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Sensitivity analysis for hydrogen end-use technologies through Energy System Optimization Models: an application to TEMOA-Italy

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Summary

Abstract

The increasing global focus on hydrogen as a pivotal means to achieve decarbonization objectives prompts a critical inquiry into its future economic viability. Addressing this uncertainty necessitates using powerful analytical instruments, among which Energy System Optimization Models.

Given the foundation of such models on the detailed techno-economic characterization of technologies composing the energy system, they are inherently data-driven and possibly subject to a notable degree of uncertainty concerning input parameters and, consequently, output results. For this reason, sensitivity analysis is commonly used to assess the robustness of the technology characterization.

The objective of this thesis is to evaluate the sensitivity to some key parameters of the possible future hydrogen end-use technologies penetration in the energy system, according to alternative scenarios. The study is focused on the TEMOA-Italy model, an energy system model based on the open-source platform TEMOA and developed by MAHTEP Group at PoliTO.

A comprehensive description of each subsector under investigation is presented, highlighting notable updates in the technological characterizations with respect to the previous version of the model.

A technique based on the "one at a time" sensitivity analysis method is implemented to examine a spectrum of transportation and industrial technologies, including fuel cell vehicles, hydrogen-powered aircraft, and hydrogen-based direct reduction of iron for steel production. The sensitivity analysis in this study focused on two crucial parameters: technology efficiency and investment cost. These parameters were selected due to their significant influence on model optimization process. The analysis was conducted within the context of a decarbonization scenario.

The results of the analysis highlighted the heavy-duty and automotive sectors as the most sensitive to the characterization of end-use technologies. Additionally, the aviation sector displayed a high degree of dependence on the carbon dioxide storage capacity of the model. In general, the analysis indicated that the model exhibited greater sensitivity to changes in efficiency rather than variations in investment costs.

List of acronyms

BAU	Business As Usual
BF-BOF	Blast Furnace – Basic Oxygen Furnace
EAF	Electric Arc Furnace
CCUS	Carbon Capture and Utilization
ESOM	Energy System Optimization Model
GSA	Global Sensitivity Analysis
HDRI-EAF	Hydrogen Direct Reduced Iron Electric Arc Furnace
LSA	Local Sensitivity Analysis
RES	Reference Energy System
TEMOA	Tools for Energy Model Optimization and Analysis

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1 Introduction

1.1 Hydrogen prospective

The European Union's commitment to achieve carbon neutrality by 2050, as articulated in the European Green Deal [1], represents a pivotal step in addressing the pressing challenge of climate change. The transition toward what is claimed as a “sustainable future” necessitates a multifaceted approach, embracing various energy vectors. Among these, hydrogen has emerged as a cornerstone of the EU's decarbonization strategy [2].

Hydrogen, as an energy carrier, holds the potential to reshape the energy landscape in several critical ways. It is not merely a medium for storing excess electricity generated from renewable sources; it also serves as a versatile fuel for transportation, penetrating heavy-duty and aviation sectors. Furthermore, hydrogen finds its place in industries notorious for being "hard-to-abate," such as steel and chemicals production, facilitating cleaner and more sustainable manufacturing processes. Its applications extend to the production of synthetic fossil fuels and direct use in heating and cooling systems, contributing to a comprehensive energy transformation [3].

As of the current energy landscape, hydrogen production in Europe predominantly relies on fossil fuels, thereby yearly releasing 70 to 100 million tons of carbon dioxide (CO_2) into the atmosphere [2]. While hydrogen's share in the energy mix remains modest, constituting less than 2% of the total energy consumption [4], the ambitious objectives set forth by the EU are poised to significantly elevate its role. Forecasts project a substantial increase, aiming to raise hydrogen’s share to 13-14% with respect to the total final energy consumption by 2050, concomitant with a commitment to decarbonize hydrogen production [5]. This is supported by a plan to install 40 GW of electrolysers by 2030, enabling the transition from fossil-fueled hydrogen production to green hydrogen generated through electrolysis, thus significantly reducing CO_2 emissions [2].

Amid this transformative energy landscape, Italy, too, has unveiled a strategy for harnessing the potential of hydrogen to align with decarbonization objectives [6]. At present, hydrogen generation within Italy predominantly rests on steam methane reforming, serving the chemical and refinery sectors [7]. However, the current contribution of hydrogen to Italy’s final energy consumption is relatively modest, amounting to approximately 1% [8]. In alignment with Italy's pursuit of carbon neutrality, the government envisions a substantial shift. By 2050, the country's vision projects hydrogen to assume a far more substantial role, contributing to 20% of the final energy consumption [7].

1.2 Energy System Optimization Models

Energy system optimization models (ESOMs) are computational tools used to analyze and optimize complex energy systems [9]. Their purpose is to assist decision-makers and researchers in making well-informed decisions related to energy production, distribution, and consumption. These choices take into account a variety of factors, including environmental, economic and technical constraints. Thus, the significance of ESOMs is notably pronounced within the field of energy planning [10].

A schematical description of the energy model environment can be done by identifying the core of the model which is a linear programming problem solver. Its formulation is done by accounting for three important elements: decision variables (the unknowns determined by the problem), objective function (generally it consists in the minimization of the total system cost), and constraints (equalities and inequalities according to features that the modeler wants to analyze in the system) [11].

Concerning the time scope, the time horizon can be indeed a short or a long period depending on the model objectives. A short-term model usually analyses the energy system in a target year while the long-term does it over the long run (usually decades) [11]. Long-term models do not simulate every year in the time horizon but usually use a time discretization with time periods that can represent several years. In order to represent each time period a representative milestone year is chosen and then the outcomes are evaluated only for the selected years [12].

Two approaches to the optimization model are possible: perfect foresight or myopic [13]. The perfect foresight approach assumes that the modeler has complete knowledge of the future evolution of important input parameters such as service demands, improvement of modelled technologies, or cost trends. This leads to a unique optimization problem that simultaneously analyses all the time periods. The myopic approach is realized by a sequence of optimization problems without complete knowledge of the future evolution of the previously listed parameters [11].

A key aspect of ESOMs is the detailed technology characterization. Usually, it has an extensive database containing both economic and technical parameters to describe a wide range of technologies that concur to create the reference energy system (RES) [14].

1.3 Sensitivity analysis

Being ESOMs strongly data-driven, uncertainty assessment is a key aspect to be considered. Among the most diffused methodologies used to assess the reliability of these models, there are sensitivity analysis, Monte Carlo analysis [15], robust optimization [16], and modelling to generate alternatives [17].

