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Will hydrogen be a game-changer in the Italian decarbonization pathways? Exploiting Energy System Optimization Model for a multi-scenario analysis

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Summary

Abstract

Hydrogen is expected to become an undisputed player in the ecological transition throughout the next decades. The decarbonization potential offered by this energy vector provides various opportunities for the so-called “hard-to-abate” sectors of the economy, including industrial production of iron and steel, glass, refineries and the heavy-duty transport. Indeed, heavy-haul, long-range trucks may be difficult to electrify due to the technological limits for the application of traditional batteries, whereas the old diesel-based passenger trains and many naval routes may improve their efficiencies and quality of service and simultaneously contribute to decarbonize the energy system with the use of hydrogen and derivates as propellants. In this regard, Italy, in the framework of decarbonization plans for the whole European Union, has been considered a wider use of hydrogen to provide an alternative to fossil fuels in hard-to-abate sectors.

This work aims to assess and compare different options concerning the pathway to be followed in the development of the future Italian energy system in order to meet decarbonization targets as established by the Paris Agreement and by the European Green Deal, and to infer a techno-economic analysis of the required asset alternatives to be used in that perspective. To accomplish this objective, the Energy System Optimization Model TEMOA-Italy was used, based on the open-source platform TEMOA and developed at PoliTo as a tool to be used for technology assessment and energy scenario analysis.

The adopted assessment strategy includes two different scenarios to be compared with a business-as-usual one, which considers the application of current policies in a time horizon up to 2050. Since the focus concerns hydrogen penetration in the energy mix, the additional scenarios are based on the up-to-date hydrogen-related targets and planned investments included in the National Hydrogen Strategy and in the Italian National Recovery and Resilience Plan, with the purpose of providing a critical assessment of what is proposed there. One scenario imposes decarbonization objectives for the years 2030, 2040 and 2050, without any other specific target. The second one (inspired to the national objectives on the development of the sector) promotes the deployment of the hydrogen value-chain, constraining the consumption of hydrogen without specifying in which sectors.

This configuration of scenarios, as will be described in the results, provides feedback about the actual possible applications hydrogen could have in the energy system, including transport, industry and synfuels production. Furthermore, the decarbonization scenario where hydrogen production is not imposed, will make use of this energy vector as well, showing the necessity of its exploitation in order to meet pledged targets by 2050.

The distance of the planned policies from optimal conditions for the achievement of Italian objectives will also be clarified, revealing possible improvements of various steps of the decarbonization pathway, which seems to have as a fundamental element Carbon Capture and Utilization technologies for its accomplishment.

The necessity of exploiting all the available technologies for meeting environmental objectives is also hereby underlined by the premises and the results of the two additionally defined scenarios and, in line with the European Commission open science guidelines, the transparency and the robustness of the presented results is ensured by the adoption of the open-source open-data model such as the TEMOA-Italy.

List of acronyms

AR6	Sixth Assessment Report
BAU	Business As Usual
CapEx	Capital Expenditure
CCUS	Carbon Capture Utilization and Storage
CHP	Combined Heat and Power
DRI	Direct Reduced Iron
ESOM	Energy System Optimization Model
ESR	Effort Sharing Regulation
ETS	Emissions Trading System
GDP	Gross Domestic Product
GHG	Green House Gas
IPCC	Intergovernmental Panel on Climate Change
MAHTEP	Modelling of Advanced Heat Transfer and Energy Problems
NGA	Natural Gas
LCV	Light Commercial Vehicle
LTS	Long Term Strategy (for GHG emissions reductions in Italy)
LULUCF	Land Use, Land Use Change and Forestry
OF	Objective Function
PA	Paris Agreement
PNIEC	National Integrated Plan for Energy and Climate
PNRR	National Recovery and Resilience Plan
RES	Reference Energy System
TEMOA	Tools for Energy Model Optimization and Analysis
WEM	World Energy Model

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Chapter 1

Introduction

1.1 Climate change and the role of hydrogen

Hydrogen is expected to play a major role in the track towards decarbonization [1] [2] [3] [4] and in order to understand what pathway should be put in place to enable this energy carrier to accomplish this expectation, an overview about how much and where hydrogen is used as of today is necessary.

At a European level, hydrogen (in the following also “H_2”) covers less than 2% of energy consumption with a demand of 8.4 million tonnes per year, being mainly used in refineries (49%), ammonia (31%) and methanol (5%) production and being produced almost completely from steam methane reforming processes accounting for a total amount of 10.5 million tonnes per year [5]. Nevertheless, the possible uses of this energy vector spread extensively beyond the current exploitation, covering a wide range of different purposes and sectors. Among these, it can be used directly as a fuel in electrolytic cells, especially for heavy transport and non-road categories, it can work as a feedstock for long-term energy storage and carrier, it can be exploited for high temperature industrial production processes and several other purposes including residential and commercial heat and power production and electricity generation [1].

However, even though positive signals are coming from worldwide and European hydrogen applications, current pace in its value-chain development is not sufficient to be on track for meeting net zero emissions targets in 2050 [6]. Specifically, hydrogen demand is estimated to reach up to 115 million tonnes by 2030 from the current 94 million tonnes world-based value (in 2021), but with barely 2 million tonnes employed for new uses. In comparison, to simply meet currently announced pledges that amount should grow up to 130 million tonnes by 2030, with a 25% coming from new uses, and to meet decarbonization targets in 2050 this should be additionally raised up to 200 million tonnes by 2030 [4].

Considering what stated in the recent Sixth Assessment Report, AR6, from the Intergovernmental Panel on Climate Change, IPCC, defining an increasingly worrying framework for climate development [7], it is of primarily importance to intensify the actions for slowing down and reverse the current long-lasting environmental depletion trend put in place by anthropogenic activities. In this perspective, hydrogen can exert a fundamental role in enabling decarbonization pathways in several strategic subsectors and in order to study its potential, a "technologically-neutral" approach is preferred, to equally compare all the existing alternatives and obtain a broad range of possible solutions [8].

Being Italy one of the ratifying countries since the establishment of the 2015 Paris Agreement, PA [9], its commitment in achieving the prescribed objectives required the publication of planned interventions by 2020, which was done through the Long-term Italian strategy for emissions reduction, LTS, [10].

To understand what this document contains, and how hydrogen should be fostered in Italian economy development for reaching the pledged targets explained in further chapters, it is necessary to have an overview of the Italian energy system, which is reported in Figure 1 as of 2018 [10].It is noticeable the high reliance on petroleum products for transport (dark blue branch) and on natural gas for power generation and residential sectors (red branch). Use of renewable sources is limited and losses from electricity production weight for almost half of the total energy output (grey arrows compared to the sum of yellow and pink branches).

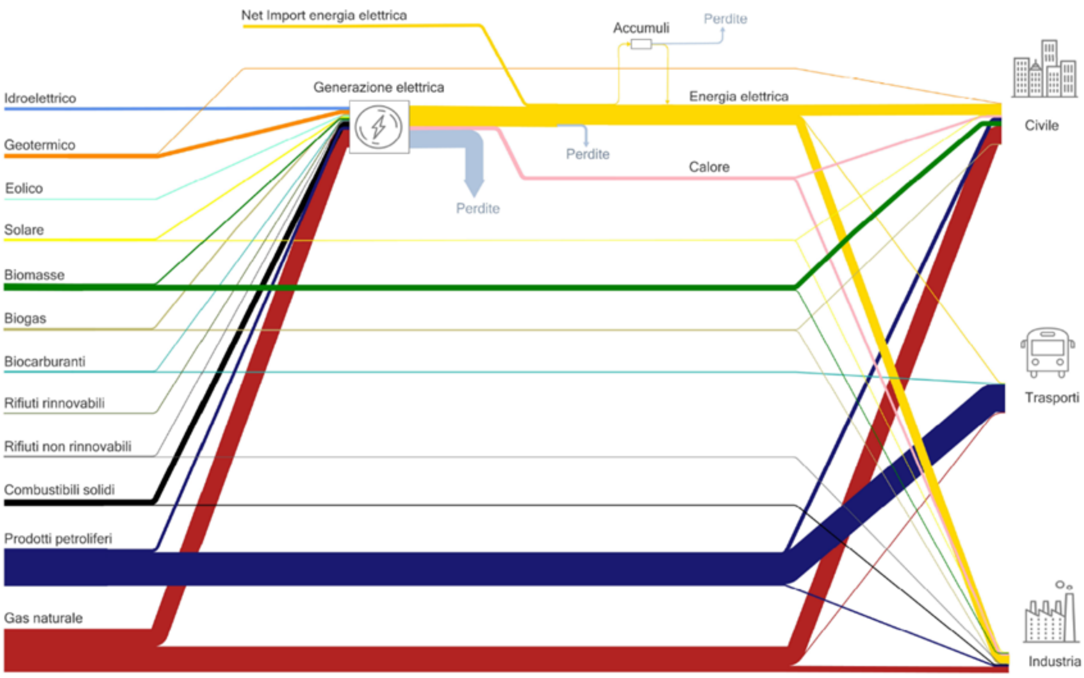

Figure 1: Italian energy system commodities consumption and allocation [10]

The described system refers to year 2018 and it corresponds to the last column of Figure 2, reporting total GHG emissions in million tonnes of CO_2 equivalent for the country, divided sector by sector. Major contributes derive from energy industry (blue), transport (light blue) and manufacture and construction industry (grey), followed by other combustion processes (dark blue) and the remaining sectors. Negative contributions from LULUCF are represented as well, accounting for about 35 million tonnes of CO_2 equivalent absorption in 2018. [10]

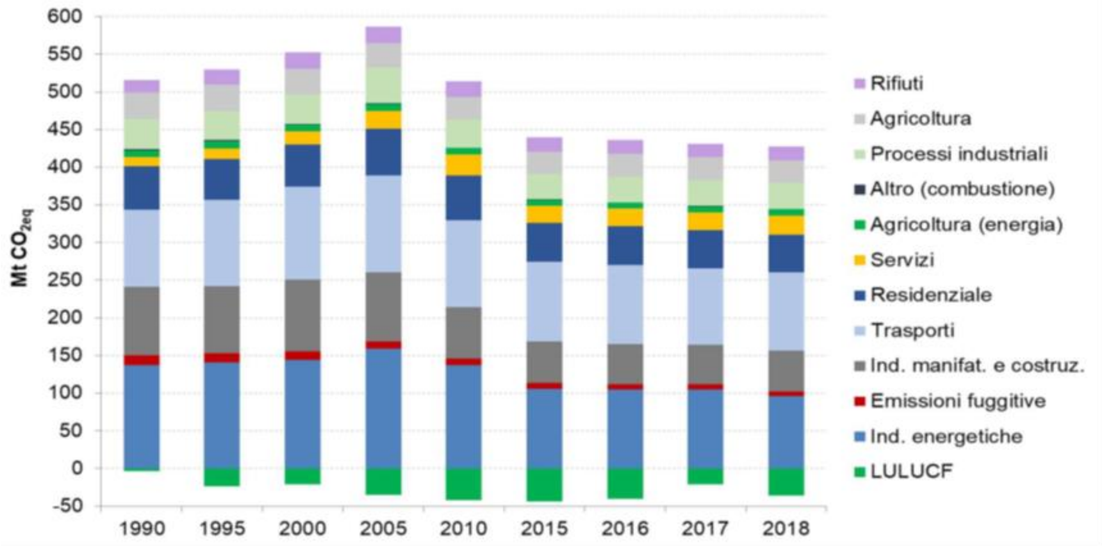

Figure 2: million tonnes of CO2 equivalent emissions by sector from 1990 to 2018 [10]

Given this national framework, hydrogen can be considered for its high decarbonization potential in the different categories cited above, among which are the so-called “hard-to-abate” emissive sectors [11].

Italy is the fifth country in Europe for hydrogen consumption, with a current demand of about 0.6 million tonnes per year, 70% of which is destined to refinery, and the remainder to chemical production. The amount of resource needed for refineries and ammonia production is in total 0.51 million tonnes per year and is currently satisfied through grey hydrogen supply. In order to replace only this amount with green H_2, the additional renewable source feedstock required would be of about 104 PJ [5], corresponding to 22% more than solar feedstock consumed to produce electricity in Italy in 2020 [12]. Moreover, a possible blue hydrogen replacement would imply new possibilities for the production of synfuels and lower carbon intensity propellants [13], but also significant reductions in the efficiency of hydrogen synthesis and a cost for prevented CO_2 emissions of about 100-111€ per tonnes of carbon dioxide, depending on the capturing efficiency, with a CO_2 cost of 90 € per tonne on ETS market (in 2022). Furthermore, in the case of green hydrogen the prevented carbon dioxide cost would grow up to an unbearable 900€ per tonne [5]. Water electrolysis feedstock supply requirements would also present many difficulties not only from an energetic but also from a logistic and an economic point of view, as will be further explained in later chapters [14].

For these reasons, the most convenient techniques for hydrogen synthesis, as of today, still implies the use of fossil fuels, annihilating its qualities in decarbonization potential [4].

All the previous hints raise the needing of a deeper approach for exploring hydrogen penetration in the energy system, in order to accomplish such an ambitious task as the carbon neutrality by 2050. Within this perspective, this work is intended to raise awareness about hydrogen possible uses and associated outcomes for the broader environment, such as costs, needed infrastructure, and interactions with other system elements. [11]

Following the REPowerEU guidelines [15], economic supports to hydrogen development accelerated all over European territory, and the contribution expected from this energy carrier to decarbonization consists not only in enabling the transition for those “hard-to-abate” sectors previously mentioned, but also for the production of low-carbon fuels as ammonia, methanol and kerosene, that should account for 10% to 12% of the global energy consumption to achieve Paris Agreement target by 2050 [16].

1.2 Energy system modelling

The multi-scenario analysis of this work is carried out using a bottom-up energy system model (ESOM). These tools are becoming increasingly important worldwide for the energy planning development of countries to be in line with decarbonization goals [17], representing a reliable instrument in the framework of quantitative assessment analysis for technological progress and related feasibility interacting with economic dynamics.

One of the main peculiarities of bottom-up ESOMs is the high level of detail of technical and economic parameters they can associate to a specific technology, describing it completely and including it in a complex system composed of other technologies similarly defined. These systems can work with a high disaggregation level and for this reason it needs considerable amount of input data usually provided through a database. [18]

Relevant characteristics of bottom-up models are [18]:

i. Economy development exogenously assumed
ii. Energy and energy use processes with physical or engineering relationships
iii. Demand related to socio-economic variables
iv. Demands often not affected by pricing effects

This last aspect in particular could be highly critical for very elastic fuel demands.

Despite their growing importance in the decision-making process, these tools are usually still limited, in their modelling strategy, to the schemes provided by traditional macroeconomics rules, oriented to least-cost optimization and implementing complex environmental issues only with few constraints usually applied on the GHGs emissions, evaluated with proper emission factors [19]. This aspect can extensively affect the obtained results when studying possible development for decarbonization pathways, and further improvement for the integration of innovative paradigms in bottom-up models are already under development [20]. However, applying the correct interpretation process of the results, they still represent a valid instrument for scenario analysis and energy system improvement strategies. This has been widely demonstrated in several studies in which the use of energy system models was carried out to define and solve optimization problems for energy scenarios. [18] [21] [22]

1.3 The aim of the work

The purpose of the thesis is to assess the decarbonization potential of hydrogen in reaching the Italian climate targets. Such a potential was estimated implementing a multi-scenario analysis using an open-source bottom-up ESOM, namely the TEMOA-Italy model [18].

In particular, 3 scenarios were considered and compared: a Business-as-Usual (BAU) scenario based on the currently implemented policies [23], a decarbonization scenario based on the Italian decarbonization targets [10] and a scenario with the same decarbonization targets combined with a minimum H_2 consumption. While the BAU is a baseline scenario intended to show how far Italy is from reaching the PA goals, constraining the consumption of H_2 in a decarbonization scenario in TEMOA-Italy, and comparing it with an unconstrained decarbonization scenario, allows to understand the cost-effectiveness of a hydrogen-based economy, since such an ESOM is based on a minimum cost optimization.

In this optic, the results about the hydrogen supply and consumption were also compared to the up-to-date Italian policies, in order to critically oversee current Italian policies for hydrogen-related technologies development and dedicated funds relevance [24] [11].

In order to accomplish this purpose, the thesis is structured in four additional chapters. The following one will present and describe the framework of Energy System Optimization Models, ESOMs, and the more specific TEMOA-Italy model, providing the context in which this work is inserted. Also, the introduction of the relevant changes included in the same model for pursuing the objectives of this study will be detailed, specifically addressing hydrogen value-chain in its various steps.

The third chapter will exhaustively describe the process and rationale followed for the construction of the analysed scenarios, reporting corresponding policies nowadays implemented or projected for the inclusion of hydrogen utilization technologies.

The results will be portrayed and discussed in the fourth chapter, presenting the different analysis provided to completely define the outcome of the provided model with the implementation of the stated scenarios.

Finally, conclusions are reported in chapter five, with the definition of future perspectives for deepening and improving the presented analysis.

Chapter 2

The TEMOA-Italy model

2.1 Energy System Optimization Models

Energy System Optimization Models, ESOMs, are bottom-up energy system models aiming to evaluate the optimal configuration of the modelled energy system, usually according to an economic optimization paradigm. This feature can present two alternatives: myopic approach or with perfect foresight. While the latter means a perfect information on the present and future system parameters along the entire time horizon, the myopic optimization consists of a sequential optimization of shorter time periods that compose the time horizon [19].

Time resolution is a discriminant feature for the ESOMs, being defined by the subdivision of the modelled time horizon in a finite number of time steps. The density of time steps can both remain constant or change (e.g., a higher resolution in the past year period, to validate the model against the historical data, while a lower resolution in the future years, due to the uncertainty on the future evolution of an energy system).

Also, spatial resolution is a characterizing parameter for these models. Macroscale, mesoscale and microscale sized structures can be modelled with ESOMs, where former one refers to national or multi-countries energy systems, as for example World Energy Model, WEM [25], mid one can manage region-like sized frameworks, and the latter ranges from cities to single-building systems. The case discussed by this study implies a macroscale energy model, regarding the whole Italian energy system, and its boundaries are defined according to the economic framework of the country, concerning energy resources trades. [18]

The energy system under investigation can include all the energy sectors or alternatively only few selected ones. In the former case the model has the possibility to assess and maximize the efficiency of the whole system and to evaluate the advantages of synergies among different sectors (sector-coupling).

The core of energy system optimization models is the objective function, OF, which leads the optimization process according to its formulation. The traditional OF is the minimization of the total system cost (including investment and operation and maintenance costs), provided by the optimization process.

Among the most useful advantages of ESOMs, as previously mentioned, is the technology-rich description of the system. This characteristic allows a detailed integration of each sector in the framework of the energy system. In particular, technologies are defined by [26]:

a. Name: which is univocal.
b. Efficiency: its value defines the year from which the technology enters into force, and the amount of output *commodity* produced, related to an input commodity consumption.
c. Existing capacity: to define installed capacity already in place at the first year of the modelled time horizon.
d. Lifetime: usually taken as the average or projected lifespan of the technology.
e. Capacity factor: it defines the percentage of time the technology is available for production.
f. Costs: investment cost, variable and fixed operation and maintenance costs defined where necessary to account for the utilization of each technology in the economic assessment.
g. Emission factor: this can be associated both to *commodities* and to technologies.

Also, other deeply technical parameters can be defined for more detailed analysis and all of them can vary along the modelled time horizon to follow realistic evolution of the system, as variations of the technical parameters due to technology improvement or aging of the infrastructures and so on.

