the one of this technology that is much more complicated. This is a value not coherent, as a consequence has been chosen to rise this value up to $200\ M€/GW$. These values have then been transformed in $M€/PJ$ to be compliant with the other natural gas producing technologies.

Due to the absence of any specific projection about the cost trend of this technology, it has been assumed a constant value for both the economic parameter.

Hydrogen based steel

This is one of the possibly more appetible and fast improved applications of the hydrogen in the end-uses. The technology is based on the production of hydrogen on the basis of a direct reduction of the iron using the hydrogen. This is one of the possible ways to decarbonise a hard to abate sector such as the steel production one.

This technology is modelled neglecting the direct presence of hydrogen within the process but considering also in this case the passage directly from electricity to steel, the hydrogen is produced and used within the technology.

The technical parameters used to characterize the technology are:

- Conversion factor: $0{,}062\ Mt/PJ$ [44] this is the parameter correspondent to the efficiency for the other technologies, in this case is dimensioned since the produced commodity is the steel measured in mass terms.
- Lifetime: 25 years [44].
- Capacity factor: 85% assumed equal to the one of an electric arc furnace plant already implemented in the code due to the absence of other specific information.

The economic parameters where not easily available, only the OPEX was underlined in [44] as equal to the 1% of the CAPEX, as a consequence the choice has been to take the CAPEX value of the electric arc furnace used also for the capacity factor and rise it by 10%, obtaining a cost of $500\ M€/Mt$.

Due to the absence of any evidence about possible trends, these values have been kept constant until the time horizon of the simulation.

Hydrogen trucks

This is the last technology implemented in the code, and it uses the hydrogen commodity outside of the power sector. The idea behind this application is to decarbonise the freight transport sector that is a hard to abate one.

The trucks are equipped with some fuel cells that must be substituted after their end of life and it will be smaller with respect to the one of the classical PEMFC since the cycles at which they are subject in a mobility application are much more damaging for the cell itself.

This technology belongs to the transport sector and consequently also this technology is characterized by a conversion factor to satisfy the demand expressed in billion vehicle per kilometre (Bvkm); the technical parameters will so be:

- Conversion factor: equal to $0{,}2\ Bvkm/PJ$ [45]
- Lifetime: equal to 15 years considering the substitution of the cells every 5 years [45], this last parameter has been used in the economic calculation of the operation and maintenance cost as done for the electrolysers and fuel cells.

It is important to underline that the equivalence in Bvkm has been done considering the projections of the travelled distance of such technologies, this value is strongly dependant on the specific case and these assumptions do not always reflect actual trends.

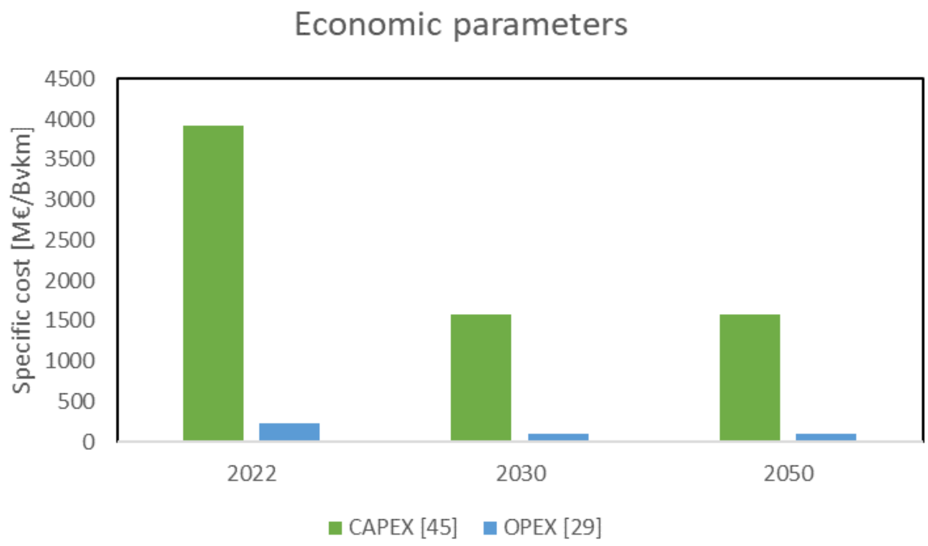

Figure 5. Economic parameters of hydrogen trucks

The economic parameters show a constant trend from 2030 to 2050 due to the lack of specific data, in absence of any evidence have been chosen to keep the value of the CAPEX constant; the OPEX follows the same trend since it is a fixed percentage of the CAPEX, in particular it is equal to 6%.

Possible changes in the modelling structure and code modifications

The new technologies implemented in the code required a coupled modification of the code itself, also some targets that have been set cannot be easily implemented in the actual code configuration.

Storage technologies

The first big difference that has to be properly managed in the code writing is the presence of storage technologies that have to be specified in a proper way since are technologies able to work both as producers and consumers of the stored commodity.

The first difference is in the specification within the "technologies" table, the technologies able to perform energy storage have to be defined with the specification "ps" that for the code represents the storage production technologies.

The second required step is the definition of the "tech_storage" table in which are defined the technologies for which later can be defined the *StorageDuration* that is the parameter needed in order to account the charging and discharging time of the storage.

It is important to evidence that in the presented results the storage technologies are not used by the model, according to their very high costs probably, but the code has been proved to work with the definition of these simple parameters. The tests have been performed on a smaller database in which it was easier to force the code to install the storages, while in our code, instead, it is not so trivial also because some parameters as the *MinimumActivity* cannot be defined for the storage technologies.