Sensitivity analysis is a quantitative method utilized in a wide range of fields [18]. Its purpose is to evaluate how alterations in input parameters or assumptions of a model or system impact the model's output results [19]. This analytical approach empowers researchers and decision-makers to explore hypothetical scenarios and gain insights into the potential ramifications of parameter variations on the outcomes of a given model or system [20].

Sensitivity analysis can be broadly categorized into two main families: local sensitivity analysis (LSA) and global sensitivity analysis (GSA). LSA is the first approach to sensitivity analysis. It examines how small changes around nominal values of input parameters or specific points of interest affect a model's output [21]. LSA implies a deterministic approach, since it does not involve assigning probability distributions to model inputs. Instead, it focuses on assessing sensitivity around specific points of interest in the model's input space [20].

Conversely, GSA is distinguished by its consideration of the entire range of input variations. Unlike local sensitivity analysis, which assumes linearity, normality, and local variations, global sensitivity analysis takes a more comprehensive approach. In GSA, simulations are conducted with inputs assigned probability distributions. The aim is to assess the impact of input variance on the output distribution [21]. Depending on the chosen method, one or more inputs can be varied simultaneously, enabling the identification of interactions among multiple inputs. Various techniques like Monte Carlo simulation, Latin hypercube sampling, and others can be employed to propagate the range and relative likelihood of inputs [22].

LSA methods lack the ability to comprehensively understand interactions between parameters, whereas GSA overcomes this limitation by simultaneously varying all parameters.

It's worth noting that GSA methods tend to be more intricate and require a greater amount of information, while LSA is computationally less demanding [23].

Thanks to the above-mentioned characteristics, LSA methods are frequently employed as screening techniques to identify non-influential inputs using a relatively small number of model calls. This approach helps determine the most influential inputs, which can then be further analyzed using more sophisticated methods [21].

In the context of ESOMs, sensitivity analysis serves as a valuable tool for mitigating uncertainty related to parameters [24]. Many studies employ the "one at a time" method, an LSA method where specific parameters are modified one by one while holding other assumptions constant. Examples of application of such variations include adjustments to electric vehicle battery costs [25], emission constraints [26], and discount rates [27].

1.4 Aim of the work

The aim of this thesis is to assess the sensitivity of the TEMOA-Italy model to some specific parameters constituting the techno-economic characterization of selected end-use hydrogen technologies. Such technologies have been chosen over the hydrogen production ones for their relatively lower technology readiness level (RDL) [28] which correspond to a higher degree of uncertainty.

To attain this objective, the "one at a time" sensitivity analysis method was selected as the reference approach. Within this method, each parameter undergoes variation individually while holding all other parameters constant. This systematic procedure facilitates a detailed examination of the impact of parameter changes on the model's behavior.

Two parameters, namely technology efficiency and investment cost, were chosen for thorough investigation. These parameters play a pivotal role for the optimization process of end-use hydrogen technologies. The context for this analysis is set within a decarbonization scenario, closely aligned with Italy's decarbonization targets. This provides a practical and relevant backdrop against which the sensitivity of the TEMOA-Italy model can be evaluated, and this choice will be further justified in the following chapter.

Chapter 2 provides an extensive description of the adopted methodology. It not only explicates the "one at a time" sensitivity analysis method, but it also offers insights into the specific model sectors that are under analysis. Moreover, it underpins the modifications and adaptations made to these sectors to align them with the research objectives. Within this chapter, readers will also find a comprehensive overview of the TEMOA-Italy model (in an updated version used for the purposes of this thesis), grounding the subsequent analysis in a solid understanding of the model itself.

Chapter 3 focuses on the results of the sensitivity analysis. For each of the end-use hydrogen technologies examined, the results are systematically presented, offering quantitative insights. Furthermore, this chapter introduces various scenarios and constraints that further enrich the understanding of the model's response to parameter variations.

Finally, Chapter 4 concludes the work, identifying the sectors within the TEMOA-Italy model that exhibit heightened sensitivity. These sectors are earmarked for future, more rigorous sensitivity analyses, with the objective of deepening our comprehension of the model.

2 Methodology

This chapter offers a comprehensive overview of the employed sensitivity analysis methodology. It also provides insights into the work framework, elucidating the structure of the TEMOA-Italy model. The configuration of the end-use demand sectors considered, specifically the updates made for this study, are highlighted. Finally, key characteristics of the scenarios employed for the analysis are presented.

2.1 Sensitivity analysis methodology

As discussed in Section 1.3, various approaches can be selected for assessing the model sensitivity to input data. Each of them presents both advantages and drawbacks. In this study, since no preceding attempts were applied to the adopted model yet, a simplification of an existing methodology is proposed and described in the following. The chosen procedure is derived from a local sensitivity method called one at a time. According to the original approach, a sensitivity ranking can be obtained by increasing or decreasing each parameter by a given percentage while leaving all other ones constant and quantifying the behavior change in model output [29].

Before deepening the sensitivity analysis methodology explanation, in order to understand the framework of the work, the scenario choice must be clarified and explained. Since this entire study focuses on hydrogen-based technologies, the most valuable and interesting results are expected to be related to a NET0 scenario, where some sort of penetration from hydrogen technologies can be envisaged. This is because such technologies are closely linked to and supported by decarbonizing trajectories of the energy system future development. In TEMOA-Italy this objective is accomplished by constraining the net carbon dioxide emissions, starting from 2030 and making the constraint more stringent throughout the time horizon, with the aim of achieving carbon neutrality in 2050. Further details about the scenario are reported in Section 2.4.

Regarding the model structure, to reduce the computational effort, the number of milestone years was reduced. In the original version of the model there are time steps of five years while in this work time steps of ten years have been adopted. This choice is also justified by the fact that such a high level of time discretization was unnecessary, as this study serves a preliminary purpose of testing the model’s response.

On the other hand a year or a set of years should be selected for the input parameter variation and for the analysis of output results. The 2050 milestone year was chosen since it is usually chosen as targeted year in the decarbonization scenarios generally studied by different energy authorities [30], [31].

For the actual decision on parameter variation, in order to comprehensively understand the impact of parameter variations within a wide range, it was decided to adjust each parameter until the penetration of the studied technology in satisfying its total output commodity production reached 0% and 100%. However, a constraint was imposed to ensure that the variation of each parameter could not exceed more than ±50% from its reference value, with the purpose of excluding clearly unrealistic values from analysis. Penetration, in this context, refers to the percentage of the respective final service demand that is met by the technology under investigation.