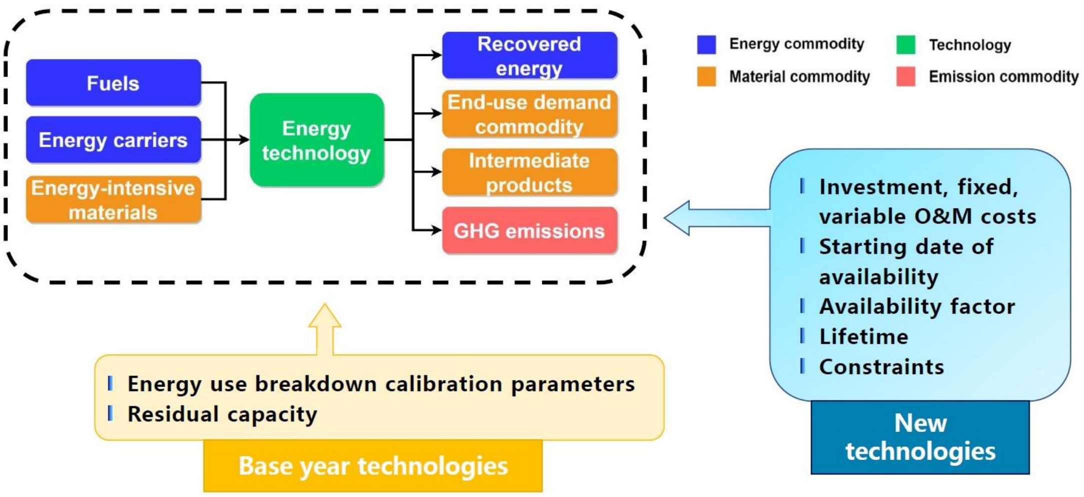

Figure 3: energy technology representation in ESOMs with interactions with input and output commodities [26]

Figure 3 reports an illustrative scheme for technology definition in ESOMs. As shown, different inputs and outputs can be associated to each technology of the system and of different qualities. These flows are called *commodities*, representing the resources consumed and produced in the energy system functioning and they can include both fuels or energy vectors, and materials. As previously mentioned, also emissions are associated to technology activities and this kind of commodity introduces the need of a further definition:

a. Physical commodities: represent flows of energy, fuels or material that are available for technologies to be used in their production processes as *input*, hence, they can be consumed.
b. Emission commodities: these constitute pollutants and output flows that cannot be used as consumption resources.
c. Demand commodities: they define the end uses requirement to be satisfied by the activity of the entire energy system. They are associated to each demand-side sector and are defined according to the existing and future evolution of the real system.

2.2 The TEMOA modelling framework

Tools for Energy Model Optimization and Analysis, TEMOA, is a python-based environment which allows energy system definition. The upper-level framework is called Pyomo, a collection of packages which allows the constitution of five strictly necessary classes for problem optimization: sets, parameters, variables, objective and constraints [26].

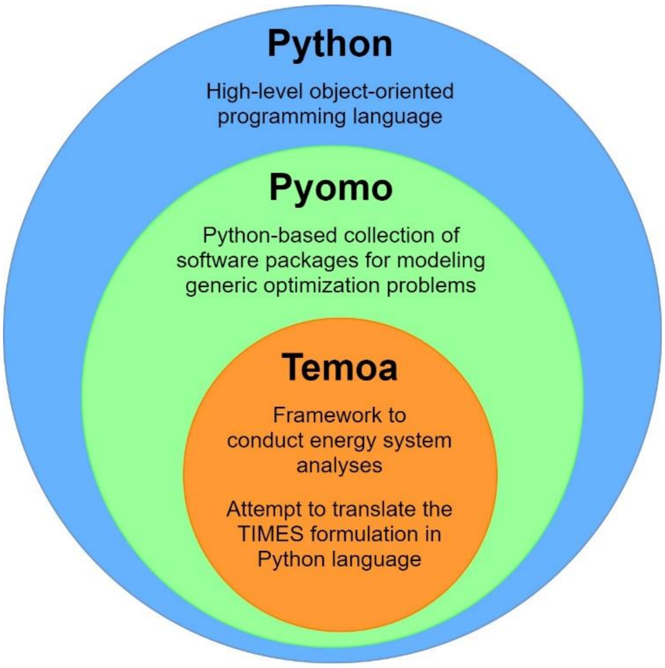

Figure 4: TEMOA framework development structure [18]

As represented in Figure 4, this contains TEMOA, the actual framework for system analysis, the core of which is a technology explicit ESOM defined by an external database provided in python language. This allows to shape the characteristic of the desired system from technical and economic points of view, in order to provide it to the actual TEMOA environment which proceeds in applying the model rules and shaping the configuration of the system. It needs to interact with an external solver to run the model in the pursuit of an optimal solution and this optimum is defined through the single-objective function of minimum total cost of the described system and the solution is determined stochastically. [18]

The whole TEMOA framework has been developed in an open-source perspective. The choice of elaborating an Italian energy system model based on TEMOA in such a fully accessible framework is made after the current European policy tendencies for open-science approach, which can largely favour the contribution from different parts to solving problems of common interest, enhancing quality, efficiency and responsiveness of research, preserving the solution from being as far as possible anyhow conditioned. European Commission in particular, articulates its objectives in regards of open science in 9 milestones [27]:

- Open data: FAIR (Findable, Accessible, Interoperable and Re-usable data) and open data sharing as a mandatory condition for EU-funded research.
- European Open Science Cloud: a shared platform for to store, process and reuse research digital objects.
- New generation metrics: renovate indicators to assess research outcomes.
- Multi-countries collaboration for promoting shared problems scientific approach and open science methodology.
- Encouraging early sharing of different research outputs and free access to all peer-reviewed scientific publications.
- Promoting rewards for scientific research.
- EU-funded research adherence with standards for research integrity and reproducibility of results.
- Spread knowledge and method about open science approach and application among European scientists.
- Possibility for public to contribute and get awarded for science knowledge producers.

This method ensures a higher level of reliability, transparency and robustness of the results thanks to the continuous double-checking process, occurring especially for those projects which are being frequently updated due to changing conditions in the system they represent, and this is the case for TEMOA-Italy. [27]

2.3 The Italian Reference Energy System

The specific environment that allowed the development of this work is the previously existing TEMOA-Italy model, an Italian reference energy system representation in bottom up ESOM, developed by MAHTEP research group at PoliTO [18]. The purpose of this project is to conceive an energy system optimization model for Italy in open-access, open-data framework, providing the possibility to explore possible future development strategies with a deep level of techno-economic detail. TEMOA-Italy reflects closely the structure of Italian Reference Energy System, RES, including the different following sectors [18]:

- Upstream
- Power generation
- Agriculture
- Commercial
- Residential
- Transport
- Industry

The base year for the model is 2006 and the time horizon runs until 2050, meaning that all the time periods except 2006 are modelled as future years, nevertheless, historical coherence of the model until 2020 is ensured by a complex set of constraints and a proper calibration and has been verified with the most up-to-date version of the model.

The RES, which follows the representation previously presented for technology modelling, is entirely depicted in Figure 5, where the above-mentioned sectors are represented, and their interconnections are explicated. Also, a synthetic description of the demand side for each sector is included in the figure and summarizes the service demands that must be satisfied by the optimization result.

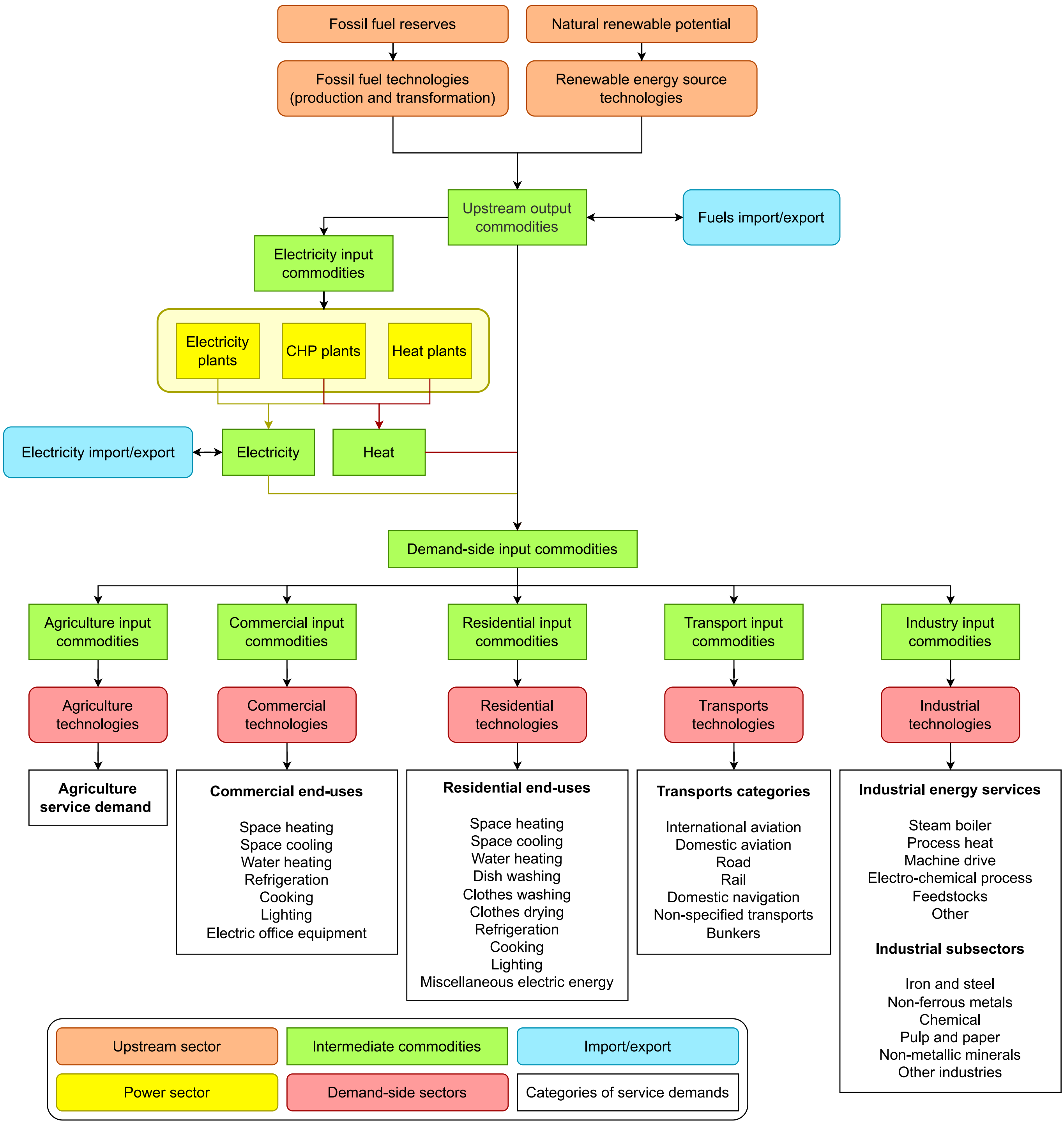

Figure 5: Representation of the Reference Energy System including all sectors and related connections [18]

2.3.1 Hydrogen module

A high- level description of the hydrogen value chain is provided in Figure 6, where it is possible to address the four phases of the production-consumption cycle, namely: production, storage, delivery and consumption. The first one is differentiated by resource use and provides hydrogen with its characteristic colour [28]:

- Fossil fuel derived H_2: GREY hydrogen
- Fossil fuel derived H_2 combined with Carbon Capture and Storage (CCS): BLUE hydrogen
- Water-electrolysis derived H_2: YELLOW hydrogen
- Low emissive sources derived H_2: GREEN hydrogen, distinguishing H_2 from biomass to the one from decentralized water electrolysis (since in TEMOA-Italy the decentralized power plants are only renewable sources-based)

There are also additional hydrogen typologies which are not yet considered in the model since the needed infrastructure is as of today not implemented (namely, nuclear energy derived H_2: PINK hydrogen).

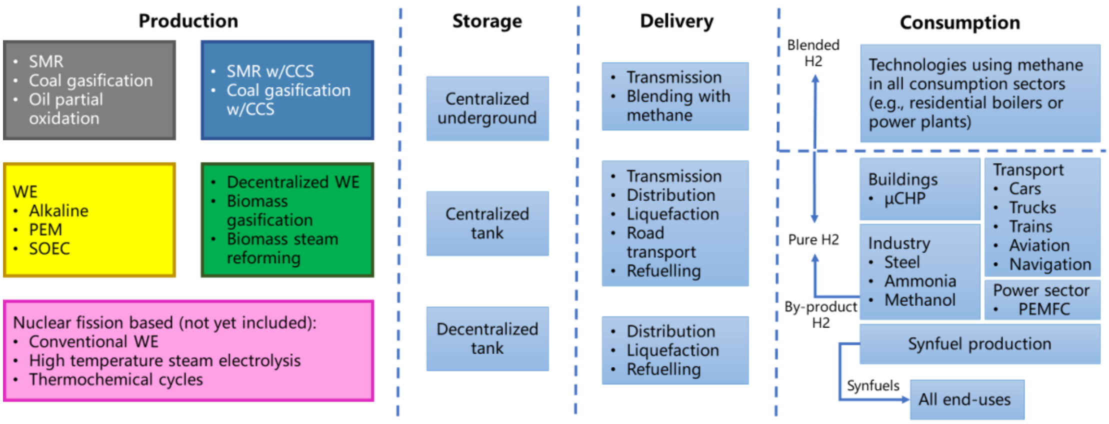

Figure 6: General overview on hydrogen value-chain including the four main phases of its life cycle. [29] For a more detailed analysis of specific hydrogen processes as modelled in TEMOA-Italy framework, see Figure 38 in appendix D.

The implementation phase of the production side followed a logic of size definition and location detail. This means that different plant sizes are distinguished in:

- Small
- Medium
- Large

This distinction is implemented with different costs and lifetimes, in order to realistically represent the possible infrastructure to be chosen by the optimization process. Furthermore, the location of the plant has been identified with two different possibilities:

- Centralized
- Decentralized

This associates or neglects, respectively, transportation-related costs and commodities consumption for H_2 dispatchment, increasing the variability of possible combinations for hydrogen production configuration at system scale.

It is relevant to underline that blue hydrogen production technologies are formally implemented in the model in another module, called CCUS, standing for Carbon Capture Utilization and Storage, and described in the following paragraph. This one contains a duplication of hydrogen production technologies through fossil fuels, or grey hydrogen production technologies, which are associated with capture technologies, in such a way that their activities are tied together.

These blue hydrogen production technologies have different costs, efficiency and in general a different set of techno-economic parameters according to the existing or under development technologies.

It is fundamental to notice that the model has not the possibility to “retrofit” or “refurbish” existing grey hydrogen production plants (or any other), with the integration of carbon capture technologies, transforming them into blue hydrogen production facilities. It can only install brand new blue (or grey, as green) hydrogen production plants. Clearly, this is a noticeable simplification when studying hydrogen development, since the costs associated to new installations compared to refurbishing ones has a much different impact on sector economy and refurbishing strategies implementation could be one of the next future refinements of the current model. Nevertheless, being the model optimized with a perfect foresight approach, this would have an impact only on technologies that are already existing in the first year, while all the new instalments would be chosen to best fit the system’s requirements, hence, being hydrogen-related installed capacity very low in the first year, this approximation does not lead to relevant changes in the model behaviour.

Storage system is defined by three different technologies depending on the kind of hydrogen produced, namely: centralized tank-allocated, decentralized tank-allocated or centralized underground-allocated hydrogen.

Distribution phase is used in the model to define the use of hydrogen by sector, since each of them is going to be accounted for with diverse combination of techno-economic factors. Alternatively, hydrogen can directly enter the production of synfuels without any delivery process to be accounted for, since the assumption for these facilities is that synfuels are produced in situ where hydrogen is extracted. The distribution step also includes hydrogen transformation for blending use: this specific utilization is modelled with a mixing limit in order to respect actual natural gas infrastructure constraint, and it does not imply additional costs for H_2 presence in the natural gas grid, although costs are included for the technology which allows hydrogen to be used for blending purposes, modelled as a previous step in the value-chain. In this case, where blending is considered and used in the system, the emission computation takes into account the reduction provided by hydrogen contribution in natural gas consumption [30].

It is important to underline that a specific distribution process exists for industry, though fictitious in the case of ammonia and methanol, due to the fact that in this case the two processes (H_2 production, in particular from decentralized electrolysis, and ammonia or methanol manufacture) take place in the same facility, hence, without generating any transportation cost. Another peculiarity of industrial sector is related to the hydrogen production, in fact there are various processes which have hydrogen as a side-product, namely, chlorine production through membrane, diaphragm and mercury cells. This hydrogen amount is usually negligible and does not appear in the final accounting analysis due to the extremely low volume produced, furthermore, it can be exploited exclusively in the same sector in which it is produced, namely, industry.

End use technologies constitute the main structure of the consumption phase of hydrogen, although also other technologies belonging to secondary transformation are included in this group. These are the ones needed for the synfuels production and are going to be described in the following paragraph. Consumption side includes all the economic sectors of the system as hydrogen can be exploited in each of them in different forms:

- Commercial and residential: Combined Heat and Power (CHP) systems for electricity and heat production
- Industry: iron production through direct reduction
- Power sector: electricity production through fuel cells
- Transport: gaseous and liquid hydrogen for road and non-road transport categories
- Upstream: hydrogen combined with captured CO_2 for synfuels production
- Blending: mixing with natural gas for all the sectors which use it

Specific parameters implemented in the model for grey and blue hydrogen technologies, including efficiencies and input commodities, are reported in Table 1, and costs in Table 2.

Table 1: summary of efficiency and input commodities values for grey and blue hydrogen production technologies [29]

Technology	**Efficiency [%]**	**Input commodity [PJ/PJ$_{H2}$]**			
		Natural gas	*Coal*	*Oil*	*Electricity*
SMR, centralized large (2020)	75	1.32			0.02
SMR, centralized large (2030)	79	1.25			0.02
SMR, centralized small (2020)	62	1.58			0.03
SMR, centralized small (2030)	67	1.48			0.02
SMR, decentralized medium (2020)	62	1.36			0.25
SMR, decentralized medium (2025)	75	1.27			0.07
SMR, decentralized small (2020)	53	1.81			0.07
SMR, decentralized small (2030)	63	1.55			0.05
SMR w/CC, centralized large (2020)	64	1.52			0.05
SMR w/CC, centralized large (2030)	70	1.40			0.04
SMR w/CC, centralized small (2020)	58	1.65			0.07
SMR w/CC, centralized small (2030)	69	1.40			0.04
Coal gasification, centralized large (2020)	54		1.77		0.07
Coal gasification, centralized large (2030)	79		1.25		0.02
Coal gasification, centralized medium	57		1.75		
Coal gasification w/CC, centralized large (2020)	53		1.77		0.11
Coal gasification w/CC, centralized large (2030)	61		1.62		0.02
Coal gasification w/CC, centralized medium	58		1.72		
Oil partial oxidation	74			1.30	0.06

*Table 2: summary of costs for grey and blue hydrogen production technologies [29]. *Updated according to [31]*

Technology	**INVCOST** $[\frac{M€}{PJ_{H2}}]$	**FIXOM** $[\frac{M€}{PJ_{H2}/year}]$	**VAROM** $[\frac{M€}{PJ_{H2}/year}]$
SMR, centralized large (2020)	6.38	0.31	0.08
SMR, centralized large (2030)	5.02	0.24	0.05
SMR, centralized small (2020)	13.69	0.52	0.14*
SMR, centralized small (2030)	10.92	0.41	0.05
SMR, decentralized medium (2020)	15.40	0.89	0.04
SMR, decentralized medium (2025)	11.95	1.33	0.04
SMR, decentralized small (2020)	52.10	1.41	0.65
SMR, decentralized small (2030)	36.71	0.73	0.04
SMR w/CC, centralized large (2020)	9.03	0.45	0.53
SMR w/CC, centralized large (2025)	8.65	0.45	0.53
SMR w/CC, centralized large (2030)	6.07	0.36	0.07
SMR w/CC, centralized small (2020)	17.92	0.94	0.20
SMR w/CC, centralized small (2030)	14.29	0.76	0.07
Coal gasification, centralized large (2020)	14.67	0.87	0.16
Coal gasification, centralized large (2030)	11.13	0.71	0.12
Coal gasification, centralized medium	18.18	0.45	0.22
Coal gasification w/CC, centralized large (2020)	16.50	1.30	0.20
Coal gasification w/CC, centralized large (2030)	11.53	0.72	0.13
Coal gasification w/CC, centralized medium	20.95	0.87	0.26
Oil partial oxidation	13.69	0.68	0.14

Similarly, for water electrolysis produced hydrogen, in Table 3 and Table 4.

Table 3: summary of efficiency and input commodities values for water electrolysis hydrogen production technologies [29]

Technology	**Efficiency [%]**		
	2020	*2030*	*2050*
AEL centralized large	70	71	80
AEL decentralized small	63	65	70
PEM centralized large	60	68	74
PEM decentralized small	56	63	67
SOEC centralized large	81	84	90
SOEC decentralized small	74	77	77
AEM-WE			74

*Table 4: summary of costs for water electrolysis hydrogen production technologies [29]. *Updated according to [3]*

Technology	**INVCOST** $[\frac{M€}{PJ_{H2}}]$	**FIXOM** $[\frac{M€}{PJ_{H2}/year}]$
AEL centralized large (2020)	15.85	0.48
AEL centralized large (2030)	12.68	0.38*
AEL centralized large (2050)	6.34	0.19
AEL decentralized small (2020)	44.39*	1.33
AEL decentralized small (2030)	26.95	0.81
AEL decentralized small (2050)	22.20	0.67
PEM centralized large (2020)	34.88	1.05
PEM centralized large (2030)	20.61	0.62
PEM centralized large (2050)	6.34	0.19
PEM decentralized small (2020)	57.08	1.71
PEM decentralized small (2030)	47.56	1.43
PEM decentralized small (2050)	28.54	0.86
SOEC centralized large (2020)	88.79	2.66
SOEC centralized large (2030)	25.37	0.76
SOEC centralized large (2050)	15.85	0.48
SOEC decentralized small (2020)	177.57	5.33
SOEC decentralized small (2030)	88.79	2.66
SOEC decentralized small (2050)	31.71	0.95
AEM-WE	6.34	0.19

In the same way, Table 5 and Table 6 are reported for other low-carbon hydrogen production technologies parameters implementation.