Blending

This is one of the most complex modifications that have been applied to the code because the modelling of the mixing between different commodities accounting all the technical constraints is a complex task.

The idea is the implementing of the possibility of substituting part of the natural gas in the national grid with hydrogen. This is actually possible in the real world but, without supposing dramatic variations of the infrastructure, it can be done only up to the theoretical 20% in volume fraction that correspond roughly to the 7% of energy supplied by the hydrogen. In order to be conservative, the maximum percentage of substitution, in energy terms since as said both hydrogen and natural gas are considered as energies, has been set at 5%.

In order to implement correctly in the code this possibility, have been defined for the transport, commercial, residential and industry sector some fictitious fuel technologies and commodity. To be precise have been defined for all these subsectors a fuel technology, named for example "COM_FT_BLEND_N", able to transform the hydrogen produced by the power sector, "ELC_H2", in a sector specific commodity used only for the blending, as the "COM_H2_BLEND". These fictitious technologies are characterized by a unitary efficiency and null cost since are simply used to diversify the hydrogen commodity.

The second step has been the definition of a technology group in each sub-sector containing the already present natural gas fuel technology, and, as an assumption, this has been done only on the new fuel technologies and not for the existing ones. With the definition of these groups, named like "COM_BLEND_GRP", it is possible to impose the parameter *MaxInputGroup* that limits a given commodity, in this case the sector specific hydrogen for blending, to a certain percentage of the total input; this has been done considering a trend starting with a 1% blend in 2025 and ending at the fixed 5% from the 2030.

This passage is required since on the single technologies is not possible to set maximum values of the different inputs but only minimum ones. In order to set the *MaxInputGroup* it is necessaire to set both the *MaxInputGroupWeight* for the technology within the group, in this set equal to 1; also, the *MinGenGroupWeight* is a required parameter for the working of the code, set also in this case equal to 1.

The last required step is to define a new efficiency for the fuel technology making it possible to convert the sectorial hydrogen in the sectorial natural gas that can be used by all the sectorial end-use technologies.

Using this escamotage, the code is able to use the hydrogen in the natural gas mix, to account the emission reduction coupled with the use of hydrogen in the mixture the idea has been to define a negative *CommodityEmissionFactor* for the new added sectorial hydrogen commodities, in this way the code is able to account the reduction in emission caused by the lower use of the natural gas; according to this reasoning, the value have been set equal to the emission factor of the natural gas with a negative sign.

Emissions

The targets that have been set are on the total emitted CO_2 and, consequently, is needed a way in to calculate the total emissions of the system. Actually, the code computes only sectorial emissions, with commodities as the “RES_CO2”, and it is possible to impose the parameter *EmissionLimit* only on them.

As said the problem is that the targets are generally expressed on the total emissions and not on sectorial ones, therefore the *EmissionLimit* should be set on this and is pointless to set it on specific sectors since the code should be free to choose where is more convenient to intervein, in this way can also be possible to decide which is the more efficient pathway to follow.

To allow this possibility the choice has been to create a new commodity, the “TOT_CO2”, accounting the total emissions, this has been done duplicating all the emission factors, both commodity and activity ones, and making each technology emit two different type of CO_2 commodity, the total and the sectorial one. At this point the limits can be imposed on the total emission and the model is free to choose how to respect them; of course, while calculating in the post process phase the emissions should be carefully considered this duplication and avoid the double counting of emissions.

Groups

The last significant modifications have been performed on the groups, in particular, it has been defined a new group of the different electrolysers technologies on which have been later set the already presented targets in order to be compliant with the analysed scenario.

Another big change has been the addition of the chemical looping technology to the solar technology group, on this group have been raised the limits that were imposed on the *MaxGenGroupLimit* in order to make possible the reach of the new targets, this increasing has been simply done adding 50 PJ to the limit. Indeed, during the first run, the code was not able to find a solution, since the minimum target to be reached set by the modellers by means of *MinGenGroupTarget* was too close to *MaxGenGroupLimit* value present in the database. Therefore, the optimization process was strict to work within a very narrow range and we avoided this issue by enlarging it properly.

For the wind technologies have been defined two different groups accounting one for the onshore technologies and the other for the offshore ones, as stated in scenario chapter. To make possible to do so have been applied maximum and minimum limits on the groups removing the ones already set on the single technologies put in the groups since the code does not work if both are present. In order to make reasonable the evolution of the offshore wind, strong limits have been imposed, anyway the model does not install this technology since it is probably too expensive.

Results analysis

Validation of the model

ESOMs are typically run starting from a past year, so that all the time frame between the base year and the present one can be used to validate the model by comparing its results with historical data regarding energy supply and consumption. For this purpose, IEA data on energy balances for Italy in years 2007, 2010, 2014 and 2018 have been involved.

The comparison deals with supply, transformation, and end-use sectors for each energy source (e.g., coal, crude oil, natural gas, wind and solar energy, heat, electricity, etc.). The unit of measure of energy flow is in TJ, in compliance with IEA data.

For supply-side, imports and production data have been taken investigating the annual activities of upstream sector technologies, while for transformation-side, the focus was on evaluating the amount of energy source spent in electricity and CHP plants, except for coal and oil products which require several steps of transformation and refinery before arriving at end-use sectors. As for end-use sectors, instead, the final consumption for each sector has been taken from fuel technologies activities. For instance, to evaluate the final consumption of natural gas in residential sector in 2018, the activity values of the fuel technologies “RES_FT_NGA_E” and “RES_FT_NGA_N” delivering natural gas to final users have been considered for that year.