This approach allowed for the identification of the two extremes of the significant parameter interval for each technology, which led to the in-depth exploration of each one of these ranges as a further step. To achieve this, specific points within the significant interval were selected with the goal of choosing values that would create penetration ranges as evenly distributed as possible, representing the full spectrum of possibilities for each technology.

Hence, after finding the extremes of the interval, the penetration corresponding to the mean value was evaluated. Subsequently, there are two possibilities: if the resulting penetration is higher than 70% or lower than 30% the only investigated interval is the larger one and the chosen value of the parameter is the mean value of the two corresponding interval extremes (see Figure 1). The resulting new wider penetration interval is investigated in the same way. This iterative process is repeated as far as five or six points are fully determined (as this number of points guarantees in average representing point distant less than 20% in terms of penetration), or all the penetration intervals are lower than 30%.

As a second possibility, if the penetration of the first mean value is between 30% and 70%, both the intervals are investigated, and the process continues, as in the previous case, until the curve has five or six points or all the penetration intervals are lower than 30% (see Figure 1).

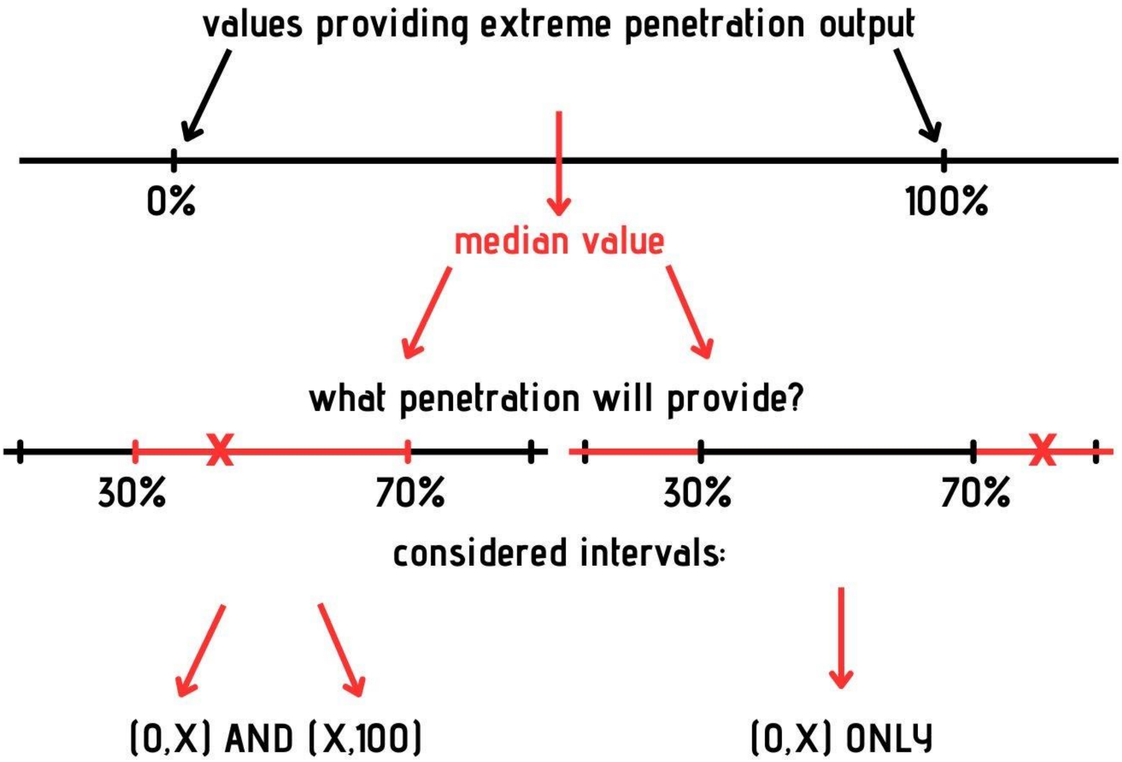

Figure 1. Sensitivity analysis methodology description

With the results, for each technology a series of curves can be displaced on graphs of efficiency or investment cost versus technology penetration, respectively, considering the relevant case and value ranges.

In this way, it is possible to observe both the sensitivity of the model to each parameter and the precise effects of specific variations.

2.2 TEMOA-Italy

The model used in this work is TEMOA-Italy [32] which is an instance based on the Tools for Energy Model Optimization and Analysis (TEMOA [33]) energy system optimization framework for the analysis of the Italian RES [34].

The TEMOA-Italy model is characterized by a long-term approach, with a time horizon that spans from 2006 to 2050, historical data for calibration are used until 2020 [35], while after 2020 the time periods are five years long each. The objective function consists of the minimization of the total system costs.

The technology richness of this kind of models allows a detailed representation of the energy system through the definition of several techno-economic parameters for each modelled technology. This technical characterization includes fundamental attributes such as efficiency, lifetime and capacity factor. In TEMOA, the efficiency denotes the relationship between input and output commodities for each of the represented process, as well as defining the starting year of availability. Additionally, the capacity factor, considers the need of future new investments for renovation. The economic characterization includes the definition of the investment costs, as well as fixed and variable operational and maintenance costs.

Each technology within the system has specific inputs and outputs of varying types. These flows are referred to as "commodities" and serve to represent the resources that are either consumed or generated during the operation of the energy system. Commodities encompass a wide range of elements, including energy sources such as fuels or energy vectors, as well as materials and emissions.

The precise RES scheme for the TEMOA-Italy instance is shown in Figure 2.