Table 5: summary of efficiency and input commodities values for other low-carbon hydrogen production technologies [29]

Technology	**Efficiency [%]**	**Input commodity** $[PJ/PJ_{H2}]$		
		Solid biomass	*Bioethanol*	*Electricity*
Solid biomass gasification, centralized medium	53	1.80		0.10
Solid biomass gasification, decentralized small	31	3.00		0.20
Solid biomass gasification w/CC, centralized medium	52	1.80		0.14
Solid biomass steam reforming, centralized	71	1.36		0.04
Ethanol steam reforming, decentralized	36		2.63	0.18

*Table 6: summary of costs for other low-carbon hydrogen production technologies [29]. *Updated according to [31]*

Technology	**INVCOST** $[\frac{M€}{PJ_{H2}}]$	**FIXOM** $[\frac{M€}{PJ_{H2}/year}]$	**VAROM** $[\frac{M€}{PJ_{H2}}]$
Solid biomass gasification, centralized medium	40.92	2.05	0.45
Solid biomass gasification, decentralized small	98.27	2.57	1.83
Solid biomass gasification w/CC, centralized medium	41.51	2.07	0.46
Solid biomass steam reforming, centralized	16.47	0.66	0.18
Ethanol steam reforming, decentralized	233.99		19.65*

The specific transport and transformation-related contributions to total cost of hydrogen in 2025 are reported in Table 7 in order to have a broader view of how the cost of hydrogen is composed in phases different from the production one. It is possible to notice how the transformation phases, especially when decentralized, affect the final cost of this energy vector. For example, liquefaction compared to on-site liquefaction have a x7.5 multiplication factor, which would not be compensated by possible transportation costs, keeping the centralized option as more convenient regarding this aspect. Similarly, refuelling phase from "Gas to Gas" has a cost slightly higher than one fourth for larger facilities with respect to smaller ones.

Table 7: step-specific cost contribution for hydrogen transport and transformation [29]

Step	Cost (€/kg)
Compression	0.09
Transmission pipeline	0.28
Liquefaction	1.05
On site liquefaction	7.47
Road Transportation Short	0.05
Distribution pipeline	1.80
Refueling Liquid to Liquid	1.15
Refueling Liquid to Gas	3.13
Refueling Gas to Gas (large)	1.01
Refueling Gas to Gas (small)	3.74
Underground Storage	0.25
Gas Storage Bulk	0.73
Local Gas Storage Bulk	1.42
Liquid Storage Bulk	0.18

2.3.2 Carbon Capture Utilization and Storage module

In order to obtain a complete overview on the hydrogen value-chain as implemented in the model, it is also necessary to describe the CCUS module, which contains carbon capture technologies, blue hydrogen production technologies and synfuels production technologies, some of which exploit also hydrogen in the process.

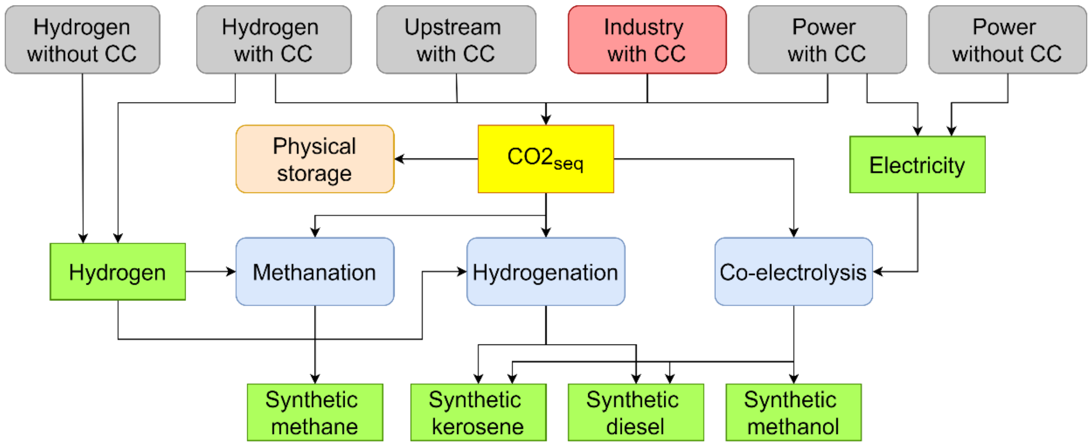

Figure 7: carbon capture utilization and storage module scheme and synfuels production [30]

Figure 7 represents a simplified scheme of the CCUS module, highlighting synfuels production and carbon capture connections with other sectors as in it contained. Hence, if the model chooses to produce blue hydrogen, CCUS techs are recruited including CO_2 capture activities. Blue hydrogen technologies have an emission factor which corresponds to the one of grey hydrogen production ones, minus the average of the captured CO_2 in the correspondent process. This value is then transformed from emission commodity to physical commodity, as previously explained, in order to model CO_2 storage technologies for sinks.

In general, synfuels are produced from previously captured CO_2 and an energy commodity, such as electricity or hydrogen. In TEMOA-Italy, three processes producing CO2-based synfuels were modelled:

1. Methanation: a process used to produce synthetic natural gas, (syn-)NGA, from captured carbon dioxide and hydrogen
2. Hydrogenation: in this case same components are combined to produce different synfuels, like synthetic kerosene or synthetic diesel
3. Co-electrolysis: captured CO_2 is combined with electricity to obtain same products of step 2. or synthetic methanol.

These technologies are quantitatively defined for input and costs as summarized in Table 8 and Table 9.

Table 8: quantitative definition of input commodities for synfuels production [29]

Technology	**Input commodity**		
	Hydrogen $[\mathbf{PJ}/\mathbf{PJ}_{\mathbf{synfuel}}]$	**Electricity** $[\mathbf{PJ}/\mathbf{PJ}_{\mathbf{synfuel}}]$	**CO2** $[\mathbf{kton}_{\mathbf{CO2}}/\mathbf{PJ}_{\mathbf{synfuel}}]$
Methanation (2020)	1.28		56.1
Methanation (2030)	1.25		56.1
Methanation (2050)	1.22		56.1
Hydrogenation for diesel and kerosene production	1.28		72.3*
Co-electrolysis for diesel and kerosene production from CO2 from emissions (2025)		2.33	72.3*
Co-electrolysis for diesel and kerosene production from CO2 from emissions (2030)		1.83	72.3*
Co-electrolysis for diesel and kerosene production from CO2 from atmosphere		3.00	72.3*
Hydrogenation for methanol production	1.22		69.30**
Co-electrolysis for methanol production from CO2 from emissions (2025)		2.18	69.30
Co-electrolysis for methanol production from CO2 from emissions (2030)		1.75	69.30
Co-electrolysis for methanol production from CO2 from atmosphere		3.00	69.30

** This value is an average between the CO2 emission factors of diesel and kerosene: indeed, the related technology can produce freely both synthetic diesel and synthetic kerosene, without any constrained shares.*

*** CO2 emission factor of the gasoline.*

Table 9: summary of quantitative data for synfuels production costs [29]

Delivery process	**INVCOST** $[\frac{\mathbf{M€}}{\mathbf{PJ}_{synfuel}/\mathbf{year}}]$	**FIXOM** $[\frac{\mathbf{M€}}{\mathbf{PJ}_{\mathbf{synfuel}}/\mathbf{year}}]$	**VAROM** $[\frac{\mathbf{M€}}{\mathbf{PJ}_{synfuel}}]$
Methanation (2020)	19.03	0.95	
Methanation (2030)	14.27	0.71	
Methanation (2050)	7.93	0.40	
Hydrogenation for diesel and kerosene production (2025)	15.47	2.85	0.06
Hydrogenation for diesel and kerosene production (2030)	12.43	0.33	
Co-electrolysis for diesel and kerosene production from CO2 from emissions (2025)	31.57	5.70	0.12
Co-electrolysis for diesel and kerosene production from CO2 from emissions (2030)	28.22	0.66	

Co-electrolysis for diesel and kerosene production from CO2 from atmosphere (2025)	126.26	22.81	0.46
Co-electrolysis for diesel and kerosene production from CO2 from atmosphere (2030)	112.86	2.63	
Hydrogenation for methanol production	26.94	1.72	0.10
Co-electrolysis for methanol production from CO2 from emissions	59.42	3.26	0.22
Co-electrolysis for methanol production from CO2 from atmosphere	237.68	13.06	0.87

Synfuels, either produced from hydrogen or not, enter end-uses phase themselves to satisfy corresponding demands in various sectors: they can be consumed in blending with the corresponding fossil fuels, hence in the existing end-use technologies (e.g., synthetic kerosene and fossil kerosene in jet kerosene-based airplanes), or they can be also consumed as pure in innovative technologies (e.g., synthetic methanol in ships).

Chapter 3

Scenario development

After integrating the whole hydrogen value-chain in the model the next step is to design two different scenarios to be compared with a baseline – a Business-As-Usual one – that should represent possible pathways for both decarbonization and hydrogen penetration in the energy system.

3.1 The studied scenarios

Considered the aim of the work, scenarios should be representative of a decarbonization pathway which can or not include hydrogen technology uses, in order to compare their convenience with respect to the model unconstrained choices. Provided the high complexity of constraints that a precise reflection of PNRR-related hydrogen development would have involved, and the lack of a set of precise values from it, it was decided to implement a simpler set of constraints, in order to better interpret results of the model. It is necessary to underline that increasing the number of constraints acting on the model, the optimization process possibility to provide a robust and reliable result decreases proportionally, furthermore, many strong assumptions would have been needed to apply these constraints in order to adhere to PNRR precise projections, further weakening the robustness and reliability of the results and ultimately, undermining the usefulness of present analysis.

For this reason, the path of minimum constraint was chosen for the scenario definition, using the following configuration of three scenarios in total, as described in Table 10.

Table 10: summary of defined scenarios for energy system modelling

			BAU	NZE	NZE w/H2	Sources
Definition			A scenario based on current policies development. It includes planned interventions as described in PNIEC for 2030 and forwarded with same trends until 2050.	A scenario reflecting 2015 Paris Agreement target of reaching Net Zero Emissions in 2050. It accounts for a residual amount of emissions due to the lack of LULUCF sector implementation in the model. This amount reflects what contained in LTS.	A scenario with the same emissions constraints of NZE one. Additionally, it includes forcings on hydrogen production for years 2030, 2040 and 2050 reflecting the objective of meeting 2% of final energy demand through hydrogen use in 2030 and 20% in 2050.	
Objectives			Showing that currently implemented policies are not enough to achieve PA target by 2050.	Showing what would be needed in each sector for meeting PA target by 2050.	Showing what advantages and/or disadvantages would bring to include a high use of hydrogen in the system.	
Constraints	Total CO2 [kton]	2030	-	114000	114000	Least reasonably achievable with respect to Fit for 55 [32]
		2040	-	85000	85000	Interpolated value
		2050	-	45000	45000	Maximum LULUCF absorption capacity according to LTS [10]
	Hydrogen production and consumption [PJ]	2030	-	-	88	2% of BAU final energy demand in 2030 [11]
		2040	-	-	489	Interpolated value (with respect to 890 PJ in 2050)
		2050	-	-	600	Starting from 890 PJ (20% of BAU final energy demand in 2050), reduced until a solution could be found [11]

The choice developed in the table above is going to be deeply justified through the complete analysis of utilized sources in the following paragraphs. The collection of the information reported in the following constitute the basis for the inference of such a scenario configuration and is going to be used as a reference also in the comparison phase, occurring in the following chapter.

It has to be noticed that the final values used in the model as constraints are somewhat approximations. This is due to various factors that influence the functioning of the model itself and a compromise was needed to be established between the desired constraints and the feasible ones. Considering hydrogen production values, for example, the ambitions reported in the Italian hydrogen strategy were taken as a reference [11], applying the targets of covering the 2% and the 20% of the final energy demand to the years 2030 and 2050, respectively. Nevertheless, the model resulted in an unfeasible solution and the system could not be solved. Consequently, a procedure for attenuating these constraints was followed:

- In the first place, the objective for 2050 was kept as a reference, since that directly reflects the emissions target to be achieved, modifying and diminishing the other constraints, but this did not produce any positive outcome on the results.
- Secondarily, the same imposed boundary condition was omitted, keeping the remaining ones as established by the reference, in order to verify whether it was constituting reason of failure for the model or not. As assumed, it was, and for this, the following step was executed.
- Since the constraint for the year 2050 was revealing a problem, some iterations were performed, progressively lessening its value, until the final working figure of 600 PJ was reached.
- It must be noticed that since the 2040 value did not provide any unfeasibility for the model, the higher interpolation value was used for this year.

A similar procedure was followed also for the total carbon dioxide emissions constraint, but in this case the year under investigation was 2030. Since the boundary for 2050 is already considerably ambitious, the purpose of this iteration was to try reducing the total amount of emissions before reaching that target, in order to verify what the model considers feasible:

- The reference value was the Fit for 55's target of reducing CO_2 emissions by 55% by 2030 with respect to 2005 [32], and the reference value for 2005 for Italy was taken from LTS [10]. This established a limit of 153 million tonnes of carbon dioxide for the country, to be respected in 2030.
- After the verification of the feasibility of this constraint, the procedure followed in reducing it progressively, until an unfeasibility condition was found or a totally unreasonably value was reached.
- The last value providing a valid result was 114 million tonnes of carbon dioxide, which is a considerable 25% additional reduction with respect to an already remarkably ambitious target of minus 55%.
- 2040's constraint value was consequently interpolated and applied, and a solution could be found.

These values could already represent a non-realistic target for decarbonization pathways, but considering the results obtained, and hereby analysed, this was taken into account as a maximum effort representation in meeting the international objectives.

The established constraints were applied in particular as follows:

- Carbon dioxide emission limit: it represents the net emission of aggregated carbon dioxide coming from all the sectors included in the model, where CCUS technologies provide negative output amounts. Hence, these facilities can be used in order to respect the limit imposed by the constraint.
- Hydrogen production limit: this constraint is applied in such a way that it does not force any specific hydrogen related technology, instead it requires the system to produce (and consequently consume) a specified amount of H_2, identified by an energy amount, corresponding to the related percentage of final energy demand as previously described. In order to apply this generic constraint, a

group of technologies was created in the database of the model, including all those technologies that transform produced hydrogen in sector-specific hydrogen, and this group was later constrained to have the established activity, meaning that the output energy, provided to final demands, corresponded to the desired amount. The list of technologies belonging to this group and, in general, the modification applied to the TEMOA-Italy database are reported in Appendix 1.

3.2 National Recovery and Resilience Plan

National Recovery and Resilience Plan was developed consequently to COVID-19 pandemic as the main device of the Next Generation EU intervention from the European Commission, established as a recovery measure for the Italian and the other European countries' economy [24]. PNRR is devoted to settle growth trends for Italian economy along with the integration and improvement of several national systems and infrastructures that contribute to the social, environmental and health sectors of the country. In order to foster this growth, Italian government set up six different missions allocating resources to each of them and establishing pathways to accomplish corresponding tasks. The total amount of earmarked funds is 191,5 billion euros with investments covering years from 2021 to 2026 and also adding resources from other European established funds. Missions cover many economic sectors and are focused mainly on digital evolution and implementation, quality of services offered, and environmental and efficiency objectives. In particular they are declined as follows [24]:

- Mission 1: Digitalization, innovation, competitivity, culture and tourism
- Mission 2: Green revolution and ecologic transition
- Mission 3: Sustainable mobility infrastructure
- Mission 4: Education and scientific research
- Mission 5: Social inclusion and cohesion
- Mission 6: Health

"Mission 2" is dedicated to energy transition and ecology, in which is also explicitly included hydrogen development and deployment fostering as one of the main alternatives for the decarbonization of the Italian industry, especially in steel and iron production, as well as for contributing to accelerate transport emissions cutting. The details of how investments are deployed in these areas of interest are reported and commented in the following paragraphs.

However, the goals that the PNRR proposes for hydrogen reflect what already state in the Italian Hydrogen Strategy [11] and are of two different natures: on one hand it sets a generic achievement to be accomplished by 2030 and 2050, which is to cover final energy demand with hydrogen accounting for 2% and 20% of the total share, respectively. This estimation leaves some uncertainty in the implementation process, due to the fact that the energy demand in 2030 and 2050 for Italy is not known a priori and the PNRR does not provide any further estimation: this led to implement values corresponding to BAU scenario, and assuming these would be acceptable. On the other hand, it recommends sector specific objectives to be gained with year-by-year funds allocation that shall be exploited through competitive bidding processes established on project proposals base. [24]

3.2.1 Transport Sector

Transports represents as of today the second emissive source for carbon dioxide in Italy, accounting for 30% of the total emissions [10], representing one of the sectors with the most suitable opportunities for transition towards low-emissive energy carriers. Almost 95% of the CO_2 produced in this sector derives from road transport, with passenger cars weighting for 70% [10]. About 25% of the emissions is covered by heavy trucks and LCVs.

Hydrogen is expected to have a wide positive impact on transport, both from an environmental and a quality-of-service points of view [24]. The premises are encouraging for exploiting this energy vector in heavy and public transport carriers, in road and non-road compartments, for the latter in particular, the efficiency offered by hydrogen use should represent a possible upgrade of many current technologies. The Plan prescribes two main interventions that should play the role of pilot projects for testing new technologies and enabling future developments, and these are presented in the following.

Table 11: planned investments and main goals for transport sector according to PNRR [24]

	Main Features	**2023 [MLN€]**	**2024 [MLN€]**	**2025 [MLN€]**	**2026 [MLN€]**
RAIL 300 MLN€	Test of production, distribution and trade integrated system for H2 trains	95	95	75	35
ROAD 230 MLN€	Installation and use of 40 refueling stations	70	60	60	40

3.2.1.1 Rail

Since the majority of the connections are already electrified, the objective of this action is to substitute remaining diesel-based lines with hydrogen ones with pledges as reported in Table 11.

- Passenger transport: these kinds of links are quite spread all over the Italian territory and characterized by a high average age of the system, for this reason hydrogen use could result in a major positive effect on CO_2 reductions of this subsector. Furthermore, this intervention presents favourable opportunities to combine also with the following one.

3.2.1.2 Road

Table 11 includes also planned investments for road transport development detailed as follows:

- Trucks freight transport: road transport offers the most convenient conditions for hydrogen application on the heavy load, long-range side. In order to achieve a transition for these elements of the system, funds are established to be used for refuelling stations instalment along one of the most exploited routes of the country, placed in the northern side, running on the West-East direction.

The two actions reported offer rich interaction opportunities, since hydrogen production and refuelling need to be placed in a strategic way for both interventions, as well as for further use that are foreseen in future developments. For this reason, regarding rail passenger transport, projects including lines compatible with heavy truck routes are going to be preferred for compatibility with PNRR funds [24].

3.2.2 Industry sector

On the other hand, the industrial sector is widely acknowledged as a hard-to-abate emissive sector, mainly because its high rate of polluting processes satisfies a demand that is hardly lowered, and the nature of the processes are strongly fossil fuel-based. The most promising option for this sector is precisely hydrogen, as demonstrated by Direct Reduced Iron (DRI) process and the interactions with ammonia and methanol production. H_2 is nowadays already used in industrial sector, particularly in iron and steel production with an annual demand of 0.51 million tonnes, entirely produced through fossil fuel-based processes [5].