Looking at the results (see Annex), they look very similar, at least in the order of magnitude. The main differences arise when dealing with biomass, biofuels and waste production and consumption values, which result to be significantly lower than the ones provided by IEA, since, as stated previously, at the current stage, biofuels-based technologies are included only with a preliminary modelling. In addition, information about energy industry own use, non-specified and non-energy use consumptions were not trivial to disaggregate. In fact, except for oil products whose technologies to convert them to non-energy feedstocks are specified (e.g., “IND_CH_FS_LPG_E”, “IND_CH_FS_KER_E”, etc.), other non-energy use demand productions are provided only for coal and non-specified oil by means of “IND_NEU_TECH” and “TRA_NEU_E” technologies.

In any case, every value underestimating or overestimating the historical data was compared with what was obtained from “TEMOA_Italy.sql” database available on the university website to check whether this difference was due to a lack of modelling or something else already in the model itself. Making this comparison the obtained results are compliant with the ones of the original TEMOA-Italy database, consequently they should be caused by the definitions within the original code.

Overall comparison between the scenarios

The following results mainly focus on the electricity sector, as most of the constraints and new technologies introduced by the modelers deal with it.

As for renewable energy generation, the projections done by the European Commission are already fulfilled in BAU scenario, reaching 60% (with solar, wind and hydropower), with respect to the expected 55% in [8]. Clearly, this result is even higher in our scenario, where renewable generation reaches 66% in 2030, as showed in Table 9. Electricity from hydrogen, instead, reveals to be almost negligible, reaching 1% in 2040, produced all by PEMFCs which are the most convenient fuel cells in terms of investment cost.

	2007	2008	2010	2012	2014	2016	2018	2020	2022	2025	2030	2040	2050
ELC TOT	1061	1094	1082	1084	997	928	820	820	852	929	1110	1243	1428
ELC SOLAR	0	0	7	68	74	80	96	105	149	216	326	389	466
% SOLAR	0%	0%	1%	6%	7%	9%	12%	13%	17%	23%	29%	31%	33%
ELC WIND	14	22	22	22	20	18	18	12	11	11	191	208	226
% WIND	1%	2%	2%	2%	2%	2%	2%	1%	1%	1%	17%	17%	16%
ELC HYDRO	172	172	172	173	175	177	179	181	183	206	211	216	221
% HYDRO	16%	16%	16%	16%	18%	19%	22%	22%	21%	22%	19%	17%	16%
% TOT RES	17%	18%	19%	24%	27%	30%	36%	36%	40%	47%	66%	65%	64%

Table 9. Percentage of renewable electricity generation throughout the years in our scenario, expressed in PJ and %.

For what concerns installed capacity, as it is shown in the following figure, the two scenarios have the same trend up to 2025 and, after that, our scenario experiences a steeper increase due to the targets expressed for hydrogen, solar and wind technologies. In particular, solar-based technologies contribute more in terms of both capacity and activity, reaching by 2050 almost 49 GW producing 126 TWh in both scenarios. However, the difference is made by wind technologies, since the total installed capacity amounts at only 1.6 GW in 2050 in BAU, while in our scenario it reaches almost 40 GW, doubling the goal set for 2030. This result looks quite interesting, since no target was imposed on wind technologies groups by 2050. This occurs mainly because the cost investment of the most installed technology “ELC_WIN_TYPEA_N” experiences a great reduction, passing from 950 M€/GW in 2030 to 550 M€/GW in 2040. However, this result may mislead the reader if it is not compared with the actual *MaxCapacity* already set in TEMOA-Italy database and then removed by the modelers for the reasons explained in technical constraints chapter. This actual value amounts at roughly 20 GW. If it was respected, by properly reducing *MinGenGroupTarget* value for “ELC_WIN_ON_GRP”, it would still be significantly higher with respect to the result obtained in BAU for what concerns wind technologies but, looking at the overall trends, the two scenarios could look more similar. It is fundamental, on the same time, to remember that, even in that case, this similarity would be only in terms of values, as our scenario includes another player, the hydrogen.