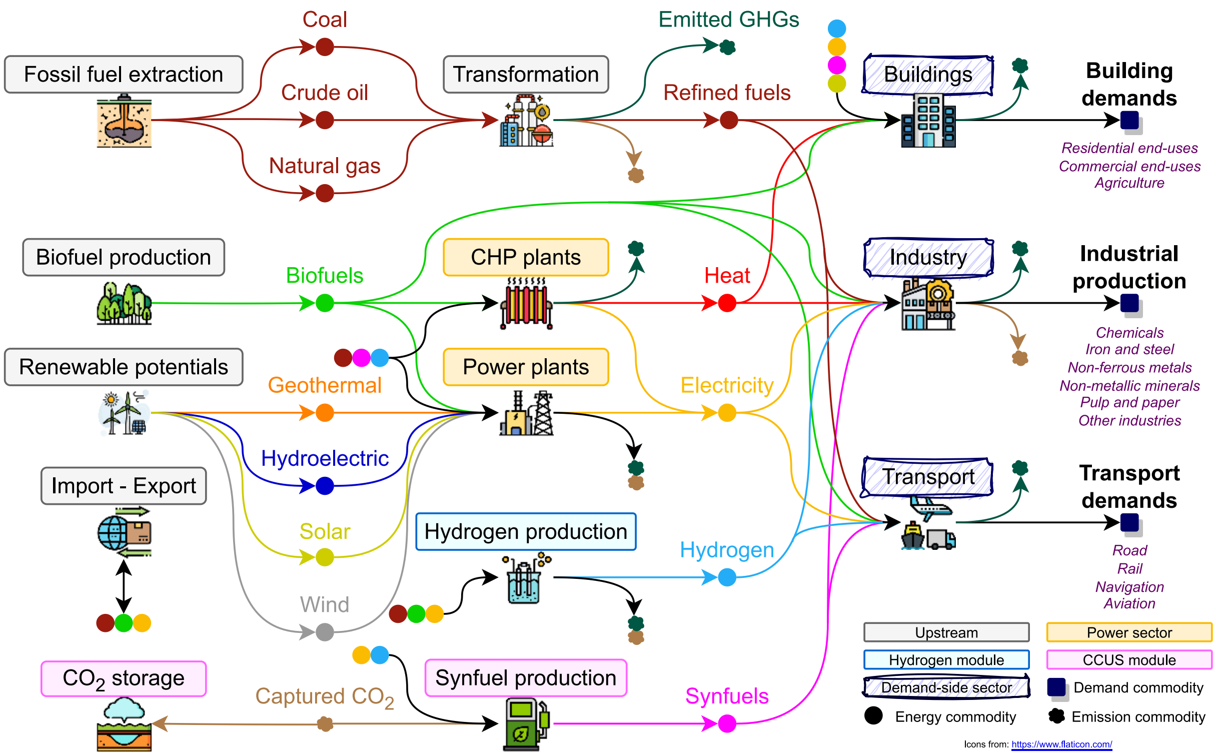

Figure 2. Representation of the TEMOA-Italy energy system [36].

The TEMOA-Italy RES is composed by three main sector groups: the upstream sector (for primary energy production), the transformation sectors, and the demand sectors (modeling the final consumption of energy).

In the upstream sector, the model incorporates the representation of various aspects, including fossil fuels extraction and refining. It also encompasses the modeling of biofuel production and the quantification of renewable energy potentials. Furthermore, the model accounts for the processes related to the import and export of commodities. In the context of the transformation sectors, a comprehensive set of electricity. hydrogen and synfuels production technologies is modeled. Demand sectors are comprised of various end-use technologies that have the role of fulfilling the demands outlined within the model. These primary demand sectors encompass buildings (residential, commercial and agriculture), industry, and transportation.

To attain a comprehensive understanding of the hydrogen value chain, a description of the hydrogen and CCUS modules is needed. As described in Figure 3, hydrogen production in the model encompasses various methods [37], including the utilization of fossil fuels, which is implemented through conventional technologies (referred to as “grey hydrogen”) and methods involving carbon capture (known as “blue hydrogen”). Additionally, hydrogen production is facilitated through biofuels (green hydrogen) which can be generated both with and without carbon capture. The model also accounts for hydrogen production through electrolysis (“yellow hydrogen”).

To ensure the efficient transfer of hydrogen from production sources to end-use technologies, the model includes transportation and distribution processes as intermediate steps. These processes bridge the gap between hydrogen production and its consumption by end-use technologies.

Hydrogen is directly consumed in the transport and industrial sectors. However, it can also be blended with natural gas, or used to generate electricity and heat through the utilization of fuel cells.

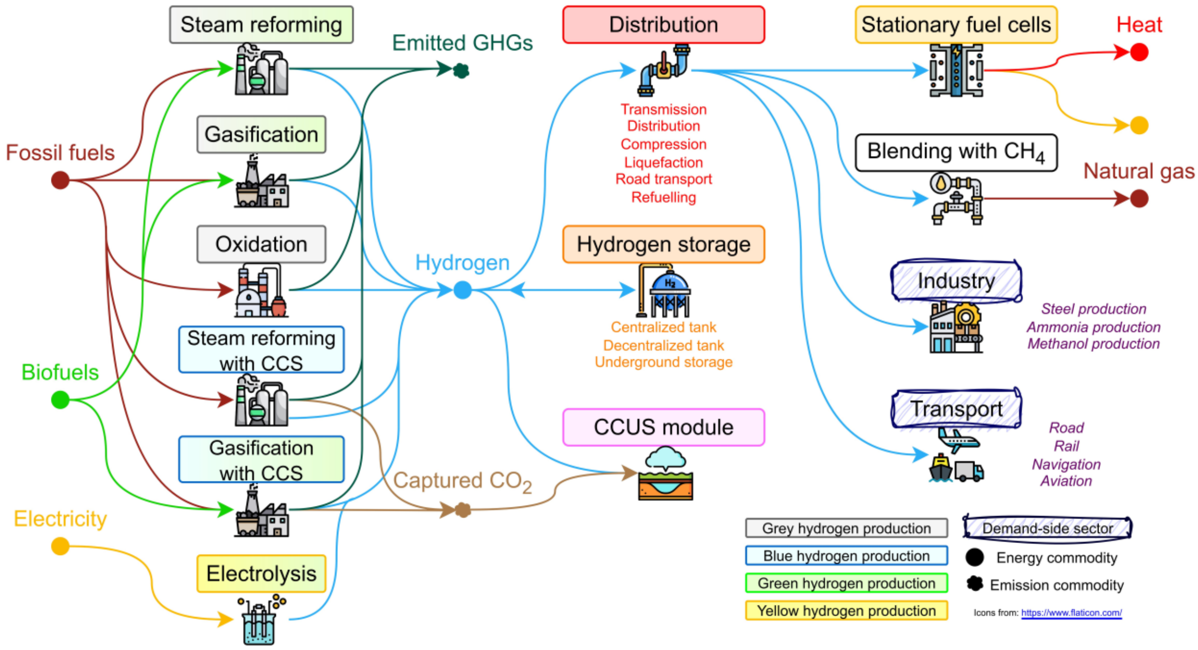

Figure 3. Representation of the hydrogen module in the TEMOA-Italy model [36].