	Main Features	**2023 [MLN€]**	**2024 [MLN€]**	**2025 [MLN€]**	**2026 [MLN€]**
INDUSTRY 2 BLN€	Retrofitting/refurbishing and substitution of industrial fossil fuel use with blue and green hydrogen	200	450	650	700

3.2.2.1 Planned interventions

The efforts, according to Italian recovery plan, should be devoted to [24]:

- Conversion of current grey hydrogen production, hence, fossil fuel sourced, to blue hydrogen, through the addition of Carbon Capture phase after production, which presents both high decarbonization potential and possible criticalities on lowering the production efficiency.
- Integration of the system with new green hydrogen production plants, mostly deriving from water electrolysis. This kind of process is allegedly controversial with respect to decarbonization strategies [14] [5]. On one side, it presents a non-emissive source of hydrogen in the production cycle, on the other one, this decarbonization potential strongly depends on the energy mix with which is fed, since it absorbs electricity and water, producing hydrogen and oxygen. That is why, in the recovery plan, new renewable energy sources installations are included in this

intervention to supply the energy requirements of this technology, and on this point some other issues emerge:

a. Hydrogen production through water electrolysis presents very high energy intensity, and it results much less convenient than fossil fuel-based alternatives, even where renewables show most favourable conditions [14]

b. Renewable energy sources are hardly matching this very high energy demand and new installations would be unsuitable with sustainable development (land use, critical raw materials use, etc.)

c. Moreover, variable renewable energy sources such as wind and solar energy provide intermittent energy output with high peaks and zero-productive periods, while hydrogen output is expected to be stable and constant to a desired value when a demand is established. In order to face these issues, plants should be largely oversized, and storage should be considered on electricity or hydrogen side (or both), increasing capital and operating costs as well as complexity of the plants. [14] [5]

All the overseen aspects need to be accounted for during the integration of the hydrogen value chain within the TEMOA-Italy model and some objectives need to be defined. In fact, this implementation is not a standalone modification of the existing system, it is instead thought and made in the perspective of the construction of decarbonization scenarios, which should enable the user to interpret, after comparing them with a BAU pathway, the advantages and obstacles of this energy vector for a sustainable development.

In this regard, Italian perspectives and policy framework for a sustainable growth were analysed and shall be presented in later paragraphs.

3.3 Decarbonization objectives

Italian government has recently published a reference document for decarbonization plans throughout the 2020-2050 time period, titled “Long-term Italian strategy for Green House Gases emissions reduction”, which described Italian energy system and economic sectors with emissions inventory and current and future policies to be adopted in the perspective of reaching Net Zero Emission objectives in the year 2050 [10]. This document adopts 2015 Paris Agreement’s perspective and responds to European Green Deal for carbon neutrality by 2050 with the elaboration of possible scenarios based on the rationale of promoting efficiency as a decarbonization mean and possibly the highest GHG reduction strategy.

3.3.1 Green Deal and European objectives

As so far discussed, EU explicit goal for 2050 is carbon neutrality [2]. This choice is made in the awareness of the needing for a health environment for life to keep on thriving and the strategy with which this ambitious objective must be pursuit is under continuous update and refinement. The Green Deal is the main tool for the transition to be achieved and it is an international agreement constituted by several initiatives or actions established by parties in the pursuit of development goals for energy independency of Europe, economic growth decoupled from resource use and a just transition for everyone and each territory of the continent. Several objectives are established by this agreement, touching environment, economy and energy [2]. The general approach of this intervention is to integrate change and evolution in the system as a whole, rather than addressing problems one-by-one. This is made in the perspective that each sector is influencing one another and in particular, they all interact with the natural environment.

A specifically relevant package of proposals is the so-called “Fit for 55”, a subset of actions which aims to translate Green Deal objectives into laws for Europe. In particular it includes [32]:

a) Update of the EU ETS system, including also naval transport, and update of laws for aerial transport emissions as well as the establishment of a specific emissions trading system for road transport and construction industry.

b) Update of rules for sharing efforts for non-EU ETS emissions (ESR).

c) Update of LULUCF emissions accounting rules.

d) Modification of regulatory framework for road car and heavy vehicles emissions.

e) Update of directive for renewable sources.

f) Update of directive for energy efficiency.

g) Update of directive for energy product taxation.

h) Balancing mechanisms for borders carbon exchange.

i) Update of directive for alternative fuels infrastructure adoption.

j) ReFuelEU Aviation for aviation alternatives fuels.

k) FuelEU Maritime for naval alternative fuels.

l) Social climate fund institution.

m) Update of directive for energy efficiency in construction industry.

n) Methane emissions reduction in the energy sector.

o) Update of “Energy” package about gas.

The adoption of the package Fit for 55 represents the law-binding effort of parties for a 55% emissions reduction in 2030 with respect to 1990 levels and implies a series of actions climate change adaptation strategies, biodiversity preservation and recovery, sustainable models for production and consumption and for industry, and circular economy for decoupling of economic development from resource use.

The following Figure 8 summarizes these objectives as reported by European Commission.

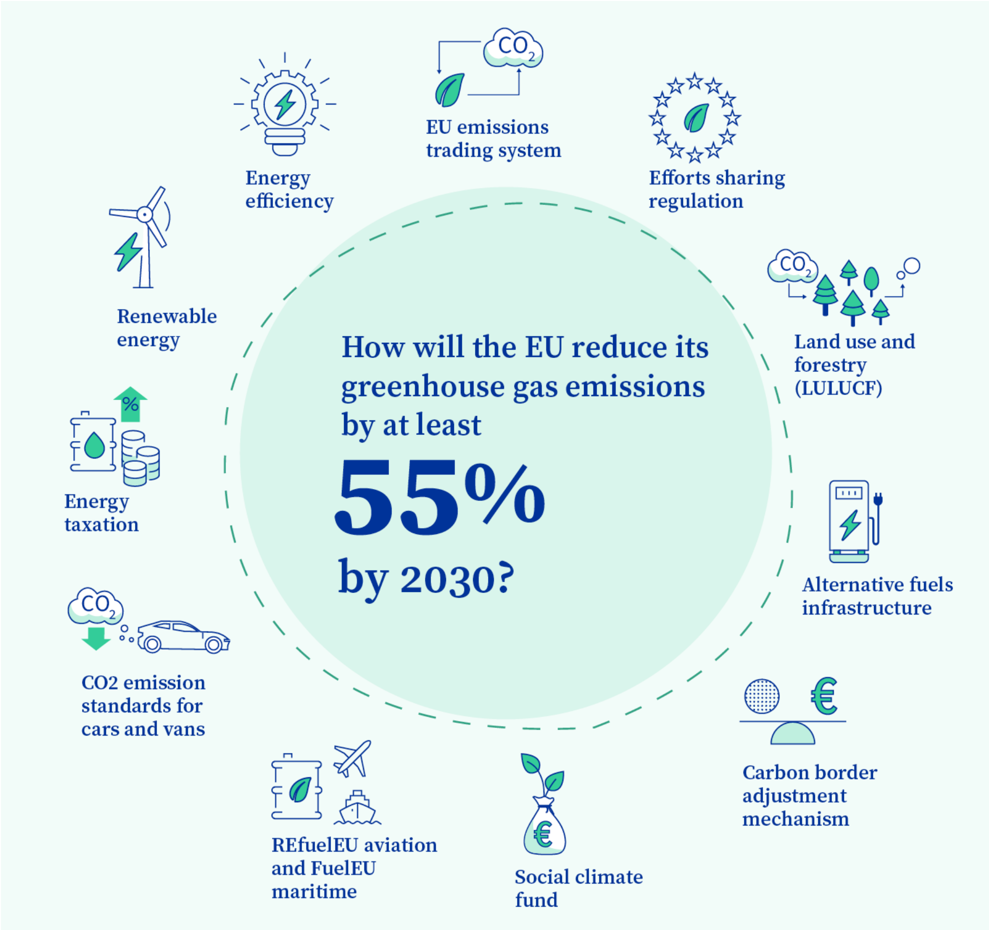

Figure 8: synthetic representation of Fit for 55 EU's objectives [32]

3.3.2 Long-term Italian strategy for Green House Gases emissions reduction

The premises to the document establish different hypotheses for the following analysis, starting from the funding principle of enterprising a strong transition in all the relevant sectors of the economy as well as in the habits of Italian people. Noticeable main assumptions that summarize the foundations of the study developed by the Italian government are listed as follow, underlining relevant differences with the present document when occurring [10]:

1. Demographic variables and fuels prices trends for LTS are based on the most up-to-date official data available. It must be highlighted that regarding the LTS, values corresponding to years until 2015 and (in some cases) 2018 are kept constant due to a lack of past information in the document. In TEMOA-Italy model, drivers are mainly based on PNIEC 2019 [23], hence, not taking into account COVID-19 consequences.
2. LTS proceeds in describing sector by sector hypotheses for scenario developing, especially regarding evolution of different demands or material flows according to their established drivers. TEMOA-Italy, differently, allocates demands to different drivers as decided PNIEC 2020 and with, in some cases, the integration of post-pandemic changes. A fundamental difference is represented by the absence of the LULUCF sector in TEMOA-Italy model, for this reason, decarbonization pathway is going to be pursuit through reaching a net emission amount of about 45 million tonnes of CO_2, including CCUS.
3. Regarding 2030 objectives, LTS considers Italy to reach PNIEC achievements, cutting emissions by a 33% with respect to 2005 levels for ESR emissions, hence with an amount standing below 230 MtonCO_2. However, for the present TEMOA-Italy model, decarbonization strategy considers the most restrictive policy for CO_2 emissions, starting from Fit for 55 EU recent adoption and additionally reducing the limit for year 2030.
4. Differently from LTS, in TEMOA-Italy model no climate change related trends are considered in the drivers’ construction.
5. LTS considers a comparison between two different evolutions of the Italian RES in 2050, one is the projection of what already implemented for 2030,

dragging same tendencies towards the further time horizon in order to build a reference scenario for Net Zero boundaries construction. The latter is the real decarbonization scenario, which is strongly related to three factors:

a. Heavy reduction of energy demand thanks to consumption drops in passenger transport and residential

b. Profound shift towards renewable sources to satisfy the energy demand, simultaneous to hard electrification of end uses and alternative fuels penetration

c. Increase in CO_2 absorption and CCUS deployment when needed

The references for energy consumption in the document refers to, in first approximation, gross primary energy demand, as shown in Figure 9, which is expressed in million tonnes of oil equivalent (Mtep). The historical datum for year 2018 reaches over 150 Mtoe, corresponding to about 6.3E03 PJ. Two other data are represented in the graph, one refers to decarbonization scenario in 2050, on the right, while in the centre a reference point is established through dragging the same objectives for the year 2030 to the year 2050. It is possible to observe how the two extremes are represented in the left and right columns, being the former the picture of the "traditional" supply system constituted mainly by natural gas (red) and oil products (blue), with minor contributions from renewables (green) which already grew considerably in first two decades of the century, and solid fuels which are being almost completely abandoned. The latter, on the contrary, depicts the ambitious goal of almost complete decarbonization, with energy supply provided by renewables accounting for more than 80% of the total. The effects of efficiency growth are extensively appreciable since the total gross energy demand diminishes from about 150 Mtoe in 2018 to more or less 105 Mtoe in 2050 in both the represented cases [10].

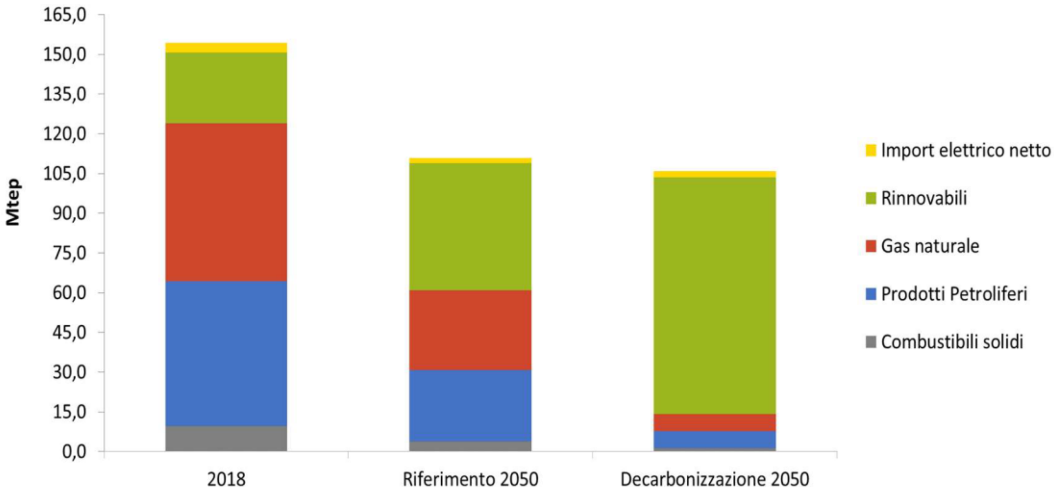

Figure 9: gross primary energy demand [10]

A refined analysis is performed in this paper, and before deepening in detail sector-by-sector the energy consumption and possible decarbonization strategies, also the end uses energy demand is portrayed, depicted in Figure 10, with a reference for 2018 of about 120 Mtoe, corresponding to 5E03 PJ. In this case the efficiency growth is even more evident for the decarbonization scenario and in this last case the electrification of the system (yellow) is more intense and accounts for above 50% of the total [10].

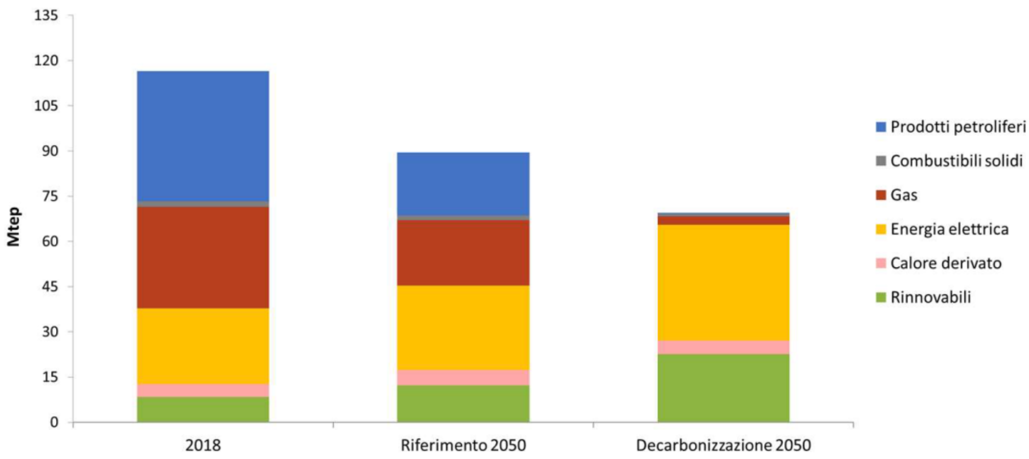

Figure 10: end uses energy demand [10]

Regarding emissions, ESR are considered in the following Figure 11, being these relevant for the present analysis since those are the ones for which a higher reduction expectation is applied by the European Commission. In the following graph emissions for years 2005 and 2018 are represented as historical data, while for 2030 PNIEC objective and the two scenarios for year 2050 are also reported. As already explained, the reference scenario in 2050 is obtained maintaining 2030 PNIEC policies and it is clear how this approach would reveal totally insufficient for a Net Zero Emission target. For this reason, a further decarbonization plan is developed and further explained in the document, with the goal of achieving a residual emissions amount of about 45 million tonnes of CO_2 equivalent, which shall be balanced by LULUCF sector only, providing negative emissions and restored at its maximum historical potential. This means that the value of residual emissions is resulting considering also CCUS contribution in the computation [10].

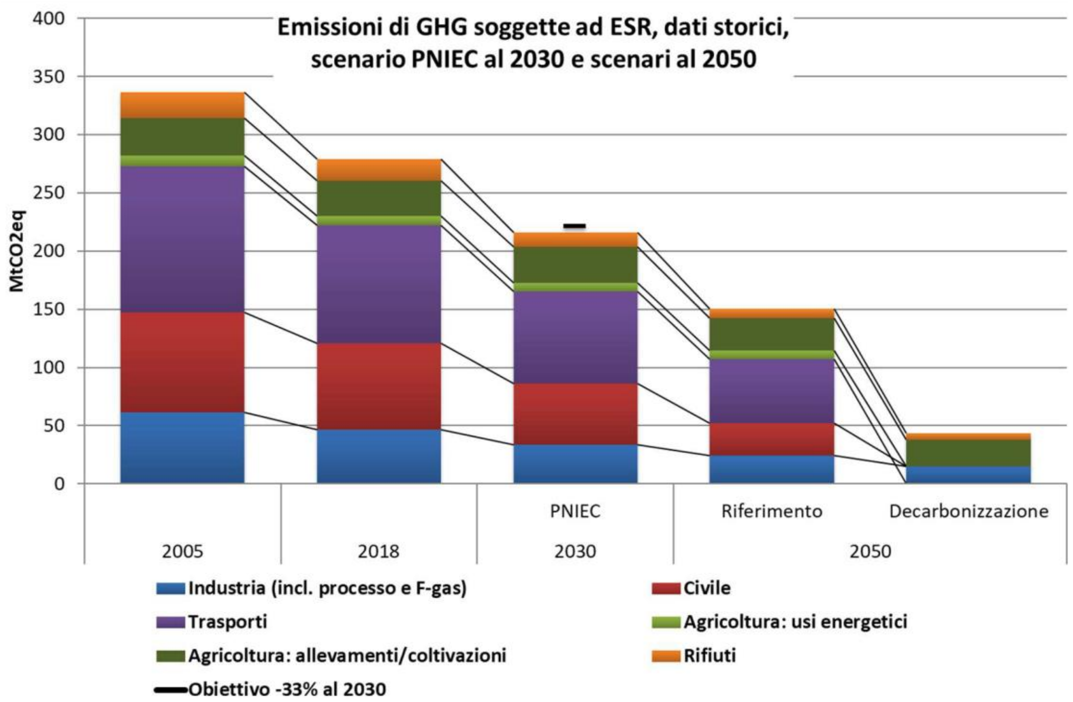

Figure 11: Effort Sharing Regulation emissions [10]

Chapter 4

Results

This chapter presents all the relevant results obtained from the three analysed scenarios. The following examination is intended in comparing the possible evolution of the Italian energy system respecting the related constraints. In all the presented cases the structure of the analysis will be the following, with minor deviations:

- In general, for each kind of result three graphs are going to be presented, one for each scenario, directly comparing different relevant features of the energy system and most considerable differences will be underlined and justified.
- Where needed, further analysis with a focus on the comparison of just two of the studied scenarios is going to be performed, to highlight important differences in the obtained profiles.
- Usually, a time step of five years will be represented in the following graphs, in the sake of clarity and conciseness. For what is represented as years 2035 and 2045, linearly interpolated values are shown.

The representation of results is organized in sections, or paragraphs, starting with a general description of the obtained evolution of the energy demand for end uses and power production in all three cases, and proceeding with the details of the hydrogen production and consumption configuration, underlining where constraints are set and where they are not, and the model is freely choosing to recruit different technologies.

4.1 End uses

The following represents the bulk energy demand used to satisfy final energy consumption, including services from agriculture, commercial, residential, transport and industry, in all the three scenarios. Figure 12 reports results obtained for Business-As-Usual, showing the evolution of the final energy demand from 2010 to 2050, and it is possible to observe how the system undergoes a slight efficiency increase process, diminishing the total amount of required energy in the first represented decade. It must be considered that this trend reflects the historical evolution of the demand and is going to be equally shown also in following scenarios.

Concerning commodities consumption, it can be noticed how the increase in the efficiency of the system represented a lessening in the oil and natural gas consumption, while electricity uses slightly increased in the time horizon. In the meanwhile, coal consumption remained almost constant and some other energy sources entered the system with a share accounting for less than 1% each, falling in the "OTHER" category.

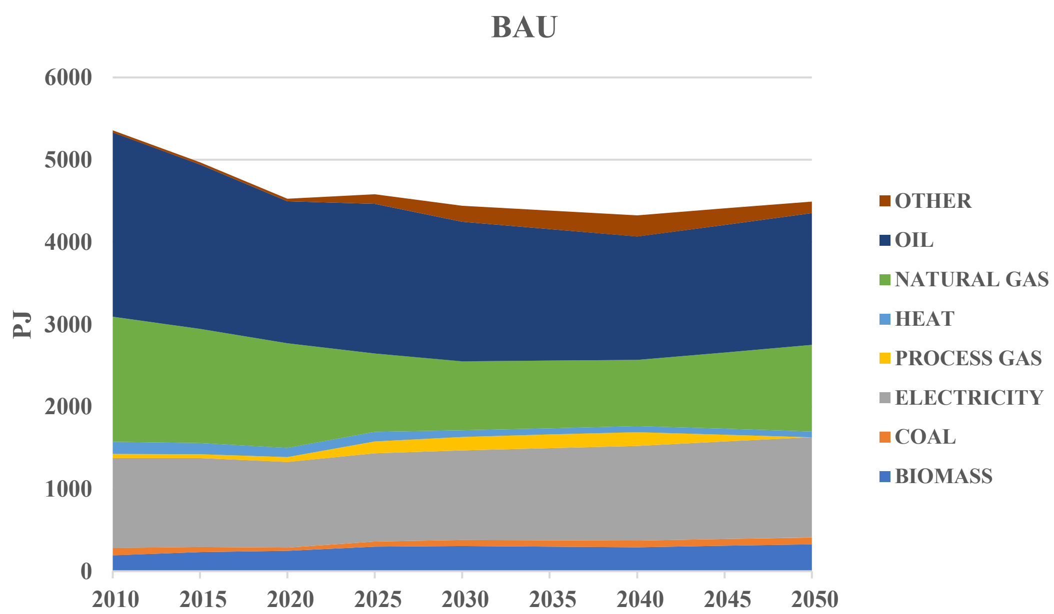

Figure 12: final energy consumption for Business-As-Usual scenario

This includes in particular renewable energy sources other than biomass, namely, solar, synfuels, geothermal and hydrogen which reasonably do not reach a high share in a Business-As-Usual scenario overall accounting for less than 2%.