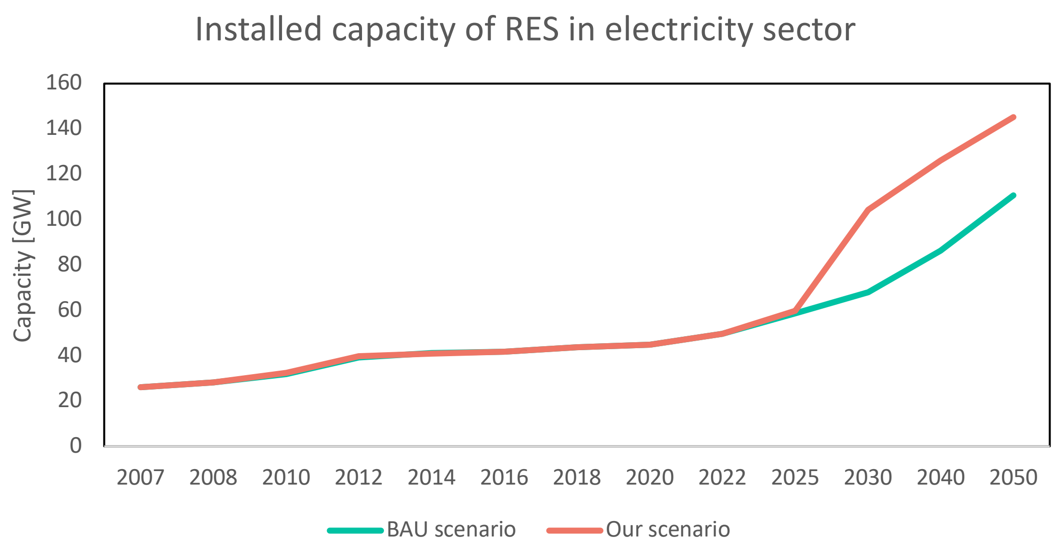

Figure 6. Installed capacity of RES in electricity sector

For what concerns CO_2 emissions, as stated previously, for BAU there are no limits imposed, differently from our scenarios. Until 2030 they both follow a decrease, arriving at almost the same value in 2030. This means that, if Italy continues its current path, it is likely to reach the target of reduction of 33% of CO_2 emissions with respect to 1990 level anyhow. However, not introducing strong limitations on emission does not reveal to be a reliable solution in the long run. In fact, after 2030, for BAU scenario the emissions start rising, almost coming back at 1990's level, thus making useless all the effort done up to 2030; analysing the results, they are probably caused by the exogenous driver profiles imposed on the original code. On the contrary, under our constraints, the emissions keep on decreasing. Indeed, the value to stay below in 2050 (200 Mt) is a result of several trials performed by the modelers while looking for the maximum allowed reduction. For instance, we tried values such as 50 Mt or 100 Mt – which represent respectively reductions of 90% and 80% with respect to 1990's level – but the optimization process was not able to find a solution. As expected, since any carbon sink technology has been modelled, not great results have been achieved in emission reductions, but they are for sure better with respect the Italian current strategy.

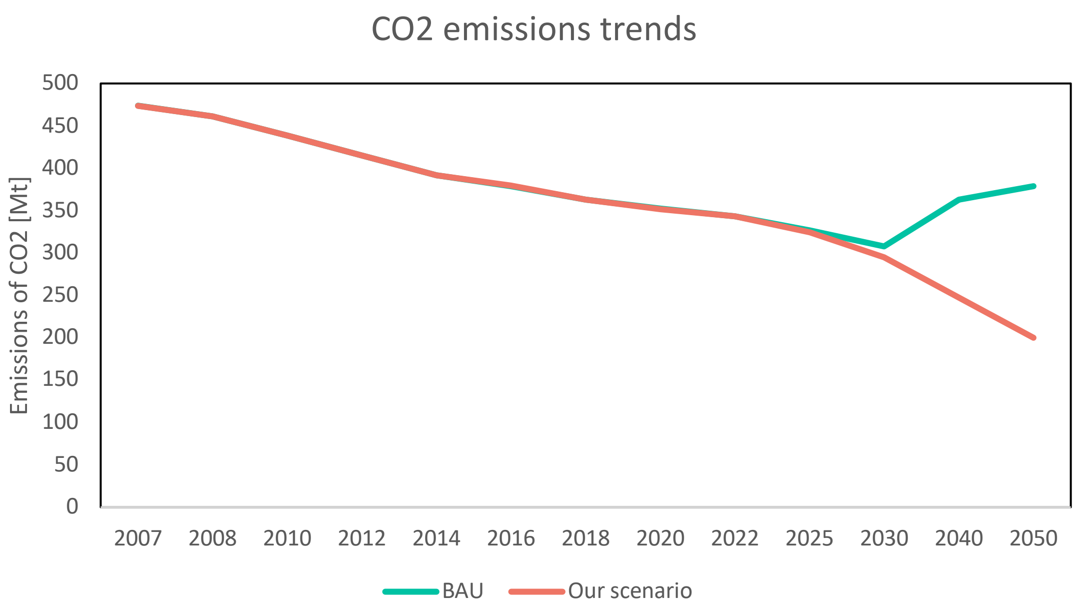

Figure 7. Comparison between scenarios in emission trends

Specific outcomes

Going into deeper analysis concerning emissions, as stated previously, we left the optimization process free to choose the pathway to follow, opting for a sector rather than another one. In light of the achieved result showed in Table 10, it is possible to make several remarks. Red-coloured cells represent the higher amounts of tons emitted, while for green-coloured ones it is exactly the opposite.

First, upstream sector does not participate significantly in emitting CO_2, since it only includes eventual leakages of fossil fuels during extraction and transformation processes. However, it experiences a reduction of 70% by 2050, since the energy mix shifts towards renewable energy sources, leaving behind fossil fuels.

For what concerns transport sector, in 2007, combined with electricity sector, it was the main responsible for emissions and it is not a surprise, as it is one of the most hard-to-abate sectors, especially for what concerns aviation and maritime transport. Indeed, its path leads to a fall of almost 37%, thanks to the penetration of hybrid and electric vehicles, also including the hydrogen trucks introduced by the modelers. This result may be even greater whether other FCEV (Fuel Cells Electric Vehicles) are modelled in road sub-sector. According to Hydrogen Council projections, by 2030, with the costs of hydrogen production and distribution falling, many more applications should become competitive against low-carbon alternatives by 2030. Examples include most road transport applications except short-range use cases (e.g., compact cars and short-distance buses), while in long term, by 2050, most of the assessed hydrogen applications considered can become competitive against low-carbon alternatives [46].

Residential sector experiences the biggest lowering, around 95%, while for industry still an effort is needed. In fact, only for CO_2 emitted during processes using clinker and lime in existing technologies ("IND_NM_CLK_DRY_E", "IND_NM_CLK_WET_E", "IND_NM_LIM_E"), by 2050 no zero emissions are achieved.

Power sector, as expected, has a steep reduction, due to the high penetration of renewable energy sources. For commercial and agricultural sectors, instead, even if they do not imply huge amounts of emissions, it would be better to make them carbon neutral by 2050, introducing new technologies.

Summarizing, the code has respected the emission limit relying on the sectors full of new and neutral technologies such as power, transport, and residential sectors, where it could be able to investigate several solutions and find the least cost and cleanest ones.