The CCUS module described in Figure 4 plays a pivotal role in the overall system, particularly in the context of the hydrogen value chain [38]. It primarily deals with the management of carbon dioxide (CO_2), obtained through carbon capture technologies and direct air capture, and offers a dual functionality such as storage and utilization.

The captured CO_2 is a key component in the hydrogen value chain. These two elements combine in processes such as hydrogenation and co-electrolysis, which are instrumental in the production of synthetic fuels. The resulting synthetic fuels include synkerosene, synmethane, syndiesel, and synmethanol.

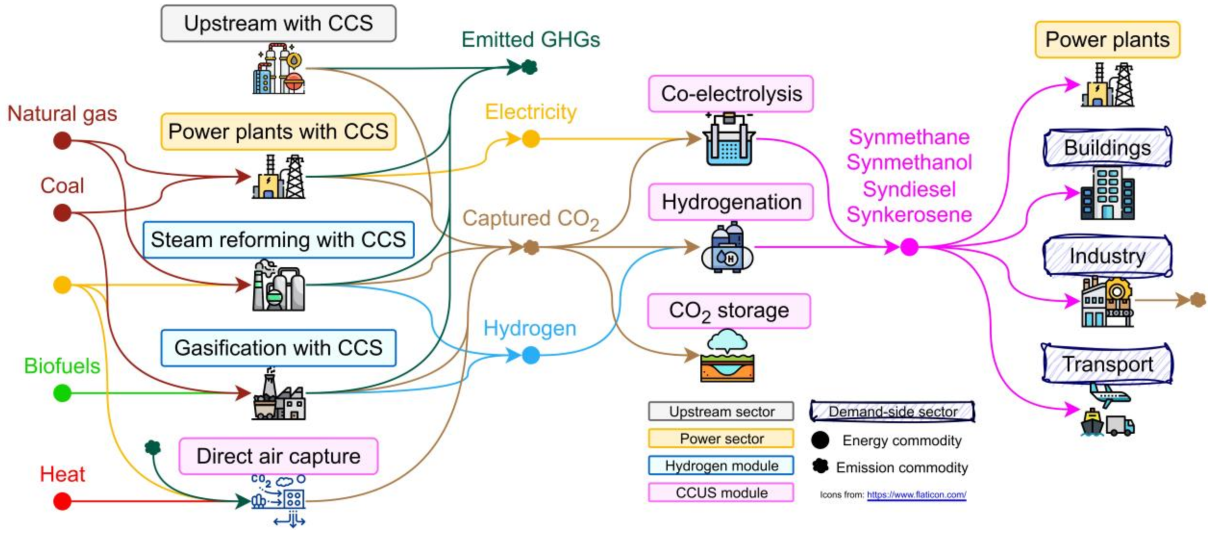

Figure 4. Representation of the carbon CCUS module in TEMOA-Italy model [36].

2.3 Database update

The first part of this work consisted of the update of several hydrogen end-use technologies in the TEMOA-Italy database, since some model data were out of date. According to [6], the sectors of greatest interest concerning the possible hydrogen penetration in the Italian energy system are the industrial and the transport ones.

Table 1 and Table 2 report carbon dioxide emissions in 2050 as computed by the TEMOA-Italy model for the Business As Usual (BAU) scenario after this work update, for the above-mentioned sectors, with details on the end-uses in which hydrogen holds potential for utilization [3]. It must be considered that the BAU scenario is a scenario without constraints on the total carbon dioxide emitted that is based on current policy development including planned intervention as described in National Integrated Plan for Energy and Climate [39] for 2030 and forwarded to 2050.

Table 1. CO_2 emissions in 2050 for the transport sector in BAU scenario for hydrogen-related subsectors.

	Cars	Aviation	Heavy trucks	Medium trucks	Ship	Rail	Bus	Total transport
Carbon emission [Mt]	64.4	33.5	20.9	3.0	5.3	1.4	2.3	150.0
Percentage emission [%]	42.9	22.3	13.9	2.0	3.5	0.9	1.5	

Table 2. CO_2 emissions in 2050 for the industry sector in BAU scenario for hydrogen-related subsector.

	Steel	Ammonia	Methanol	Total industry
Carbon emission [Mt]	5.0	0.5	0.03	27.0
Percentage emission [%]	19.0	2.0	0.1	

The most emitting end-uses technologies were involved in the update: they are cars, aviation, and heavy trucks in the transport sector, while iron and steel production in the industry ones. Moreover, the medium-duty truck transport was also studied to be compared to the heavy-duty one.

2.3.1 Iron and steel

The steel sector in the TEMOA-Italy model is composed of eleven technologies. Their output consists of two different types of steel: BOF steel in case of blast furnace basic oxygen furnace (BF-BOF) -like technologies, and EAF steel in case of electric arc furnace (EAF) -like technologies. They both concur to the satisfaction of the total national steel demand with the following shares: since 2020 the share of BOF steel with respect to the total is at least 18%, while the one for EAF steel is at least 80%, according to the current Italian situation [40]. These constraints on the minimum amount of each type of steel are kept constant for the entire time horizon.

The hydrogen-based technology for steel production was already implemented in the model and is the direct reduction with electric arc furnace technology with the use of hydrogen as a reducing agent instead of natural gas (HDRI-EAF). Table 3 shows the full list of technologies along with the main parameters and the type of steel produced before the update, modeled as described in [41].

Two main changes were made to the HDRI-EAF characterization. In the first place, the specific consumption has been changed to 14.5 [MJ/t]. This value is higher than the previous one mainly because in the original characterization of the model the energy consumption of the iron ore preparation (pelletizing) and of the casting of liquid iron were neglected. For the evaluation of the total energy consumption the value for the HDRI-EAF part [42] was added to the value for the pelletizing and casting part for traditional DRI-EAF [43], assuming that the processes are the same since the difference between the technologies is only the reducing agent [44].

Table 3. Iron and Steel technologies - main parameters as described in [36].