Configuration of the system vary considerably in the following case, as depicted in Figure 13. A remarkable variation occurs especially in later years, as expected, where oil and natural gas shares drop consistently starting from 2030, with a progressive substitution obtained through synfuels use. Also, a higher efficiency increase can be highlighted for this scenario, with a total amount of end uses demand which is much closer to 4000 PJ with respect to the previous case and achieving a reduction of 8% in 2050 with respect to BAU. Synfuels share is going to be deeper analysed in the following, but it is important to take into account what explained in previous chapters about the functioning of the CCUS module. This includes the synfuels production through the use of captured CO_2, a combination of technologies that appears to be as convenient in a scenario where constraints on total emissions are imposed. Additionally, a more intense electrification process is occurring for this and the following scenarios, increasing the share of this commodity use on the total demand and reaching a value of 32% and 30% in 2050, respectively, with respect to 27% in BAU.

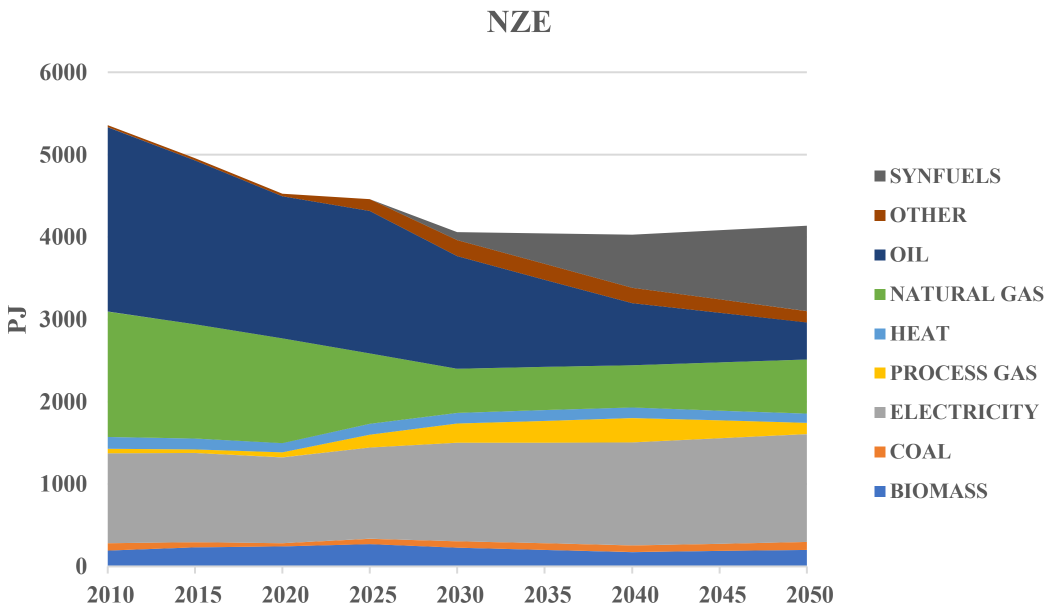

Figure 13: final energy consumption for Net Zero Emissions scenario

A very similar outcome results from the scenario with hydrogen-related constraints, and this is represented in Figure 14, for which same consideration as the previous ones can be done. Additionally, the expected introduction of hydrogen use is noticeable in this scenario, and a slightly higher total energy demand, especially after year 2040, is reported, but still 2% lower with respect to BAU. However, the same decreasing trend for oil and natural gas is provided by this optimization, which is reasonable considering that emissions constraints hold for this one as well.

A quite remarkable absence of renewable sources other than biomass can be noticed in all these results, but it must be emphasized that primary energy consumption for electricity production is not yet considered, and it will be in the following.

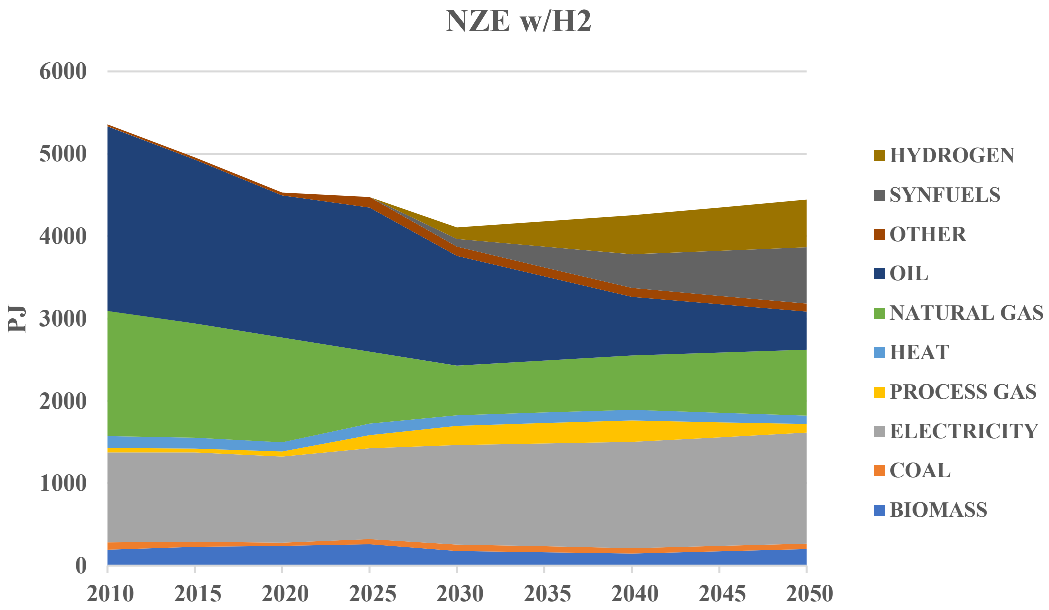

Figure 14: final energy consumption for hydrogen-constrained scenario

4.2 Power sector

The second section of the results aims to compare the model output for the electricity production in all the three configurations and, as previously, Business-As-Usual outcomes are reported firstly and shown in Figure 15. The mentioned increase in efficiency is extensively more evident in this part of the system, with a total production drop of about 25% in 2050 with respect to 2010. The actors contributing to satisfying the electricity demand are somewhat different from what represented previously and a baseline supply of electricity from geothermal and hydroelectric sources can be highlighted. These remain almost constant along the entire time horizon, as well as biomass uses and imports. Oil and coal power production disappear by 2030 and natural gas drops its share of more than a half, with an extensive substitution from solar and a minor contribution from wind energy.

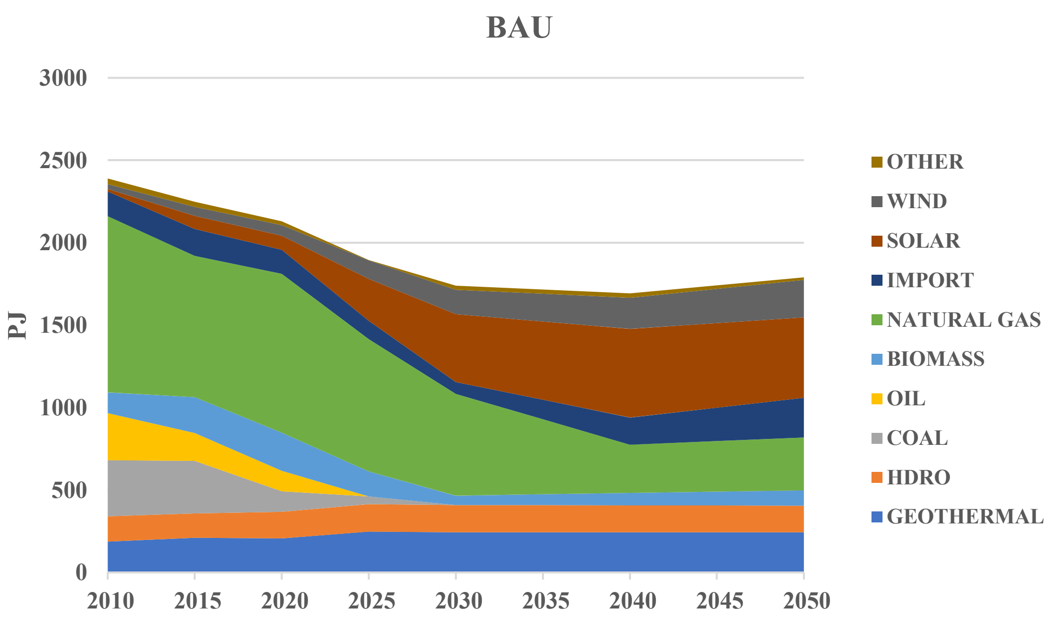

Figure 15: power sector energy demand for Business-As-Usual scenario

Gross total energy demand for Italy, would be obtained adding the graphs represented in this paragraph with the previous ones, each with its corresponding one according to the scenario represented and the resulting outcome would reproduce closely, for historical data, what considered as gross energy demand in LTS [10]. It is also to be stressed how these results well reproduce the past period trends, equally in all the scenarios considered.

In decarbonization scenarios the represented system undergoes mainly one important change, the increase of total electricity demand (of roughly 44% with respect to BaU) for year 2050, satisfied with the use of a higher amount of solar energy, as reported in Figure 16. This amount of energy supply from photovoltaic resource respects the limits imposed within the model [10] [31]. The growth of electricity uses can be related to a progressive electrification of the system, which, as previously seen, moves consumption from traditional sources to newer and more efficient ones.

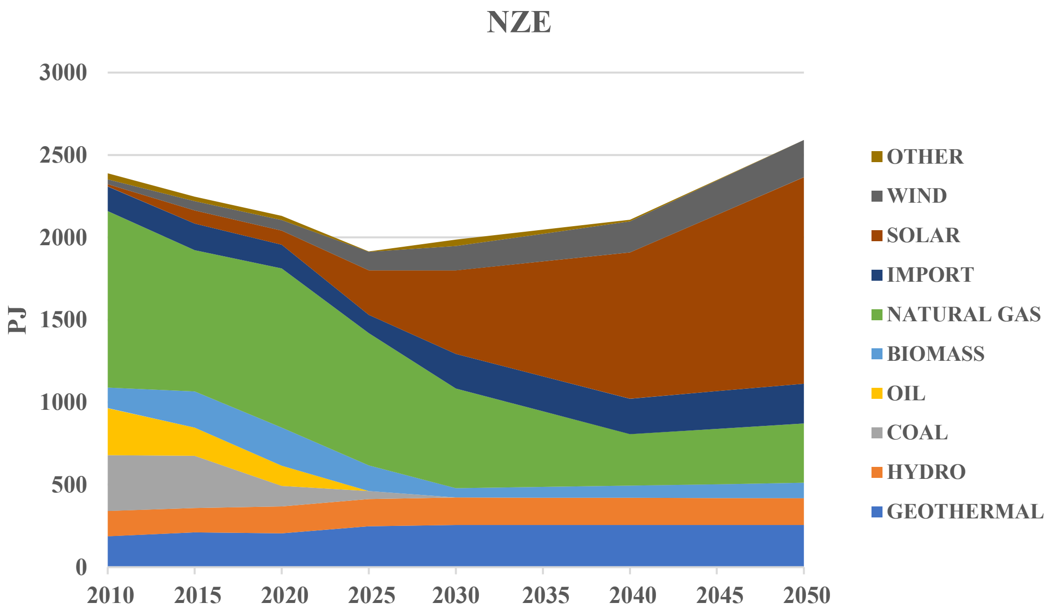

Figure 16: power sector energy demand for Net Zero Emission scenario

Same conclusions can be assumed for hydrogen constrained scenario, which results are shown in Figure 17, where this energy vector, as expected, does not intervene in the power production process, being extensively inconvenient to use it due to the high energy losses occurring in the transformation.

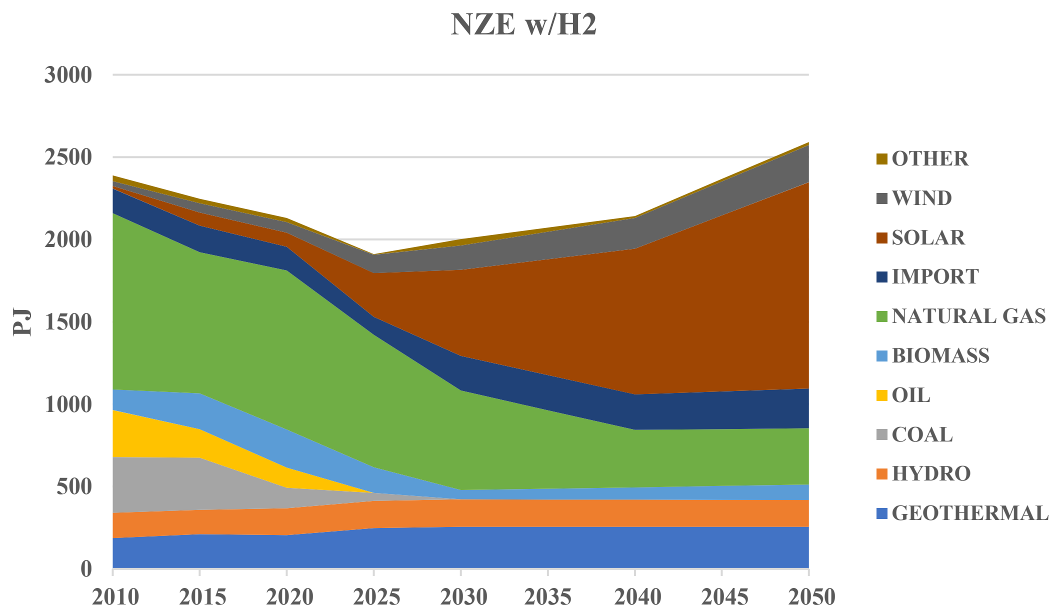

Figure 17: power sector energy demand for hydrogen-constrained scenario

4.3 Hydrogen production

Hydrogen production is one of the most important results to be analysed in this work, since the aim is focused on this specific energy vector and most of the conclusion should be supplied by these and the following results. Figure 18 represent immediately a particular outcome of the model, in fact, being this scenario unconstrained, it was not expected to freely choose blue hydrogen production, since this technology represents a higher cost with respect to the grey counterpart. However, it must be underlined that this scenario already contains some of the implementation deriving from PNIEC national plan, extended until 2050 and it must be considered the very low share that hydrogen represents with respect to energy demand, reported in Table 12.

Table 12: hydrogen consumption share in the energy demand for Business-As-Usual scenario

	2030	*2035*	*2040*	*2045*	*2050*
% gross energy demand (end uses + power sector)	0.67%	0.87%	1.06%	0.70%	0.35%
% end uses	*0.94%*	*1.20%*	*1.48%*	*0.97%*	*0.49%*

Reason for which this choice could have been made by the solver. Additionally, as is going to be displayed in further paragraphs, the hydrogen hereby produced is partially used for synfuels production, for which carbon capture is required, for this reason, the model could have done the choice of installing only a blue hydrogen technology to provide both supplies, instead of a grey hydrogen technology plus a carbon capture technology for CO_2 provision.

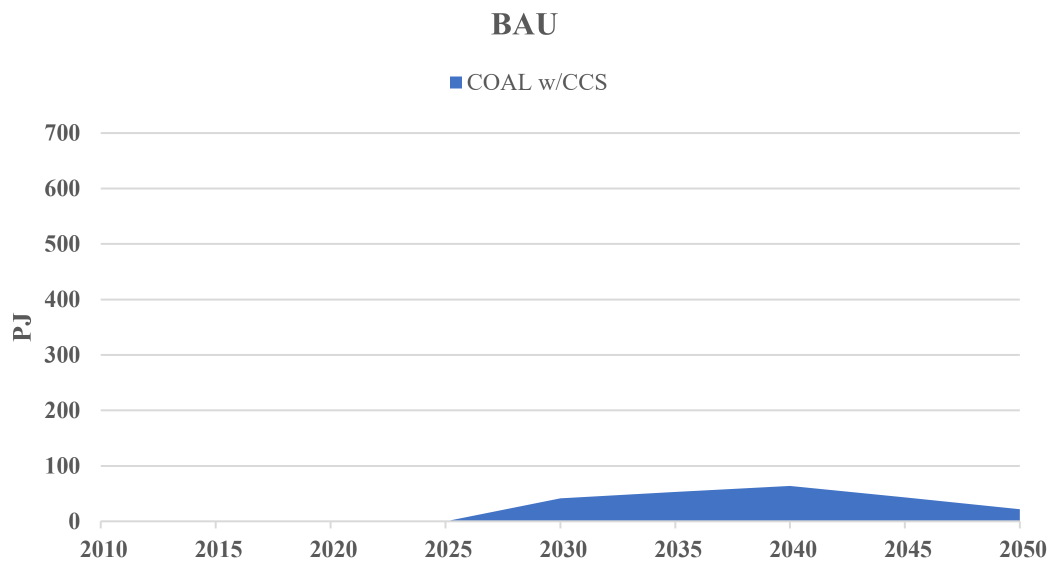

Figure 18: hydrogen production in Business-As-Usual scenario by technology

On this specific outcome, further studies shall be performed in order to obtain exhaustive explanation of this unexpected choice.

In the following Figure 19 represents the production of hydrogen for the Net Zero Emission scenario, in which the model freely chooses to include this energy vector in the system, in particular producing it through solid biomass gasification.

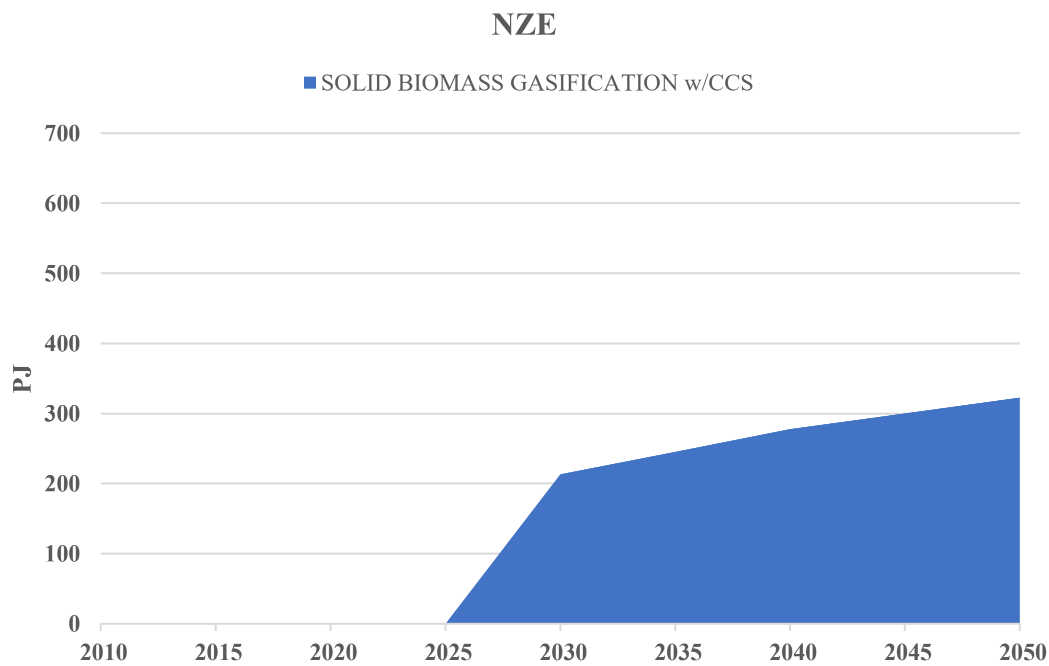

Figure 19: hydrogen production in Net Zero Emissions scenario by technology

Considering it being unconstrained, the amount of hydrogen produced is remarkable and this evidence strongly suggests that the energy vector is to be included consistently in the energy system framework in order to obtain a complete decarbonization of the economy and to put the country on track with emissions targets for 2050. Since the optimization process is obtained through a least-cost optimization, the inclusion of hydrogen technologies marks them as belonging to the convenient options needed for a net zero emission pathway. In the following section the use of hydrogen is going to be studied and analysed as optimized in the model.

It is also reported the share of hydrogen consumption on the total energy demand, described in Table 13.