	2007	2008	2010	2012	2014	2016	2018	2020	2022	2025	2030	2040	2050
Tot CO2	473588	460955	438211	415417	391787	379594	362813	351507	343549	324642	294800	247000	200000
UPS CO2	155	128	114	101	90	74	65	49	54	55	36	46	45
TRA CO2	143800	142162	136328	131840	128248	129131	129976	129854	130369	131208	126467	113320	91255
RES CO2	55204	54395	51559	50384	50924	50162	49454	48057	47142	41698	41617	26225	2852
IND CO2	78425	68603	61753	56462	55704	57307	55080	52715	52461	52140	50979	54777	57065
IND CO2 P	25280	21680	19557	17362	16865	16955	16034	14251	14001	13140	11845	10467	0
ELC CO2	142164	146007	138500	131033	114106	102307	90094	86734	81876	71605	51364	30528	37906
COM CO2	20211	20581	22723	20919	18793	16684	15216	13026	10779	7859	5359	4430	3602
AGR CO2	8348	7399	7676	7315	7057	6974	6895	6821	6866	6939	7133	7208	7274

Table 10. CO2 emissions trends in supply and end-use sectors, measured in tons.

Moreover, another player should be considered when comparing the emission sector by sector, that is hydrogen blending in natural gas grid.

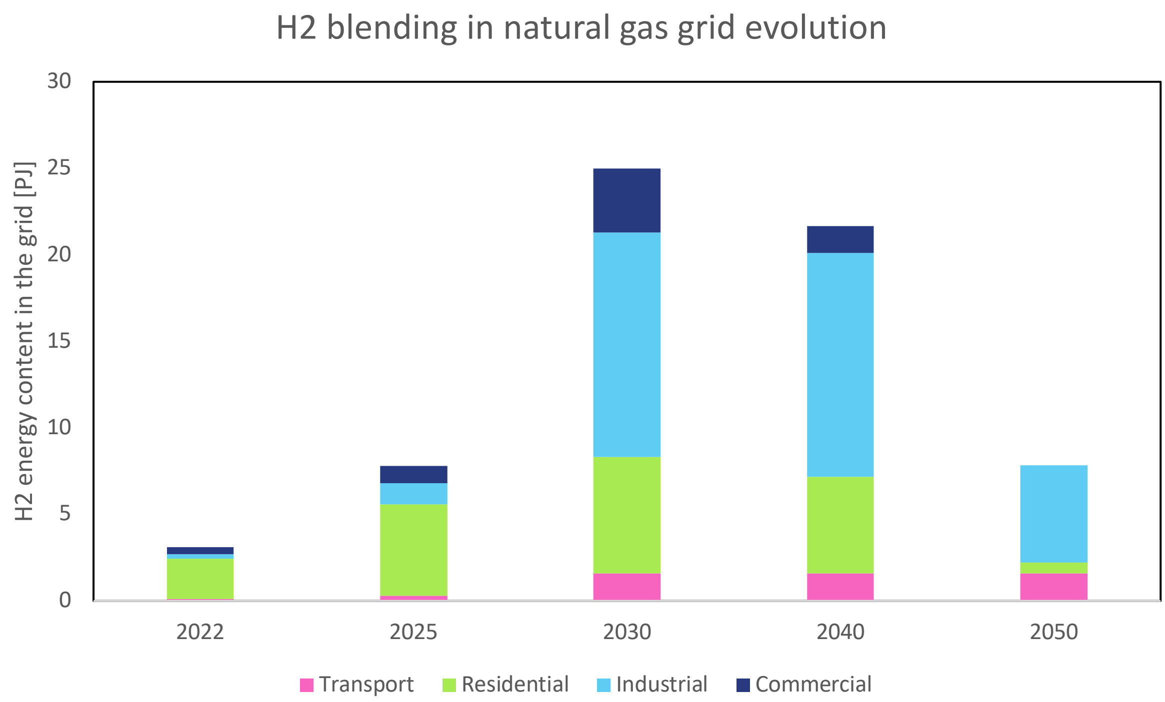

Figure 8. Hydrogen blending in natural gas grid evolution by end-use sectors

Indeed, looking at Figure 8, it comes out that industrial and residential sectors receive the higher amount of hydrogen in the gas grid, as they are the main consumers of natural gas. Also in this case, the optimization process is completely free to choose whenever deliver hydrogen in the grid even if, actually, there is only one grid, but as stated in Reference Energy System chapter, the partition of hydrogen in several commodities to enter in natural gas fuel technologies only aims at counting the emissions sector by sector. Furthermore, the decreasing of H_2 content in the grid from 2030 to 2050, can be explained analysing the natural gas consumption trend, which experiences a steep fall in those years, and it is likely to be related to decarbonisation target imposed.

Furthermore, this trend gives us the opportunity to make a final remark. Whether it is compared with natural gas consumption in power sector, it is evident that still a huge effort is needed to make this sector to get rid of natural gas, or at least of the Russian one as it represented almost the 44% of imports in 2020 [47]. Moreover, while the grid is expected to have a further decrease in the next years, the same cannot be said for power sector, as it still relies on several CHP plants using natural gas to counterbalance coal and oil plants phasing out. This leads to the conclusion that, whether the objective is to make Europe independent from Russian fossil fuels well before 2030 [5], much effort and investments in renewables are needed. In this perspective, as previously stated, hydrogen can play a fundamental role. In our case, no hydrogen methanation-based technology was installed, but in another scenario, characterised by a significative production of hydrogen, it may be used to produce methane, counteracting the fact that the grid and several end-use technologies are not still ready for a complete substitution of methane with hydrogen.