Steel type	Technology	Specific consumption [PJ/Mt]					Investment cost [€/t]
		2007	2025	2030	2040	2050	
	Blast furnace with basic oxygen furnace	16.7				14.9	582
BOF	Blast furnace with basic oxygen furnace with CCS			17.0			596
	BF-BOF with top gas recirculation with CCS				15.6		655
	Electric arc furnace	6.7		6.1			552
EAF	Electric arc furnace with CCS			7.1			596
	Hydrogen-based direct reduction with electric arc furnace			10.2			763
BOF	Hisarna process with basic oxygen furnace		13.7				440
	Hisarna process with basic oxygen furnace with CCS			14.0			493
EAF	Ulcolysis			15.8			672
	Ulcored with CCS			7.1			596

Furthermore, it was stated to make the HDRI-EAF produce BOF steel instead of the EAF one. The main reason is that the competition with the EAF technology is not comparable, since it produces steel from scrap and for this reason the specific consumption is extremely convenient when compared with technologies that produce steel from iron ore. Moreover, the scrap commodity value chain is not modelled in the model, and this further increases the disadvantages for the ore-based one, which includes higher costs and lower efficiencies. For these reasons, it appears more interesting to study the competition between HDRI and BF-BOF or BOF related technology rather than between HDRI and EAF.

The substitution of the produced steel type is possible as the only concern on the production of HDRI steel is on high-quality iron ore availability [45]: since the fraction of BOF steel is relatively small, the hypothesis that the HDRI-EAF can substitute BOF technologies was considered acceptable.

2.3.2 Ammonia and methanol

These sectors have been included in the update to facilitate a more comprehensive analysis of the industry sector. This decision was made despite the fact that, in the TEMOA-Italy model, ammonia and methanol production are characterized by low emissions, as indicated in Table 2.

The ammonia-related technologies implemented in the model and their main parameters are listed in Table 4. It is worth noting that the model's representation of ammonia production via electrolysis assumes that hydrogen is provided as an input to this technology. Therefore, the technology description does not encompass the modeling of the electrolyzer itself, relying on technologies included in the hydrogen module for the hydrogen production phase.

Table 4. Ammonia production technologies - main parameters pre update.

	Specific consumption [PJ/Mt]			Investment cost [€/t]		
	2007	2025	2030	2007	2025	2030
Ammonia-natural gas steam reforming	55.8		35.7	1043.8		867.5
Ammonia-natural gas steam reforming with CCS		55.3			903.0	
Ammonia-naphtha partial oxidation	57.0		42.6	1422		1244
Ammonia-coal gasification	53.1		41.8	2391.3		2060.9
Ammonia-biomass gasification		58.4			6000.0	
Ammonia-synthesis via electrolysis		40.3			104.0	

As for the modifications to the hydrogen technology both the efficiency and the investment cost were changed. The original efficiency probably included also the electrolyzer efficiency so, according to IEA [3], it was changed to 24.3 MJ/t. The costs, instead, was revised to 156 €/t, in line with the IEA data.

The methanol-related technologies implemented in the model and their main parameters are listed in Table 5. Similarly to the ammonia sector, methanol production via electrolysis does not encompass the modelling of the electrolyzer.

Table 5. Methanol production technologies - main parameters pre update.

	Specific consumption [PJ/Mt]				Investment cost [€/t]
	2007	2020	2025	2030	
Methanol - natural gas steam reforming	40.0	36.0			295.2
Methanol - natural gas steam reforming with CCS			36.0		319.2
Methanol-coke oven gas steam reforming	53.8			48.3	302.7
Methanol-LPG partial oxidation	37.3			33.4	290.8
Methanol-coal gasification	51.3			46.3	726.7
Methanol-biomass gasification			61.6		4896.6
Methanol-synthesis via electrolysis			24.0		44.0

No changes were done since the data appeared to be consistent with the most recent literature.

2.3.3 Domestic and international aviation

Prior to the update, the aviation sector featured two primary categories of aircraft: one for international flights and the other one for domestic flights. Within both international and domestic flight categories, the model included two types of aircraft: a reference plane powered by aviation kerosene and a hydrogen-based plane. Additionally, the reference plane had the option to incorporate synthetic kerosene in a blend with traditional fossil-based kerosene [38], [46].

In Table 6 the main parameters are described.

Table 6. Aviation technologies before the update- main parameters.

	Efficiency [Bvkm/PJ]			Investment cost [M€/PJ]
	2007	2030	2050	
International kerosene plane	$7.61 \cdot 10^{-3}$		$1.39 \cdot 10^{-3}$	1000
International hydrogen plane		$1.17 \cdot 10^{-2}$	$1.39 \cdot 10^{-3}$	3100
Domestic kerosene plane	$4.55E \cdot 10^{-3}$		$8.28 \cdot 10^{-3}$	1000
Domestic hydrogen plane		$7.00 \cdot 10^{-3}$	$8.28 \cdot 10^{-3}$	3100

This characterization presented some limitations. First, the costs were not defined as an absolute value, but a reference value of 1000 €/MJ was arbitrarily set for both the traditional kerosene technologies, while the investment cost for hydrogen technologies was normalized with respect to them assuming the same proportion of road vehicles [47]. On the other side, the efficiency values for international and domestic planes were equal for both the kerosene and the hydrogen plane in 2050. Finally, the efficiency value for the international plane was higher than the domestic plane one: however, given the unit of measurement (Bvkm/PJ) the international plane should have a lower efficiency since it consumes more fuel due to the higher mass per unit of distance [48], [49].

Trying to overcome these limitations the following new characterization was adopted. International flight planes were modelled as long-range planes (flight above 2000 km) while domestic ones as short-range (above 2000 km). This distinction was made to clearly identify the characteristics of the modelled planes. The characterization of the reference aviation kerosene planes was carried out by choosing some widespread plane models both for the long-range and for the short-range type. For the domestic aviation, the two main models in the market are the Airbus A320 and the Boeing 737-800 [50] while for international flights the Airbus A350-1000 was chosen as it is a common long-range plane of medium size [51]. Data for all the technologies were collected from [48], [49][52]. The two hydrogen-based planes were modelled according to [53] as a hybrid hydrogen propulsion plane for the short-range plane and a hydrogen turbine powered plane for the long-range one. Hybrid propulsion consists of a fuel cell for cruise and hydrogen powered turbines for takeoff and climb and hydrogen is stored in liquid form in both technologies. In Table 7 the main parameters for the four modelled planes are presented.

Table 7. New aviation technologies - main parameters.