Table 13: hydrogen consumption share in the energy demand for Net Zero Emissions scenario

	2030	*2035*	*2040*	*2045*	*2050*
% gross energy demand (end uses + power sector)	3.53%	4.03%	4.53%	4.67%	4.80%
% end uses	*5.26%*	*6.08%*	*6.90%*	*7.36%*	*7.81%*

Figure 20 shows hydrogen production technologies configuration in the case of a production constraints as previously defined, exceeding the amount spontaneously produced by the model and represented in the previous figure. Looking at the two graphs from NZE and NZE w/H2 scenarios, it could be noticed how the activity related to solid biomass gasification is preserved from the unconstrained to the constrained scenario, with the further addition of other technologies to meet the imposed limit.

It is here chosen a combination of four hydrogen production technologies, including one for grey hydrogen, one for blue hydrogen and two for green hydrogen, namely, steam methane reforming, steam methane reforming with CCS, solid biomass gasification with CCS and AEM cells, for water electrolysis, the latter intervening after 2040. Grey hydrogen production technology seems to be needed in order to accomplish the required production in year 2040, being considered also in a decarbonization scenario, where the model considers more convenient to emit in the upstream sector instead of in the demand side one.

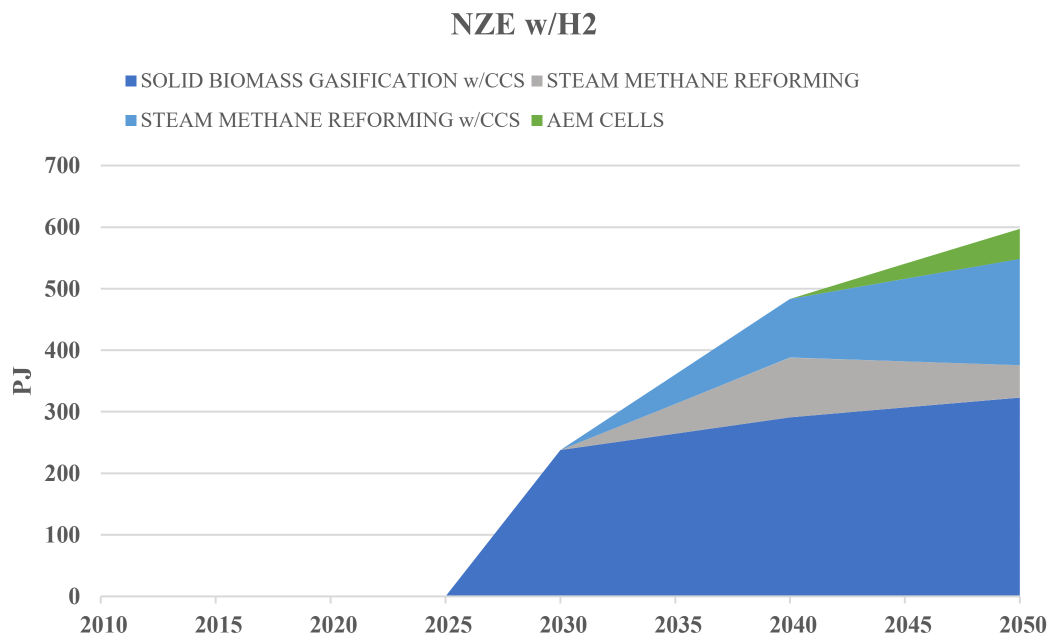

Figure 20: hydrogen production in hydrogen constrained scenario by technology

It is reported also in this case the share of hydrogen over the total energy consumption, as Table 14 shows. This can also be used to verify that the constraint foreseen of 20% of share of total demand satisfied with the use of hydrogen could not be respected, as previously stated and explained.

Table 14: hydrogen consumption share in the energy demand for hydrogen constrained scenario

	2030	2035	2040	2045	2050
% gross energy demand (end uses + power sector)	*3.89%*	*5.77%*	*7.56%*	*8.05%*	*8.49%*
% end uses	*5.79%*	*8.63%*	*11.37%*	*12.42%*	*13.44%*

4.4 Hydrogen consumption

Figure 22 shows the use of hydrogen in business-as-usual scenario, with almost half of it deployed in synfuels production, and all the rest destined to blending uses. as depicted in Figure 21, reporting the share of consumption by sector.

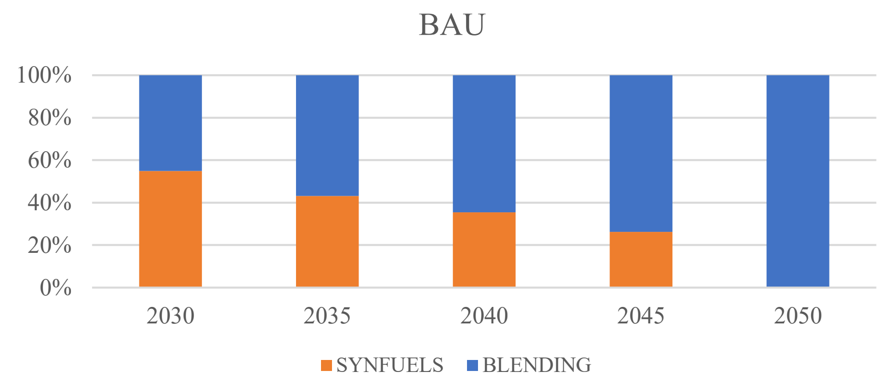

Figure 21: share of hydrogen consumption by sector in Business-As-Usual scenario

This blending follows the rules previously described for mixing limit due to restrictions of the infrastructure and can be used in all the sectors of the system to contribute to natural gas consumption decreasing the associated emissions.

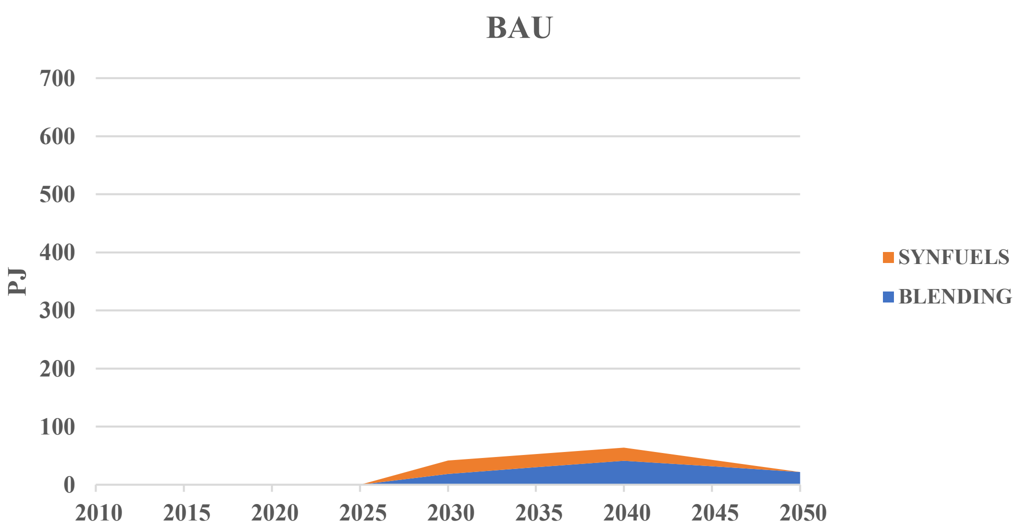

Figure 22: hydrogen consumption by sector in Business-As-Usual scenario

However, the represented amount of hydrogen produced is quite low and can be considered almost negligible with respect to the following scenarios.

As far as Net Zero Emission model results are concerned, the share of the hydrogen consumption is heavily unbalanced towards synfuels production, as Figure

24 is clearly showing. This choice made by the model is sided by the use of blending, and slight other uses including commercial sector and industry. The development of this consumption configuration also explains the rationale of having a hydrogen production with CCS, allowing to install a single technology and simultaneously obtaining captured carbon dioxide and hydrogen from it, two fundamental ingredients needed for synfuels production.

To have a clearer picture of hydrogen consumption configuration, shares are reported in Figure 23.

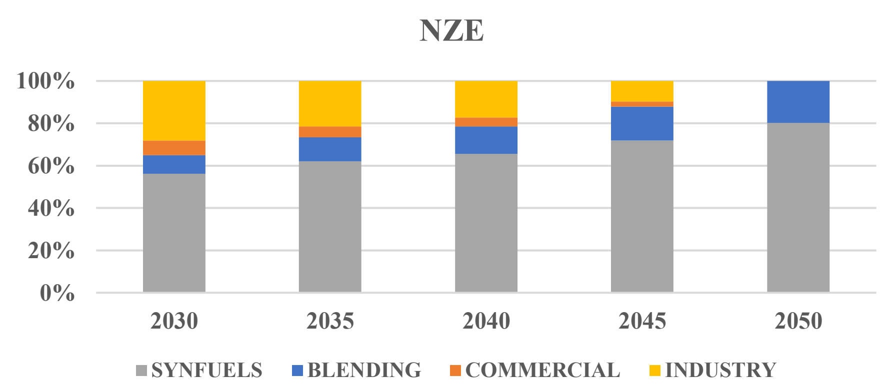

Figure 23: share of hydrogen consumption by sector in Net Zero Emission scenario

This process is going to be further analysed in following paragraph with insights over the detailed production of alternative fuels. However, the results obtained from NZE scenario can be already compared to the choices made by the model optimization for the hydrogen constrained one.

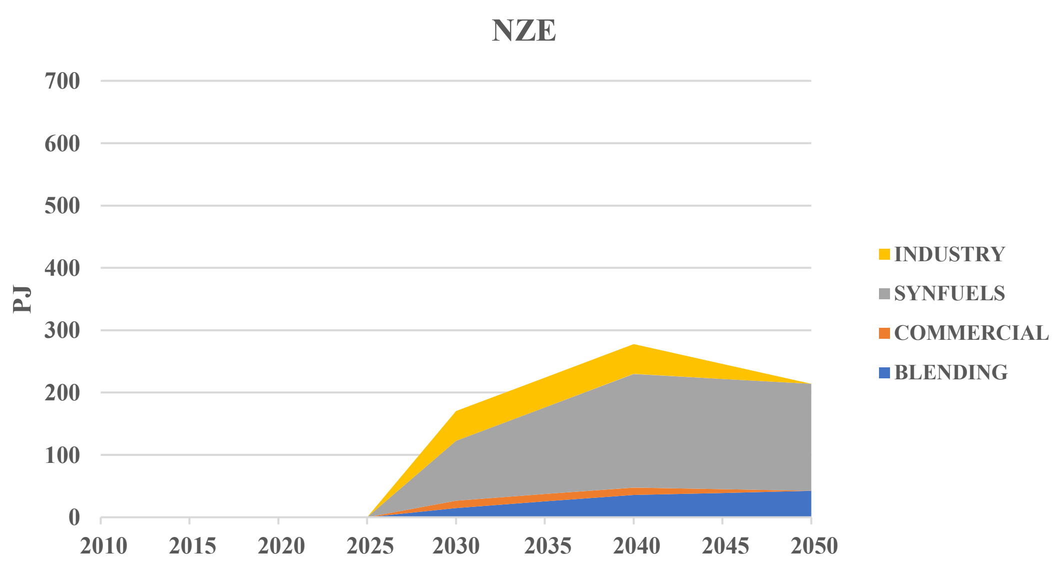

Figure 24: hydrogen consumption by sector in Net Zero Emission scenario

Figure 26 highlights an extensively different configuration for hydrogen consumption, heavily including transport and industry sectors in hydrogen end uses, also highlighted by the share graph in Figure 25.

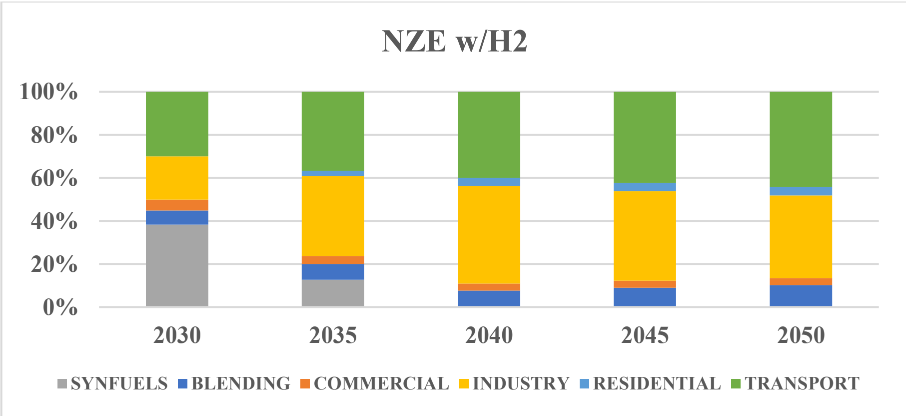

Figure 25: share of hydrogen consumption by sector in hydrogen constrained scenario

This behaviour of the system closely reflects what foreseen in PNRR projection, since hydrogen would have the major role of decarbonizing hard-to-abate emissions in industry, especially in iron and steel production, as it does in this case, and contributing to decarbonizing transportation technologies, especially in the case of heavy-duty freight transport and non-road categories. In particular, from these results hydrogen is extensively used in transport for both domestic and international aviation purposes, reflecting long-term projects and technology development in this field. However, this specific result requires further analyses and developments regarding the aviation sector modelling (also integrating proper constraints due to infrastructural prospects) to be solidly supported.

On the other hand, the results from NZE w/H_2 scenario shows a limitation in synfuels production strictly between 2025 and 2035. This specific characteristic seems to be in contrast with what expected in hydrogen developing pathway, where early blending and industry utilizations should enable the enhancement of a wider market for H_2 deployment, in order to achieve a consistent share of synfuels use and abating fossil fuels emission on long-term horizon. Obviously, synfuels have the same emissions of traditional fuels in use phase but present the great advantage of being produced through captured carbon dioxide, hence removing it from the atmosphere, and not introducing additional amounts of CO_2 in the system.

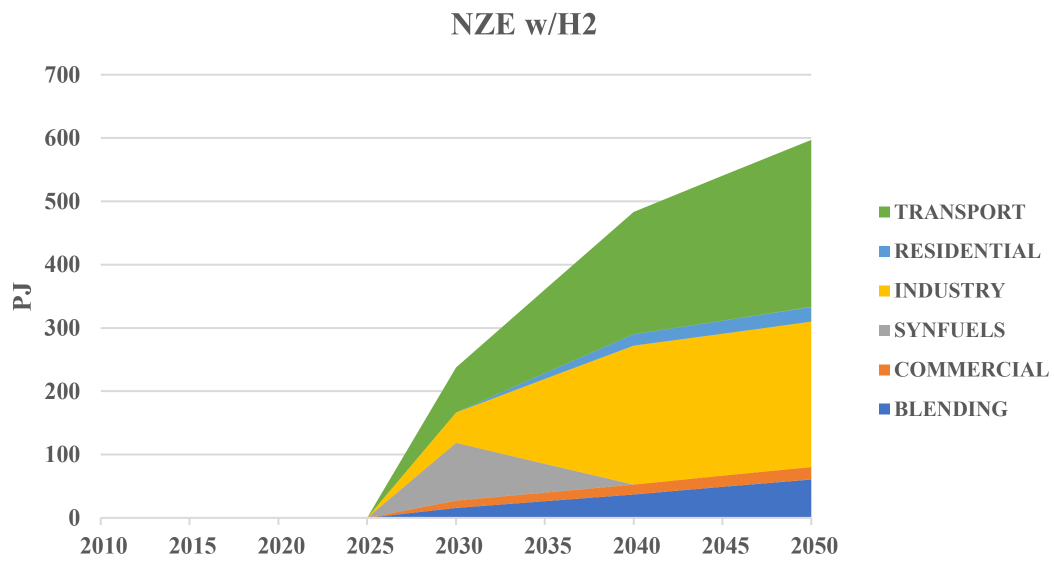

Figure 26: hydrogen consumption by sector in hydrogen constrained scenario

Conversely, what represented in the graph seems to sustain an opposite process, in which early usage of synfuels should foster later spreading of hydrogen in other sectors of the economic system. Furthermore, if compared with the previous results, the constraint on hydrogen production seems to prevent the model to get closer to the optimum, since in the NZE scenario, where hydrogen was not constrained, was produced anyway but used mainly for synfuels production.

For this reason, a modification of the NZE w/H_2 scenario was made, and the optimization performed. The results of this run are reported in Figure 27.

The modification consists of the addition of the technology that allows the use of hydrogen for synfuels production in the group which is constrained by the limit of minimum activity imposed. Previously, synfuels could be produced anyway (and it happens in NZE w/H_2 scenario), but as an additional amount freely chosen by the optimization process, standing outside the constraint. Conversely, including possible synfuels production in the restricting value, this activity is used by the model to satisfy that same limitation.

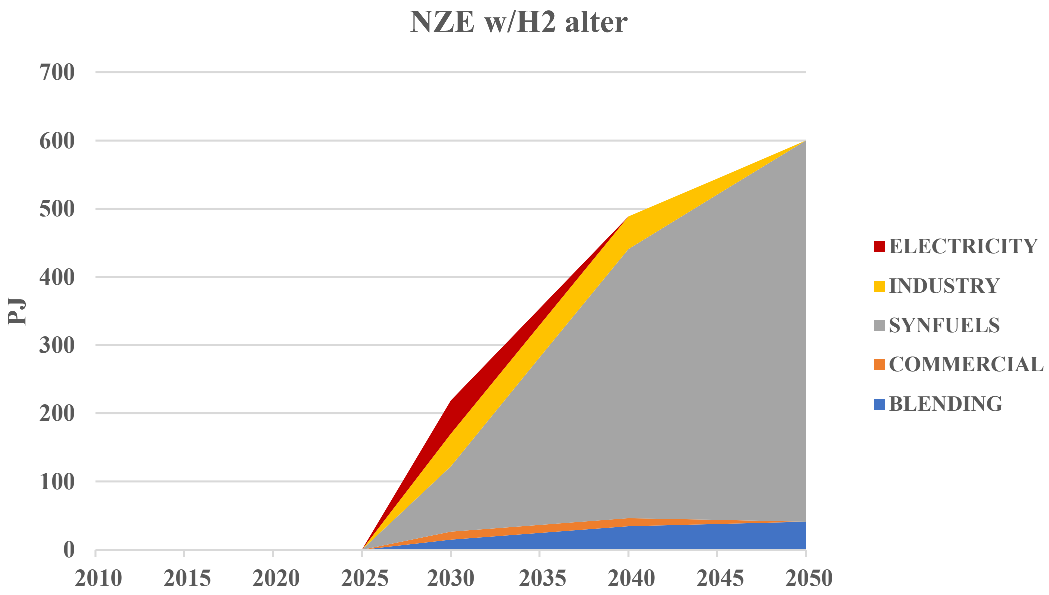

Figure 27: hydrogen consumption by sector in alternative scenario for hydrogen constraining

As also Figure 28 shows, when this modification is applied, results vary extensively, moving almost the entire amount of produced hydrogen towards synfuels production, and enhancing the effects of what already seen in NZE results.

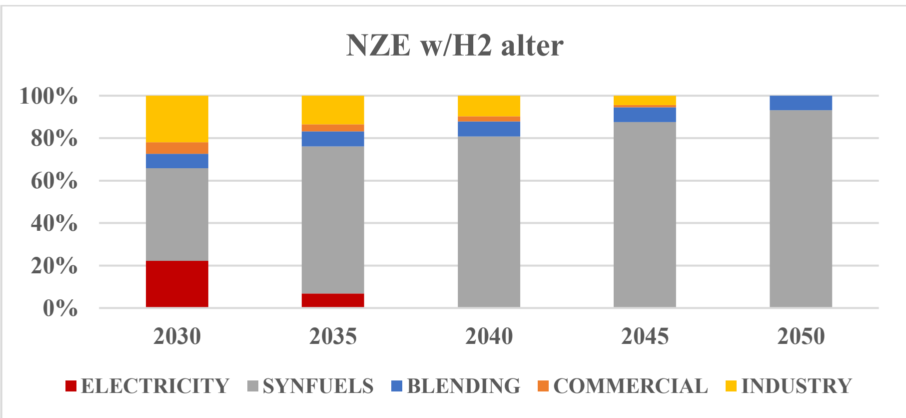

Figure 28: share of hydrogen consumption by sector in the alternative hydrogen constrained scenario

At the same time, what already stated about expectations in hydrogen development pathway, cannot be said to be met, since synfuels production occupy a consistent share of hydrogen use since 2030, and industry remain a secondary consumption purpose, while pure hydrogen do not appear in transport (as direct consumption) at all.

However, in order to better clarify what happens in consumptions steps which are closer to final demand, NZE scenario and this last one, are in the following section compared to perform a deeper analysis on the use of synfuels.