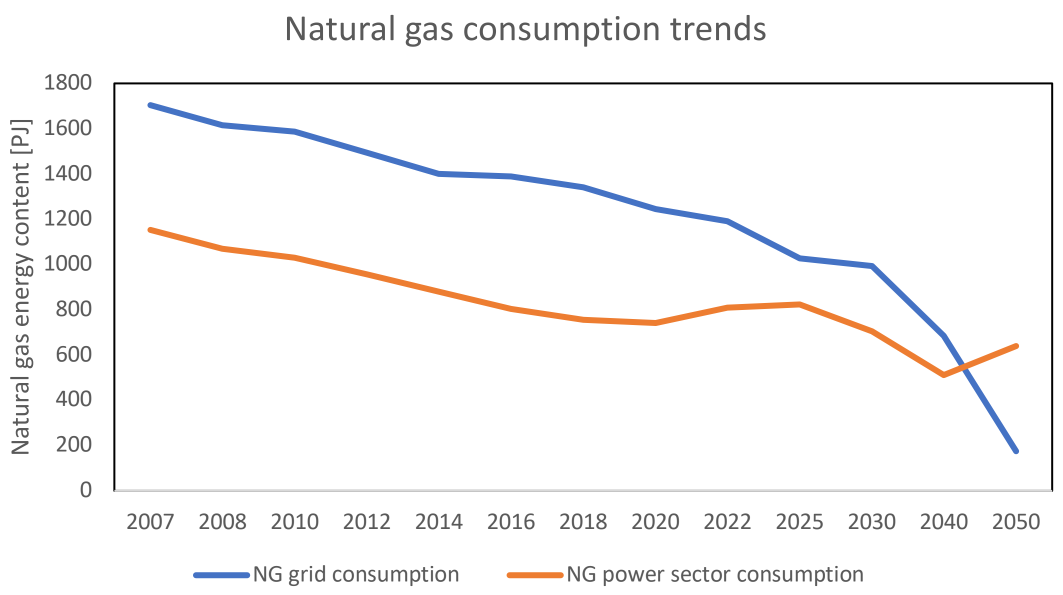

Figure 9. Natural gas consumption trend. The NG grid consumption includes commercial, industrial, residential, and commercial sectors.

Conclusion

The achieved results offer several insights for the Italian energy planning debate. In both scenarios under investigation, in power sector renewables will growth fast achieving EU targets, but natural gas will still be in the game. Whether electric storages continue to be neglected, as the optimization process has done, variable renewable sources will not be able to become predominant in the electric sector. Furthermore, the trend reversal occurring in Italy and other EU countries which are returning to rely on coal plants to face this energy crisis might further make our projections seem too optimistic.

In our best scenario, emissions will strong decrease, but net-zero emissions ambition will not be matched anyhow, and not only because CCUS technologies have not been considered. On the contrary, according to the European Commission, the long-term strategy to achieve climate neutrality by 2050 sets as priorities the fully decarbonization of EU's energy supply, promoting clean mobility, maximizing benefits from energy efficiency in buildings, developing smart network infrastructures, putting the industrial modernisation at the centre of a fully circular economy and, at the end, creating essential carbon sinks and tackling remaining CO_2 emissions with CCUS [48]. Therefore, CCUS are seen as a last chance, rather than the key for decarbonization, especially in energy supply sector.

Finally, regarding hydrogen, the results showed its potential in deeply modifying the energy system structure. Since we implemented the target set by the Italian policy in NRRP document in terms of capacity of electrolysers to be installed, we had the possibility to assess its consequences in the energy system. Whether the natural gas grid is well equipped to receive a certain amount of hydrogen and there is an increasing demand of it in end-use sectors represented by new technologies needing it, it can make the difference in reaching decarbonization targets. On the contrary, in power sector, it does not seem to be going to play a significative role in producing electricity and, moreover, heat; this evidence can be justified by the fact that almost all the hydrogen-based technologies are still in an early adoption stage. Surely it must be considered that all data about cost trends and efficiency achievements set by the modellers, bring with them all the uncertainties stated at the beginning of this work. Instead, for what concerns the way in which the target of installing 6 GW by 2030 can be achieved, as stated previously, the path chosen aims at avoiding too sudden and unrealistic changes. However, the values proposed for 2022 and 2025 equal to 100 MW and 1 GW already seems unrealizable, if compared with the latest news from the Italian government which aims at reaching a total installed capacity between 1 MW and 5 MW by 2026 [49].

Annex

In the following tables the comparison between IEA data [50] and ours. Green-colored cells contains the most similar values, the contrary is for red-colored ones.