	Efficiency [Bvkm/PJ]			Investment cost [M€/Bvkm]
	2007	2035	2040	
Long-range kerosene plane	$3.350 \cdot 10^{-3}$			115000
Long-range hydrogen plane			$2.360 \cdot 10^{-3}$	160000
Short-range kerosene plane	$7.874 \cdot 10^{-3}$			92000
Short-range hydrogen plane		$8.180 \cdot 10^{-3}$		120000

The investment cost found in the literature is the cost of the entire plane. The desired unit of measurement for the model is obtained with the calculation highlighted in Equation (1).

$$C_m \left[\frac{M€}{Bvkm}\right] = \frac{C_l[M€]}{km_a[km]} \cdot 10^9 \quad (1)$$

Where:

- C_m: investment cost in the model.
- C_l : aircraft cost; equal to 86 [M€] (i.e., millions of euros) for the domestic plane [52] and 319 [M€] for the international plane [52].
- km_a: average yearly mileage; assumed to be equal to 2.700.000 km for long-range planes and 930.000 km for short-range planes, based on [54].

2.3.4 Heavy trucks

The hydrogen-based heavy-duty vehicle was already modelled as a fuel cell truck. Other four technologies present, and their most important parameters are listed in Table 8. Both the fuel-cell truck and the full electric truck are limited by a constraint on the fuel consumption in the sector. This constraint limits the hydrogen and electricity consumption to 0% of the total sector fuel input until 2025 and then it allows both of them to grow up to 5% in 2050.

Table 8. Heavy duty trucks - main parameters pre-update.

	Efficiency [Bvkm/PJ]				Investment cost [M€/Bvkm]			
	2007	2020	2025	2050	2007	2020	2025	2050
Heavy truck diesel	0.039			0.052	2480			
Heavy truck LPG	0.035				2360			
Heavy truck natural gas	0.037				3040			
Heavy truck full electric		0.122		0.142		4790		2990
Heavy truck fuel cell			0.077	0.105			5400	4180

Both efficiencies and costs of the fuel cell truck were changed in this end-use update. For this work, it was decided to choose the efficiency of a 4×2 tractor of 40 tons as these trucks carry approximately 85% of the EU road freight transport while being around 25% of the total heavy trucks yearly sold [55]. The value was found to be 0.102 Bvkm/PJ [55]. As a value of 0.128 Bvkm/PJ was found in [3] for the generic sector, the truck was modelled with the efficiency of 0.102 for 2025 and 0.128 for 2050. For the costs, instead, the new values are 4150 M€/Bvkm in 2025 and 3100 M€/Bvkm in 2050 [3]. Finally, the upper constraints on the fuel consumption were removed both for the hydrogen and electricity to ensure a fair competition between all the technologies. The possibility to significantly deploy electric and hydrogen heavy trucks is also supported by the IEA forecast [56].

2.3.5 Medium trucks

In the model, the hydrogen-based technology is already implemented as a fuel cell medium-duty truck. Other five technologies are present, and their most important parameters are listed in Table 9.

Table 9. Medium duty trucks - main parameters pre-update.

	Efficiency [Bvkm/PJ]					Investment cost [M€/Bvkm]				
	2007	2016	2020	2025	2050	2007	2016	2020	2025	2050
Medium truck diesel	0.089				0.118	2290				
Medium truck LPG	0.08					2180				
Medium truck natural gas	0.084					2810				
Medium truck full electric			0.279		0.324			4420		2760
Medium truck plug-in hybrid		0.181			0.211		2560			2160
Medium truck fuel cell				0.176	0.239				4980	3860

The only change that was made concerned the constraints on the input of electricity and hydrogen. As for the heavy-duty sector, these fuels were limited to be maximum of 5% of the total fuel input with respect to the total final energy consumption for medium trucks, and the constraint was removed in both sectors.

2.3.6 Cars

This section presents the description of the car sector before the update, highlighting the main technologies parameters in Table 10.

Table 10. Car sector technologies - main parameters pre update.

	Efficiency [Bvkm/PJ]					Investment cost [M€/Bvkm]				
	2007	2012	2020	2025	2050	2007	2012	2020	2025	2050
Car diesel	0.375				0.500	1730				
Car gasoline	0.313				0.416	1500				
Car LPG	0.337					1530				
Car natural gas	0.367					1620				
Car mild hybrid		0.402			0.553		1790			1620
Car full hybrid			0.507		0.690			1830		1730
Car plug in hybrid		0.755			1.027	2560	2560			2280
Car full electric	1.176				1.369	2870				1970
Car fuel cell				0.637	0.936	3370			3370	2920

Since the investment cost of hydrogen fuel cell cars was found to be out of date according to IEA [3], it was updated to 2760 M€/Bvkm in 2025 and 1850 M€/Bvkm in 2050.

2.4 Scenario definition

The scenario chosen for the sensitivity analysis is a NET0 scenario.

This scenario was built with a constraint on the total CO_2 emission that cannot exceed 29 Mt in 2050, according to the "Italian long-term strategy for greenhouse gases emission reduction" [6]. This value is different from zero since in the model the contribution of agriculture, forestry, and other land uses (expected to compensate up to 45 Mt [6]) is not considered.

Other constraints are not directly connected to the NET0 scenario but are important in the context of decarbonization and for hydrogen production are the following:

- Maximum solar power plants capacity in 2050: 123 GW [57].
- Maximum wind power plants capacity in 2050: 70.4 GW [58].
- Maximum biofuels import and production in 2050: 671.5 PJ. This constraint is important for this work as zero-carbon hydrogen can be produced exploiting biofuels.
- Maximum CO_2 storage: 27 Mt for the storage onshore and 18 Mt for the offshore one (the captured CO_2 can be used for synfuel production or can be stored).

3 Results

Before the sensitivity analysis results, some general results concerning the main constraints described in Section 2.4 are reported in Table 11.

Table 11. Results concerning relevant constraints in BAU and NET0 scenario.

Constraint in 2050	Constraint value	BAU scenario results	NET0 scenario results
Maximum solar power capacity	123.0 GW	18.2 GW	123.0 GW
Maximum wind power capacity	70.4 GW	1.6 GW	70.4 GW
Maximum biofuels import and production	671.5 PJ	470.2 PJ	671.5 PJ
Maximum CO_2 onshore storage	27 Mt	0 Mt	27 Mt
Maximum CO_2 offshore storage	18 Mt	0 Mt	2 Mt

It is interesting to observe that in the NET0 scenario, nearly all these constraints are fully saturated, while this scenario represents an ambitious and environmentally responsible target, it may have an impact on the sensitivity analysis: this saturation of constraints can result in limited room for flexibility or adjustment within the model, making it more challenging to discern significant changes in technology adoption based solely on parameter modifications.