4.4.1 Synfuels

For this comparison, only the NZE and the alternative scenario for hydrogen constraint are considered, being them the scenarios within which a considerable amount of synfuels production, making the analysis consistent and useful for drawing conclusions. Starting with the NZE scenario, Figure 29 illustrates the production of synfuels provided without constraints on hydrogen utilization: it can be noticed how faster this production increases for those fuels that do not require H_2 use. Instead, captured carbon dioxide and electricity are necessary for these processes, corresponding to the grey area, justifying the choice of blue hydrogen production technology use in NZE scenario.

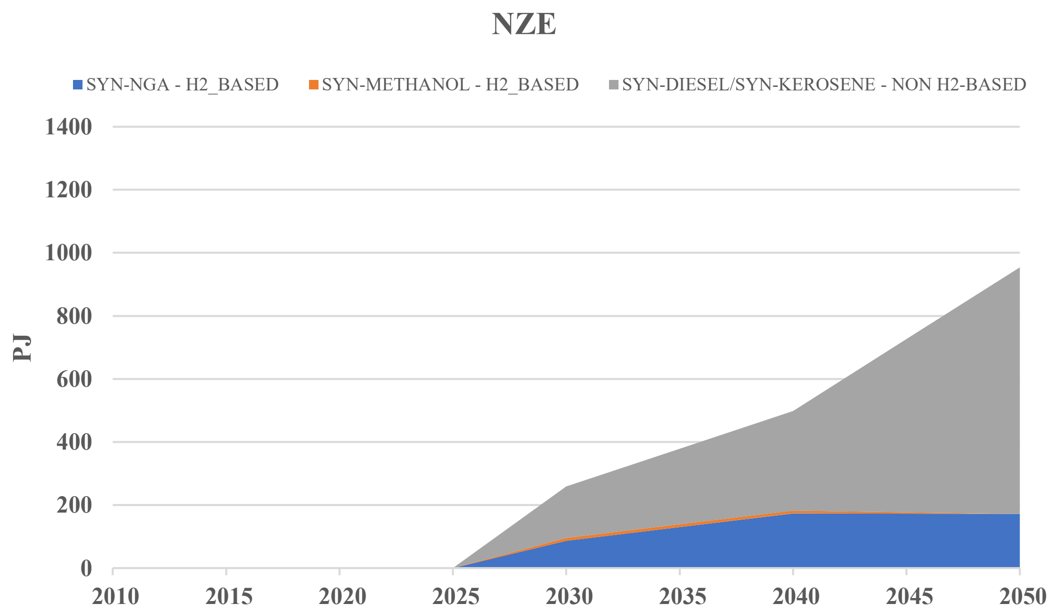

Figure 29: synfuels production, both hydrogen and non-hydrogen based, in Net Zero Emission scenario

Furthermore, Figure 30 reports the share of the synfuels consumption sector-by-sector, showing percentages corresponding to the fraction of each of the synfuel for each of the end uses demands, accounting for the cumulative amount of synfuel along the entire time horizon. This choice was made in order to prevent analysis of possibly biased data produced by single year considerations. Syn-diesel and syn-kerosene, which are produced without the use of hydrogen, are mainly consumed by agriculture and commercial sector, with former using the 12% of the total amount of syn-diesel produced and the 91% of the total amount of syn-kerosene, and the latter almost all of the remainder of the two fuels (but for 1% of the syn-diesel being consumed in residential sector). Syn-methanol is almost completely consumed in the residential sector (96%) but it must be underlined that the total amount of this propellant is almost negligible. Synthetic natural gas, which covers the large majority of the hydrogen-based synfuel production, is mainly used in the residential sector to contribute to space heating and cooking purposes (57%), equally consumed in commercial and industrial sectors (16% for each one of them), and the remainder subdivided between electricity production (9%) and agriculture (1%).

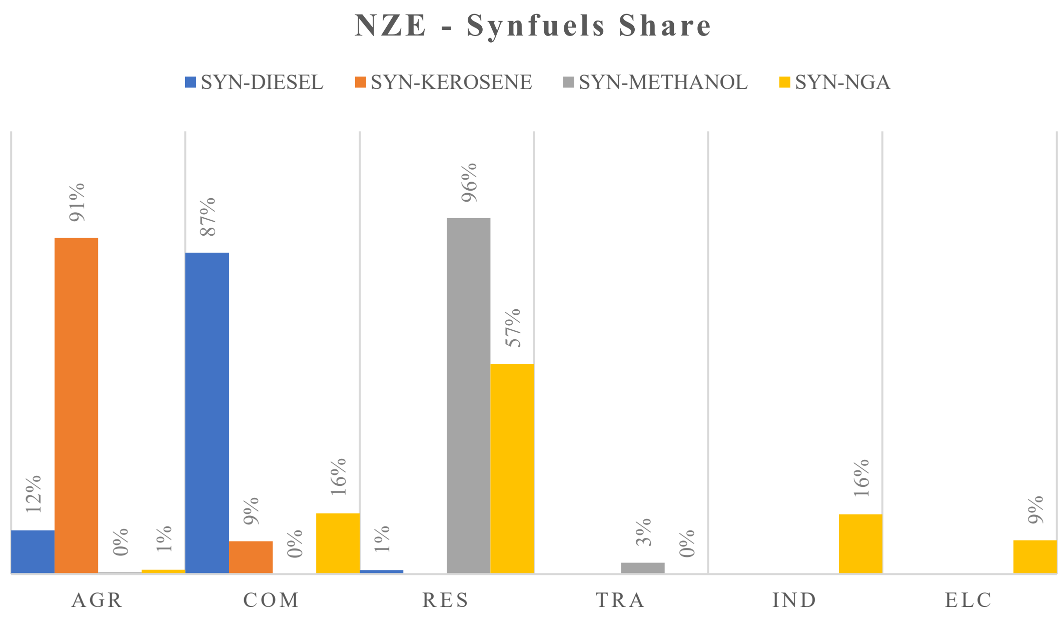

Figure 30: share in the use of synfuels by sector for Net Zero Emission scenario. The percentage is computed with respect to the cumulative amount of synfuels along the entire time horizon in order to prevent possible bias referred to single years

Same kind of analysis was performed for the second scenario considered in this section, with results reported in Figure 31. The considerations previously explained can be applied for this case also, whereas the share of hydrogen-based synfuels is much higher than before, due to the hydrogen constraint on the system. Syn-methanol, as in the former analysis, account for an almost negligible amount of total synfuels production. Being the total amount of blue hydrogen production increased, the system has at its disposal a higher captured CO_2 stock, hence, also non-hydrogen based synfuels production raised with respect to the previous case.

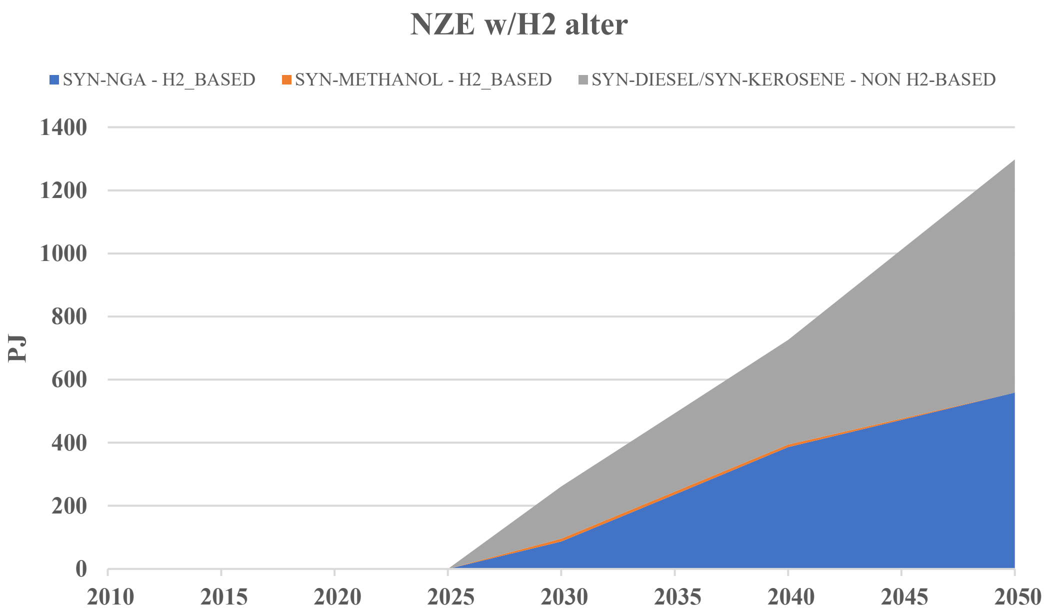

Figure 31: synfuels production, both hydrogen and non-hydrogen based, in alternative scenario to hydrogen-constrained one

Concerning synfuels' end uses, almost same configuration as the one already described is displayed in Figure 32, with some differences to be underlined only for syn-NGA, here being consumed for a 61% in residential sector and for a 33% in industry, and the remainder sectors accounting for less than 5% each.

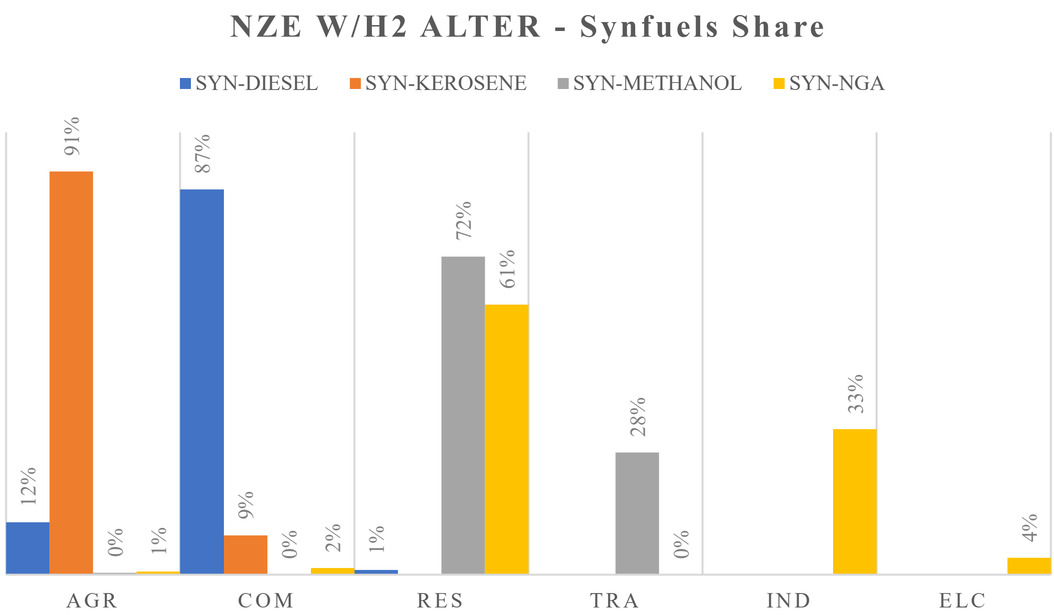

Figure 32: share in the use of synfuels by sector for alternative scenario to hydrogen-constrained one. The percentage is computed with respect to the cumulative amount of synfuels along the entire time horizon in order to prevent possible bias referred to single years

4.4.2 Sector-specific hydrogen consumption

In order to analyse the uses of hydrogen for the hydrogen constrained scenario, since the two most relevant contributions to this energy vector consumption were provided by industry and transport sector by far, these sectors where further studied to obtain the configuration of the produced end uses. Figure 33 reports the amount of consumed resource for the manufacture of ammonia, steel, and methanol, where the latter accounts for negligible amount and was included for completeness. Steel is produced through direct reduction processes, and the activity hereby shown covers more than 80% of the total domestic production, a remarkable result considering the PNRR and the National Hydrogen Strategy objectives, according to which this manufacture typology is one of the most promising for hydrogen usage and emissions abatement. In parallel, ammonia-related activities reach a coverage of 100% of ammonia production from 2040, being also this amount halved with respect to previous years.

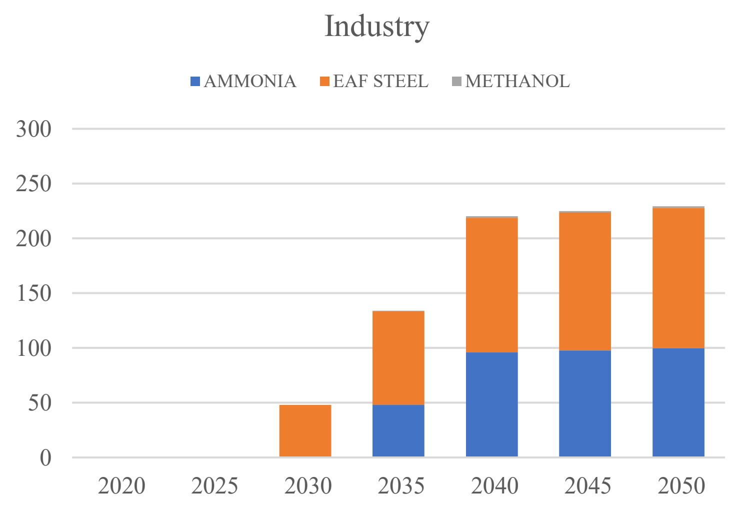

Figure 33:hydrogen consumption in industrial sector by final product in NZE w/H2 scenario

These results clearly introduce a promising framework for further hydrogen penetration analysis, since its potential lies mainly in the decarbonization power for these kinds of industrial processes.

Additionally, transport sector presents equally encouraging results, even though exclusively limited to the aviation category, as reported in Figure 34, with an increasingly important intervention of hydrogen-based mobility for this fraction of the sector, which achieves an outstanding 95% of the total domestic aviation demand and over 85% of the international one. This remarkable outcome has the same effect of the previously described one, bringing encouragement for hydrogen technologies development also for transports. However, the downside note is that these are the only hydrogen technologies related to mobility which were taken into consideration by the model, but for a negligible amount of rail passenger transport. This is also possibly related to high costs of hydrogen-based road transports, a factor which heavily affects results in such an optimization type model. Nevertheless, the real economic system presents a similar behaviour with respect to prices, favouring least-cost technology diffusion rather than other qualities, which is also the reason why these models can reliably be used for real-system applications and interpretations.

It must also be underlined that non-road transport are defined in order to satisfy a demand which is expressed in petajoules, while the most obvious unit of measurement for this sector would be billion vehicles per kilometre, which would also take into account the efficiency of the used fuel. This improvement in the model is already under development but was not ready at the time of this study. The outcomes of this refinement should however additionally favour H_2 uses in transport sector, being this energy vector more efficient than others.

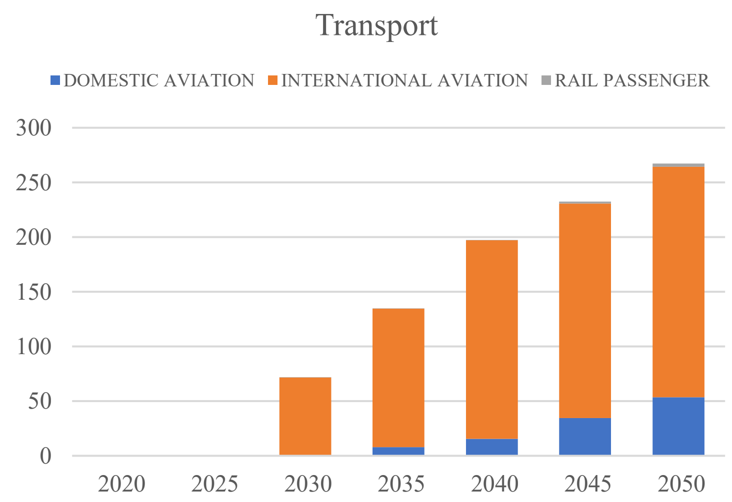

Figure 34:hydrogen consumption in transport sector by final product in NZE w/H2 scenario

4.5 Emission analysis

Finally, a deep overview of emissions configuration by sector is provided, in order to understand, together with the previous description of the scenarios outcomes, the decarbonization strategy put in place by the optimization processes.

Firstly, the Business-As-Usual related results are reported in Figure 35, indicating value labels in million tonnes of carbon dioxide per sector, and it is noticeable how some sectors, as the electricity production and, more slightly, residential ones, undergo even in this scenario a decarbonization process. Specifically, in the former this phenomenon is heavily marked, and recalling Figure 15 it is possible to understand that only a minor residual amount of natural gas is consumed for power production, with all the other inputs being zero-emissive energy sources.

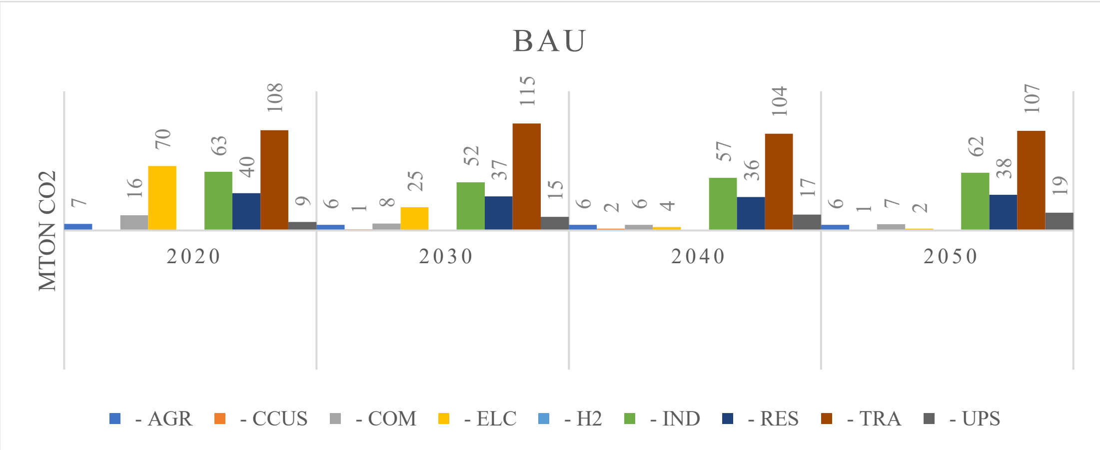

Figure 35: total CO2 emissions by sector, Business-As-Usual scenario. The abbreviations stand for: AGR – Agriculture, CCUS – Carbon Capture Utilization and Storage, COM – Commercial, ELC – Power sector, H2 – Hydrogen, IND – Industry, RES – Residential, TRA – Transport, UPS – Upstream.

Conversely, other sectors like transport and industry face a much slighter decarbonization process, remaining the two most carbon dioxide emissions intense fractions of the system. This is due to the lack of emissions constraints in the model and the difficulty in abating such sectors.

The picture drastically transforms for Net Zero Emission scenario, represented in Figure 36 and reporting different relevant changes with respect to the previous case. Almost all the sectors, in this scenario, undergo a heavy decarbonization process, with transport remaining the highest emissive one in 2050. Nevertheless, also this sector diminishes its emissions by a gross 35% along the entire time horizon, representing an extensive improvement of the system. However, the most relevant characteristic of the described decarbonization pathway, is the appearance of negative carbon dioxide emissions, representing a direct CO2 capture from atmosphere. In fact, recalling Figure 19, hydrogen production was provided through solid biomass gasification with CCS. This technology is in truth emitting carbon dioxide during use phase, hence, the capturing of the CO_2 should barely compensate this emission instead of accounting for a negative amount, nevertheless, the assumption made in this model is that biomass use is always sustained with new biomass supply, compensating emissions with increasing natural carbon sinks and therefore not introducing new fossil CO_2 in the atmosphere, instead recirculating it. This is obviously a strong assumption, yet, included in the perspective of sustainable development.

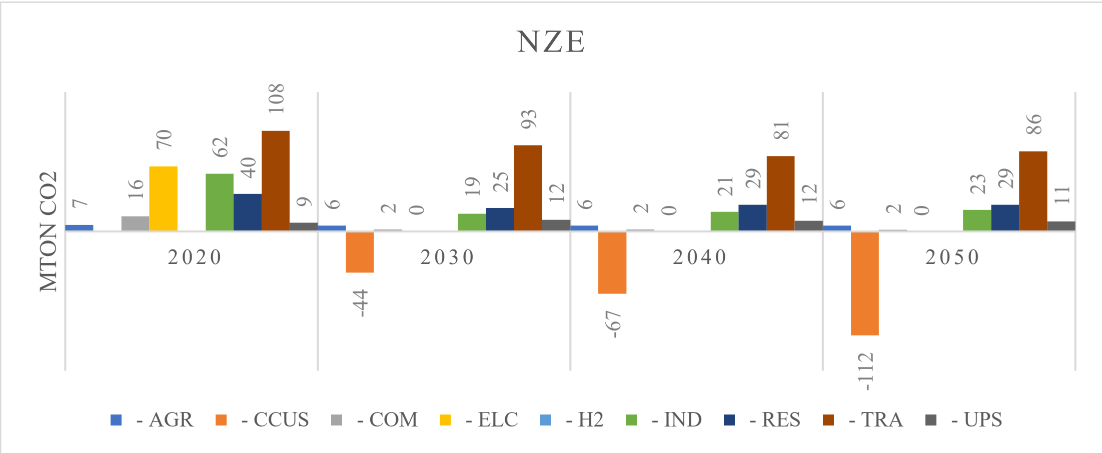

Figure 36: total CO2 emissions by sector, Net Zero Emissions scenario. The abbreviations stand for: AGR – Agriculture, CCUS – Carbon Capture Utilization and Storage, COM – Commercial, ELC – Power sector, H2 – Hydrogen, IND – Industry, RES – Residential, TRA – Transport, UPS – Upstream.