	Coal		Crude oil		Oil products		Natural gas		Hydro		Wind, solar, etc.		Biofuels and waste		Electricity		Heat	
	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ
	IEA	OURS	IEA	OURS	IEA	OURS	IEA	OURS	IEA	OURS	IEA	OURS	IEA	OURS	IEA	OURS	IEA	OURS
Production	4201	4201	264115	267600			332 819	376300	118 135	146600	226 254	235600	358 102	247564				
Imports	684661	681381	4014417	3171089	496820	501712	2 535 746	2530000					41 651	39700	176 152	176000		
Exports	-6235	-6235	-84432	-84433	-1243717	-1243718	-2 332	-2332					-77	-77	-9533	-9533		
International marine bunkers					-100647	-100648												
International aviation bunkers					-142846	-142847												
Stock changes	988	988	21901	21901	-24081	-24082	44 886	44886										
Total energy supply	**683614**	**680335**	**4216002**	**3376157**	**-1014472**	**-1009583**	**2911118**	**2948854**	**118 135**	**146600**	**226 254**	**235600**	**399 676**	**287187**	**166 619**	**166467**		
Transfers					4956													
Statistical differences	244		-21516		81023										6		2	
Electricity plants	-442768	-435025			-177452	-297147	-642686	-628451	-118 135	-146600	-215 152	-206600	-58 453	-56451	722 060	746784,436		
CHP plants	-46776	-35957			-265273	-99779	-670032	-482498					-51 525	-37206	387 536	286848,749	204 411	149893
Heat plants																		
Gas works																		
Oil refineries			-4262467	-3708735	4280913	4120816												
Coal transformation	-92728	-138381																
Liquefication plants																		
Other transformation			67981		-71011								-585					
Energy industry own use	-2427	0			-222950		-26222								-87 163		-75 806	
Losses							-23255	-32707							-75 514			
Total final consumption	**99160**	**128848**			**2615735**	**2817961**	**1548923**	**1719277**			**11 102**	**11743**	**289 113**	**88764**	**1 113 545**	**1118488**	**128 607**	**119832**
Industry	91927	122008			259600	275246	526 403	631282					10 216	11947	526 212	540086,374	118 654	86114
Transport					1708069	1970235	20 266	16466					5 846	5570	37 454	37749		
Residential	230	276			164239	210519	667 462	721150			1 800	2920	272 686	63039	241 992	239236,348	5 583	27278
Commercial and public services					41505	18883	296 053	344159			5 989	3492	339	0	287 514	281319,621	4 226	6440
Agriculture / forestry					92841	108491	6 539	6220			1 020	5331	26	8208	20 120	19845	144	
Fishing					9762	9762					2 293				252	252		
Non-specified					4859	4859												
Non-energy use	7002	6563			334859	219965	32 199											

Table 11. Energy balance data comparison for 2007.

	Coal		Crude oil		Oil products		Natural gas		Hydro		Wind, solar, etc.		Biofuels and waste		Electricity		Heat	
	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ
	IEA	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**
Production	2 685	2685	235 308	269500			288 241	316304	184 020	156000	245 284	268847	426 304	236004				
Imports	586 163	603437	3 584 180	3071366	472 451	398538	2 583 888	2335010					108 841	46600	165 553	37939		
Exports	-8 914	-8914	-73 297	-73298	-1 186 534	-1186535	-4 835	-4 836					-4 406	-4 407	-6 577	-6578		
International marine bunkers					-124 544	-124545												
International aviation bunkers					-132 612	-132613												
Stock changes	-7 437	-7437	-40 378	-40379	-424	-424	-17 898	-17 899					-1 042					
Total energy supply	**572 498**	**589771**	**3 705 813**	**3227189**	**-971 663**	**-1045579**	**2 849 396**	**2651314**	**184 020**	**156000**	**245 284**	**268847**	**529 698**	**282604**	**158 976**	**31361**		
Transfers																		
Statistical differences	217		5 709		28 832		-1								-1		1	
Electricity plants	-386130	-446174			-63 611	-436839	-462 630	-585222	-184 020	-156000	-233 247	-196665	-89 541	-86707	674 294	794114		
CHP plants	-38890	-34894			-244 750	-128682	-703 585	-464593					-58 109	-21248	401 292	273055	202 505	135819
Heat plants											-1 178		-3 407				2 836	
Gas works																		
Oil refineries			-3 784 023	-3732145	3 826 908	-4146827												
Coal transformation	-66 964	-100568																
Liquefication plants																		
Other transformation			72 502		-75 256	-39682							-308					
Energy industry own use	-1 765	34067			-221 585		-27 220								-82 982		-65 839	
Losses							-20 376	-19815							-74 052			
Total final consumption	**78966**	**88011**			**2 278 874**	**2606196**	**1 635 585**	**1593079**			**10 859**	**39685**	**378 333**	**70003**	**1 077 527**	**1001587**	**139 503**	**143616**
Industry	73361	81514			145 727	244138	433 351	451218			388		18 031	9471	460 325	444764	131 022	114943
Transport					1 487 757	1857626	29 110	31692					59 428	4249	38 398	38862		
Residential	152	237			139 227	140901	782 831	743937			4 212	34177	299 895	55587	250 380	226250	5 133	22167
Commercial and public services					34 706	37802	360 644	360000			4 308	2871	913	46	308 228	270134	2 065	6506
Agriculture / forestry					87 079	99216	5 955	6231			630	2636	65	650	19 948	21330	55	
Fishing					7 804	7 805					1 321				248	248		
Non-specified					5 461	5 462											1 228	
Non-energy use	5453	6259			371 113	226514	23 693											

Table 12. Energy balance data comparison for 2010.