For this reason, applying CCS to a technology defined in such a way, finally accounts as a real curtailment of total CO_2 in the atmosphere.

Results provided for hydrogen constrained scenario, as Figure 37 shows, represent a completely similar configuration, with slightly less biomass-based CCUS activity as well as a more intense decarbonization pathway for transport sector, probably associated to what seen in the previous paragraph with the extensive use of hydrogen in aviation, which reaches a 46% reduction in total emissions.

In general, what emerges from the two decarbonization scenarios, is that a pathway for meeting 2050 targets is not only possible but is presumably achievable through the intense use of combined CCUS with other technologies, like blue hydrogen and synfuels production, rather than through a complete abatement of sectorial emissions, and since the complete abatement of these residual emissions in seems to be unfeasible, CCUS applications reveals to be not only useful, but necessary. This result is extremely relevant for strategic planning of energy system evolution dynamics and with further improvement of the tool hereby utilized even more accurate and reliable optimization can be provided, to work as a robust pillar for policy making in Italy.

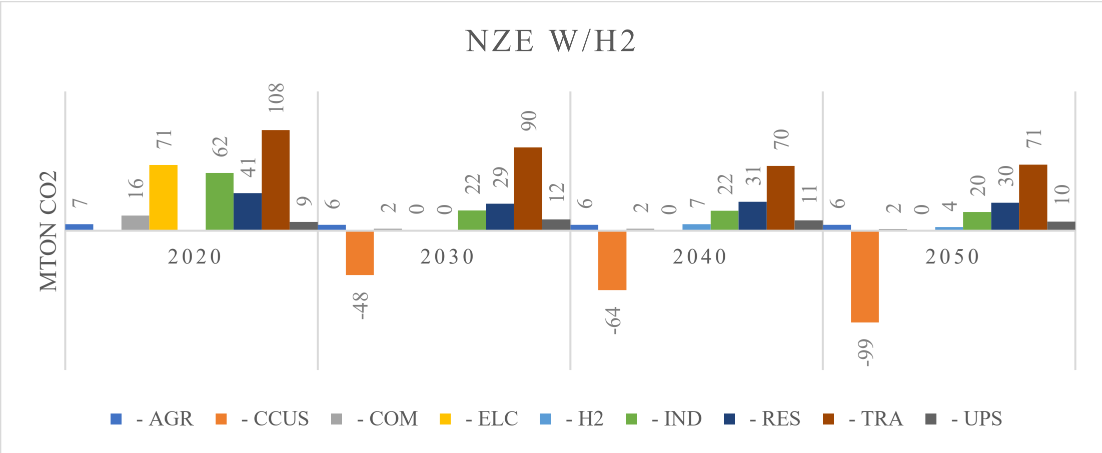

Figure 37: total CO2 emissions by sector, hydrogen constrained scenario. The abbreviations stand for: AGR – Agriculture, CCUS – Carbon Capture Utilization and Storage, COM – Commercial, ELC – Power sector, H2 – Hydrogen, IND – Industry, RES – Residential, TRA – Transport, UPS – Upstream.

Chapter 5

Conclusions

This work presented an assessment of the possible future role of hydrogen in pursuing the Italian decarbonization objectives. The current national hydrogen-related policies have been critically analysed, highlighting:

a. Hydrogen may play a key role in decarbonizing the energy system. More specifically, combined with the activity of carbon capture technologies it appears to be crucial to enable the production of synfuels, selected as the most economically convenient low carbon fuels for the end-uses decarbonization.
b. The penetration of synfuels in the final energy consumption is preferred with respect to the direct consumption of hydrogen in the demand sectors. This is in contrast with the national strategies, that aim to firstly develop hydrogen value chain in the industrial system and secondly to exploit the production capacity to produce synfuels.
c. While the optimization process seems to give credits to what is included in the national hydrogen plans in transport and industry, other sectors completely miss. This means that the optimal configuration of the system (according to the methodology adopted in the present work) is different from the proposals included in national strategies for hydrogen development.

The conclusion hereby included need to be put in the context of the model limitation as of today. The various provided assumptions, described in the different chapters, are clearly playing an important role in the optimization process and their effects on the final result can be possibly measured only when these will be removed, where needed and possible. To summarize the most critical aspects to be overseen in future studies the following synthesis is provided:

a. Transport sector could present different results once the described improvements are applied, also further favouring hydrogen use in both road and non-road categories.
b. Input data clearly make a wide difference on results obtained. For this reason, a sensitivity analysis would be needed for applying reasonable and robust

techno-economic ranges to these data, especially on newer and future technologies like hydrogen- and synfuels-related ones, providing unexpected results in this study.

c. The applied constraints are extensively simplified and limited only to a general use of hydrogen in the system. A more accurate policy framework definition would foster highly more detailed studies and corresponding more robust outcomes.
d. Finally, ESOMs have anyway intrinsic limitations in capturing the involvements of the broader context in which the energy system is included, neglecting factors which do not directly influence or act on it, and this remains a open matter in the modelling community for the improvements of these tools.

To conclude, this work opens different perspectives and the need of further improvements for providing a reliable support in the decision-making process. The mentioned limitations could be surpassed by additional developments, improving the reliability of the studied system and consequently, of the obtained results. From the point of view of the modelled framework, various elements could strengthen the study, refining the existing infrastructure with the implementation of cited enhancements as well as the introduction of additional parameters regarding, for example, environmental resource depletion deriving from the use of the different technologies. On the other side, a deeper knowledge of the actual optimization process and the mathematical computation which occurs to obtain the results, would bring increased capacity for developing even more proper models, producing an optimal overlap between the system provided to the solver and the solver itself, and eventually modifying its core algorithm to apply innovative solving paradigms which do not rely on economic interests alone.

These upgrades would enable progresses in the field of sustainability assessment, in which ESOMs would largely increase the range of possible climate change mitigation and adaptation strategies to be applied, choosing for the best fitting alternatives for each system and obtaining the most promising possible outcome.

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Appendix A: Hydrogen production technologies

Table 15: summary of hydrogen production technologies present in the model

Value Chain step	Typology/Sector	Technology	Connection	Size	Source
PRODUCTION	FOSSIL	NG steam reforming	Centralized	Large	JRC, JRC-EU-TIMES Hydrogen Module, 2019
		NG steam reforming	Centralized	Small	
		NG steam reforming	Decentralized	Medium	
		NG steam reforming	Decentralized	Small	
		Coal gasification	Centralized	Large	
		Coal gasification	Centralized	Medium	
		HOPO	Centralized	Large	
	ELECTROLYSIS	Alkaline	Centralized	Large	IEA, The future of hydrogen, 2019
		Alkaline	Decentralized	Small	
		PEM	Centralized	Large	
		PEM	Decentralized	Small	
		SOEC	Centralized	Large	
		SOEC	Decentralized	Small	
		AEM	Decentralized	Small	IRENA, Green Hydrogen Cost, 2020
	BIOMASS	Biomass steam reforming	Centralized		JRC, JRC-EU-TIMES Hydrogen Module, 2019
		Biomass gasification	Decentralized	Small	
		Biomass gasification	Centralized	Medium	
		Ethanol steam reforming	Decentralized		
	w/ CCS	NG steam reforming w/CCS	Centralized	Large	
		NG steam reforming w/CCS		Small	
		Hard coal gasification w/CCS		Large	
		Hard coal gasification w/CCS		Medium	
		Biomass gasification w/CCS		Medium	

Appendix B: Hydrogen transformation technologies

Table 16: summary of hydrogen transformation technologies present in the model

Value Chain step	Typology/Sector	Technology	Connection	Size	Source
SECONDARY TRANFORMATION	**Methanation**	Methane production from H2 and CO2			JRC, JRC-EU-TIMES Hydrogen Module, 2019
	Hydrogenation	Diesel/Kerosene production from H2C and CO2			
		Diesel/Kerosene production from co-electrolysis, CO2 from emissions			
		Diesel/Kerosene production from co-electrolysis, CO2 from DAC			
		MeOH production from H2 and CO2			
		MeOH production from co-electrolysis, CO2 from emissions			
		MeOH production from co-electrolysis, CO2 from DAC			
STORAGE	**Centralized tank**				
	Decentralized tank				
	Underground storage				
DISTRIBUTION	**Transport**	Gas H2	Centralized		
			Decentralized		
		Liquid H2	Centralized		
			Decentralized		
	Industry	Gas H2	Centralized		
		Gas H2	Decentralized		
	Residential	Gas H2	Centralized		
		Gas H2	Decentralized		
	Commercial	Gas H2	Centralized		
		Gas H2	Decentralized		
	Blending	Gas H2			

Appendix C: Hydrogen consumption technologies

Table 17: summary of hydrogen end-uses technologies present in the model

Value Chain step	Typology/Sector	Technology	Connection	Size	Source
END USES	**Transport**	Freight	Road		JRC, JRC-EU-TIMES Hydrogen Module, 2019
			Non-road		
		Passenger	Road		
			Non-road		
	Industry	Chemical	Centralized		
			Decentralized		
		Steel&Iron	Centralized		
			Decentralized		
	Residential	CHP	Centralized		
	Commercial	CHP	Centralized		
	Power sector	PEM cells	Centralized		

Appendix D: Hydrogen value-chain

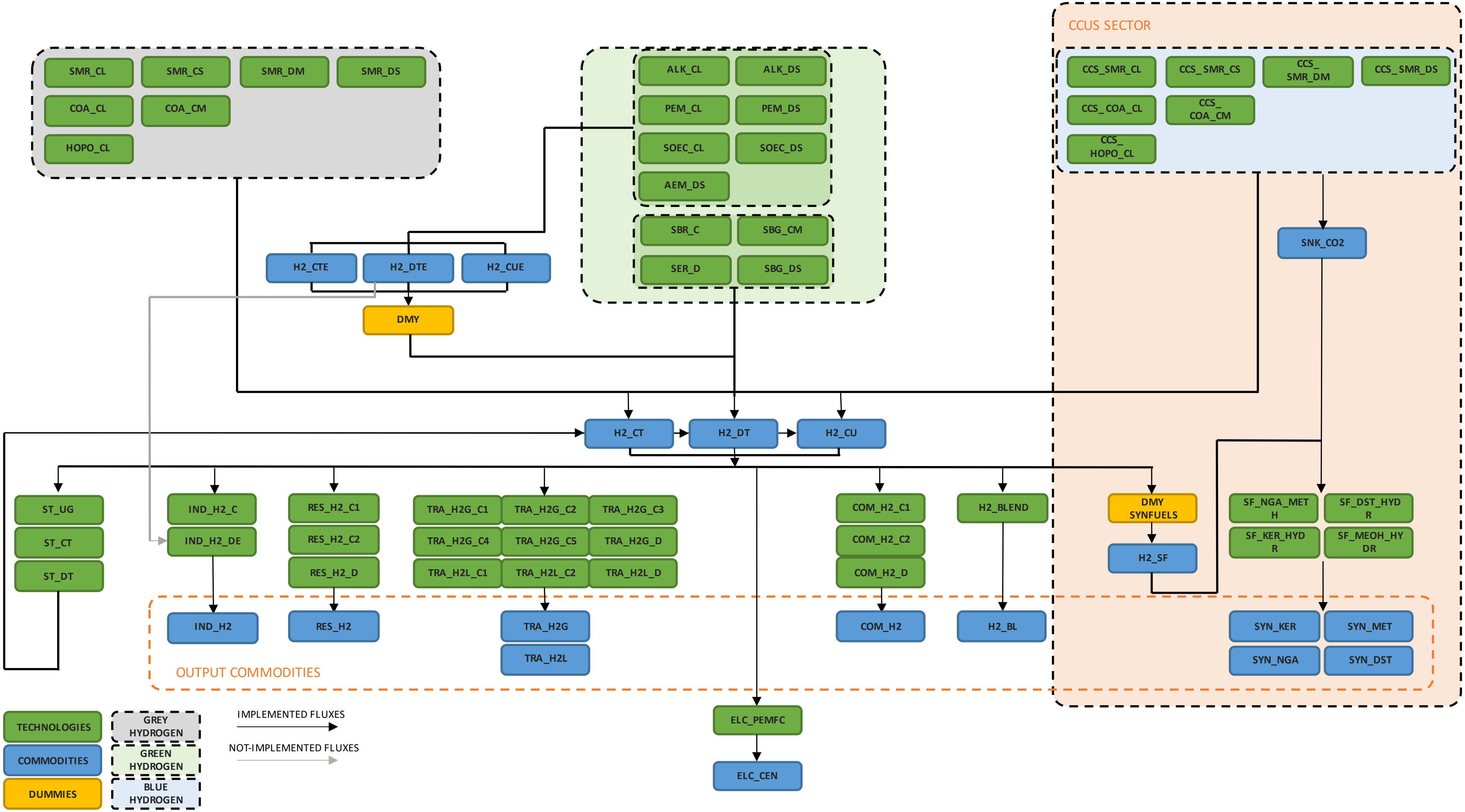

Figure 38: synthetic representation of hydrogen value-chain as implemented in TEMOA-Italy

Appendix E: Database implementation

Appendix 1: Database implementation

```
CREATE TABLE "tech_groups" (
	`tech`	text,
	`notes`	text,
	PRIMARY KEY(tech)
);
[...]
-- Hydrogen sector
INSERT INTO "tech_groups" VALUES ('H2_IND_FT_GC','');
INSERT INTO "tech_groups" VALUES ('H2_RES_FT_GC1','');
INSERT INTO "tech_groups" VALUES ('H2_COM_FT_GC1','');
INSERT INTO "tech_groups" VALUES ('H2_TRA_FT_LC1','');
INSERT INTO "tech_groups" VALUES ('H2_TRA_FT_GC1','');
INSERT INTO "tech_groups" VALUES ('H2_TRA_FT_LC2','');
INSERT INTO "tech_groups" VALUES ('H2_TRA_FT_GC2','');
INSERT INTO "tech_groups" VALUES ('H2_RES_FT_GC2','');
INSERT INTO "tech_groups" VALUES ('H2_COM_FT_GC2','');
INSERT INTO "tech_groups" VALUES ('H2_TRA_FT_GC3','');
INSERT INTO "tech_groups" VALUES ('H2_TRA_FT_GC4','');
INSERT INTO "tech_groups" VALUES ('H2_TRA_FT_GC5','');
INSERT INTO "tech_groups" VALUES ('H2_BLEND','');
INSERT INTO "tech_groups" VALUES ('H2_RES_FT_GD','');
INSERT INTO "tech_groups" VALUES ('H2_COM_FT_GD','');
INSERT INTO "tech_groups" VALUES ('H2_IND_FT_GDE','');
INSERT INTO "tech_groups" VALUES ('H2_TRA_FT_LD','');
INSERT INTO "tech_groups" VALUES ('H2_TRA_FT_GD','');

CREATE TABLE "groups" (
	"group_name"	text,
	"notes"	text,
	PRIMARY KEY("group_name")
);
[...]
-- Hydrogen sector
INSERT INTO "groups" VALUES ('H2_FT_GRP','');

CREATE TABLE "MinInputGroupWeight" (
	"regions"	text,
	"tech"	text,
	"group_name"	text,
	"gi_min_fraction"	real,
	"tech_desc"	text,
	PRIMARY KEY("tech","group_name","regions")
```

```
);
[...]
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_IND_FT_GC','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_RES_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_COM_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_TRA_FT_LC1','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_TRA_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_TRA_FT_LC2','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_TRA_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_RES_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_COM_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_TRA_FT_GC3','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_TRA_FT_GC4','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_TRA_FT_GC5','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_BLEND','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_RES_FT_GD','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_COM_FT_GD','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_IND_FT_GDE','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_TRA_FT_LD','H2_FT_GRP',1.0,'');
INSERT INTO "MinInputGroupWeight" VALUES ('IT','H2_TRA_FT_GD','H2_FT_GRP',1.0,'');

CREATE TABLE "MaxInputGroupWeight" (
       "regions"              text,
       "tech"                 text,
       "group_name"       text,
       "gi_max_fraction"     real,
       "tech_desc"            text,
       PRIMARY KEY("tech","group_name","regions")
);
[...]
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_IND_FT_GC','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_RES_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_COM_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_TRA_FT_LC1','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_TRA_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_TRA_FT_LC2','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_TRA_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_RES_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_COM_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_TRA_FT_GC3','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_TRA_FT_GC4','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_TRA_FT_GC5','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_BLEND','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_RES_FT_GD','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_COM_FT_GD','H2_FT_GRP',1.0,'');
```

```
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_IND_FT_GDE','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_TRA_FT_LD','H2_FT_GRP',1.0,'');
INSERT INTO "MaxInputGroupWeight" VALUES ('IT','H2_TRA_FT_GD','H2_FT_GRP',1.0,'');

CREATE TABLE "MinGenGroupWeight" (
	"regions"	text,
	"tech"	text,
	"group_name"	text,
	"act_fraction"	REAL,
	"tech_desc"	text,
	PRIMARY KEY("tech","group_name","regions")
);
[...]
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_IND_FT_GC','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_RES_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_COM_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_TRA_FT_LC1','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_TRA_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_TRA_FT_LC2','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_TRA_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_RES_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_COM_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_TRA_FT_GC3','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_TRA_FT_GC4','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_TRA_FT_GC5','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_BLEND','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_RES_FT_GD','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_COM_FT_GD','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_IND_FT_GDE','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_TRA_FT_LD','H2_FT_GRP',1.0,'');
INSERT INTO "MinGenGroupWeight" VALUES ('IT','H2_TRA_FT_GD','H2_FT_GRP',1.0,'');

CREATE TABLE "MinGenGroupTarget" (
	"periods"	integer,
	"group_name"	text,
	"min_act_g"	real,
	"notes"	text,
	PRIMARY KEY("periods","group_name")
);
[...]
INSERT INTO "MinGenGroupTarget" VALUES (2030,'H2_FT_GRP',88,'PJ');
INSERT INTO "MinGenGroupTarget" VALUES (2040,'H2_FT_GRP',489,'PJ');
INSERT INTO "MinGenGroupTarget" VALUES (2050,'H2_FT_GRP',600,'PJ');

CREATE TABLE "MaxGenGroupWeight" (
```

```
                          "regions" text,
                          "tech"    text,
                          "max_group_name" text,
                          "act_fraction"   REAL,
                          "tech_desc"      text,
                          PRIMARY KEY("tech","max_group_name","regions")
);
[...]
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_IND_FT_GC','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_RES_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_COM_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_TRA_FT_LC1','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_TRA_FT_GC1','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_TRA_FT_LC2','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_TRA_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_RES_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_COM_FT_GC2','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_TRA_FT_GC3','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_TRA_FT_GC4','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_TRA_FT_GC5','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_BLEND','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_RES_FT_GD','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_COM_FT_GD','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_IND_FT_GDE','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_TRA_FT_LD','H2_FT_GRP',1.0,'');
INSERT INTO "MaxGenGroupWeight" VALUES ('IT','H2_TRA_FT_GD','H2_FT_GRP',1.0,'');

CREATE TABLE "EmissionLimit" (
       "regions"      text,
       "periods"      integer,
       "emis_comm"    text,
       "emis_limit"   real,
       "emis_limit_units"    text,
       "emis_limit_notes"    text,
       PRIMARY KEY("periods","emis_comm"),
       FOREIGN KEY("periods") REFERENCES "time_periods"("t_periods"),
       FOREIGN KEY("emis_comm") REFERENCES "commodities"("comm_name")
);
[...]
INSERT INTO "EmissionLimit" VALUES ('IT',2030,'TOT_CO2',11.4E04,'kt','');
INSERT INTO "EmissionLimit" VALUES ('IT',2040,'TOT_CO2',8.55E04,'kt','');
INSERT INTO "EmissionLimit" VALUES ('IT',2050,'TOT_CO2',4.5E04,'kt','');
```