	Coal		Crude oil		Oil products		Natural gas		Hydro		Wind, solar, etc.		Biofuels and waste		Electricity		Heat	
	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ
	IEA	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**
Production	2 286	2 287	250 492	271108,116			245 139	219650	210 764	158100	361 640	334183	466 002	279268				
Imports	549 562	525493	2 506 302	2789972	477 307	349063	1 911 908	2104129					125 329	0	168 289	53987		
Exports	-9 914	-9 915	-53 723	-53 724	-833 134	-833135	-8 127	-8128					-5 987	-5 988	-10 912	-10913		
International marine bunkers					-80 084	-80085												
International aviation bunkers					-128 785	-128786												
Stock changes	4 794	4 795	-8 992	-8 993	30 002	30003	-25 958	-25959					740	740				
Total energy supply	**546 729**	**525493**	**2 694 079**	**3061080**	**-534 694**	**-662940**	**2 122 962**	**2289691**	**210 764**	**158100**	**361 640**	**334183**	**586 085**	**280008**	**157 378**	**43074**		
Transfers																		
Statistical differences	6 149		31 094		50 236										4			
Electricity plants	-419 117	-397760			-27 757	-285617	-225 828	-455595	-210 764	-158100	-347 932	-229193	-133 525	-60105	694 679	731588		
CHP plants	-21 162	-28298			-147 837	-116830	-520 643	-438942					-137 509	-21192	306 540	255937	202 448	132217,94
Heat plants											-1 531		-3 481				3 506	
Gas works																		
Oil refineries			-2 785 493	-3428099	2 834 690	-3808998												
Coal transformation	-53 720	-79541																
Liquefication plants																		
Other transformation			60 320		-63 011	-26205,76648							-308					
Energy industry own use	-1 026	29058			-108 894		-49 909								-75 184		-48 316	
Losses							-11 420	15537							-70 024		-763	
Total final consumption	**57 854**	**79020**			**2 002 733**	**2483658**	**1 315 163**	**1426345**			**12 177**	**63121**	**311 263**	**53239**	**1 013 393**	**956508**	**156 875**	**138566**
Industry	53 981	72789			93 576	237177	357 824	363646			458		24 623	9064	406 505	416287	110 078	112040
Transport					1 422 358	1747046	44 886	31235					44 598	2569	37 667	38245		
Residential		174			93 909	125316	634 335	734722			5 582	33924	237 623	40887	231 318	216471	34 264	20101
Commercial and public services					24 518	38881	251 715	291000			4 600	26722	3 525	121	318 560	265280	11 146	5484
Agriculture / forestry					81 907	91200	5 075	5742			666	2474	894	598	18 738	19620	941	941
Fishing					6 526	6 527					871				605	605		
Non-specified					4 214	4 215											446	446
Non-energy use	3 873	6057			275 726	244038	21 328											

Table 13. Energy balance data comparison for 2014.

	Coal		Crude oil		Oil products		Natural gas		Hydro		Wind, solar, etc.		Biofuels and waste		Electricity		Heat	
	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ	TJ
	IEA	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**	**IEA**	**OURS**
Production			213 129	270919			186 811	212439	175 631	161500	381 398	324938	497 776	245282				
Imports	371 428	436825	2 741 150	2688079	671 606	318993	2 327 346	1932207					121 927	0	169 813	166000		
Exports	-10 445	-10 446	-82 486	-82487	-1 168 449	-833135	-13 390	-13 391					-12 168	-12 169	-11 777	-11 778		
International marine bunkers					-113 934	-80085												
International aviation bunkers					-160 558	-128786												
Stock changes	-2 893	-2 894	30 150	30151	1 055	30003	-9 060	-9 061					144	145				
Total energy supply	**358 090**	**436825**	**2 901 943**	**2906661**	**-770 280**	**-693010**	**2 491 707**	**2144646**	**175 631**	**161500**	**381 398**	**324938**	**607 678**	**245427**	**158 036**	**166000**		
Transfers																		
Statistical differences	10 049		43 197		12 948													
Electricity plants	-266 307	-302543			-13 649	-163632	-320 309	-288804	-175 631	-161500	-365 127	-198523	-110 904	-48670	659 057	601608,95		
CHP plants	-30 100	-27021			-158 124	-96978	-647 315	-400890					-144 970	-20441	377 714	230356,56	214 637	119691
Heat plants					-183		-11 469				-1 761		-4 300				14 920	
Gas works							969						-969					
Oil refineries			-3 031 798	-3345040	3 066 301	-3716712												
Coal transformation	-33 419	-56585																
Liquefication plants																		
Other transformation			86 657		-90 071	-19437							-308					
Energy industry own use	-3 134	10564			-125 783		-66 283								-74 958		-55 332	
Losses							-13 544	-52537							-64 757		-2 446	
Total final consumption	**35 179**	**82874**			**1 921 158**	**2477423**	**1 433 755**	**1366303**			**14 509**	**76750**	**346 227**	**50573**	**1 055 092**	**990479,98**	**171 778**	**78110**
Industry	35 179	82763			84 547	218360	362 121	353000			503		27 066	21341	417 853	439166,65	108 930	60089
Transport					1 350 008	1770339	45 767	30725					52 323	855	41 544	39860		
Residential		111			92 098	82432	690 796	754966			6 808	33672	261 746	27583	234 496	204155,19	45 704	15938
Commercial and public services					22 728	35145	303 550	222000			5 133	39211	3 658	209	340 163	288122,84	15 828	1634
Agriculture / forestry					89 142	89093	5 727	5612			655	2455	1 433	585	19 751	19175	449	449
Fishing					7 121	7122					1 410	1411			1 285	1 286		
Non-specified					3 870	3871											868	868
Non-energy use					271 643	271061	25 794											

Table 14. Energy balance data comparison for 2018.

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Workload

<table>
<tr><th>Project phases</th><th>Project parts</th><th>Alessandro</th><th>Silvia</th><th>Liselotte</th></tr>
<tr><td rowspan="3">Implementation</td><td>Scenario definition</td><td>40%</td><td>40%</td><td>20%</td></tr>
<tr><td>Technology modelling</td><td>50%</td><td>50%</td><td></td></tr>
<tr><td>Analysis of results and post-processing</td><td>50%</td><td>50%</td><td></td></tr>
<tr><td rowspan="3">Writing of the report</td><td>Description of the implemented scenario</td><td></td><td>50%</td><td>50%</td></tr>
<tr><td>Description of the technology modelling</td><td>100%</td><td></td><td></td></tr>
<tr><td>Description of the results</td><td></td><td>100%</td><td></td></tr>
<tr><td colspan="2">Presentation</td><td>40%</td><td>40%</td><td>20%</td></tr>
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