3.1 Iron and steel

This section focuses on the iron and steel industrial sector and the HDRI-EAF is the investigated technology. Both investment cost and efficiency have been studied, but since the sensitivity to the former resulted negligible, only the efficiency case is shown in Figure 5.

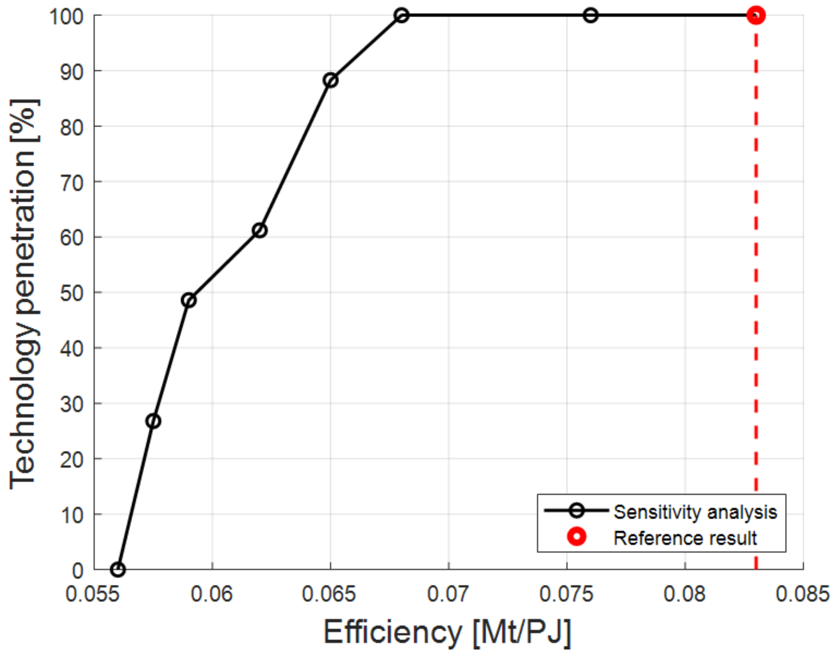

Figure 5. Sensitivity to the technology efficiency of the HDRI-EAF penetration within the BOF steel production in 2050, in the NET0 scenario.

Under the reference efficiency value, the HDRI-EAF technology achieves a penetration level of 100%. It's important to note that HDRI-EAF doesn't fulfill the entire steel demand in the model but only as much as 18%, as detailed in Paragraph 2.4. The penetration of this technology experiences variation with a decrease in efficiency ranging from -20% to -33%. Given its low technology readiness level (RTL) [28], uncertainties arise from fuel consumption, particularly for the hydrogen specific consumption by the technology.

To address these uncertainties, a comparison is made between the worst-case efficiency and reported hydrogen consumption ranges.

According to the IEA [3], the hydrogen consumption ranges from 48 kg/t to 57 kg/t, while the EPRS [59] estimates a theoretical consumption of 51-57 kg/t but a range of 65-80 kg/t is reputed more realistic. In the model's reference case, the value of 70 kg/t was chosen as a conservative estimate.

Considering the minimum efficiency value obtained with the worst-case consumption of 80 kg/t, the resulting efficiency is 0.077 Mt/PJ, marking a 7% decrease. Even with this lower efficiency, the HDRI-EAF technology maintains a 100% penetration level. This suggests that the penetration of HDRI-EAF in the steel sector is very likely, even with high hydrogen consumption values.

The main reason for the high competitivity of this technology is that the direct contender of the HDRI-EAF in the model is the HISARNA-BOF, which, being still a very efficient technology, its main input is coke, resulting in significant CO_2 emissions. Consequently, in a decarbonization scenario, its competitiveness is substantially reduced. Even the HISARNA-BOF version with carbon capture emits approximately three times the amount of CO_2 compared to HDRI-EAF technology, being outclassed by the latter.

In the work from EPRS [59] the technology was modelled with biomass input instead of natural gas, so it was interesting to understand if a change in the input commodity producing heat within the process impacts the sensitivity analysis. The results are shown in Figure 6.

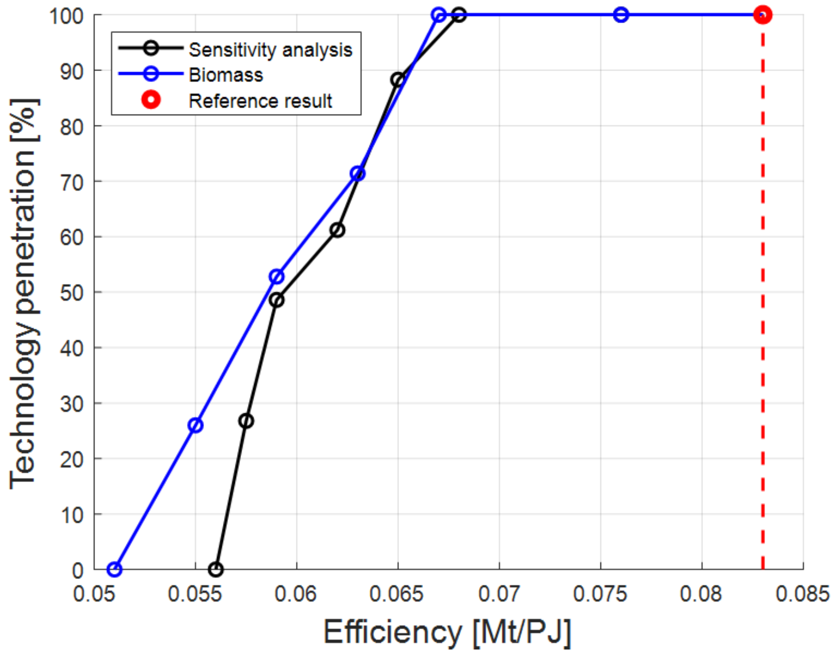

Figure 6. Sensitivity to the technology efficiency of the HDRI-EAF penetration within the BOF steel production in 2050, in the NET0 scenario. Comparison between HDRI-EAF with natural gas as heat source and HDRI-EAF with biomass as heat source.

The similarity between the two energy inputs can be attributed to the relatively low emissions of the HDRI-EAF when using natural gas. This is due to the model's decarbonization efforts, which include replacing approximately 50% of the industrial natural gas with biomethane in the decarbonization scenario.

While acknowledging that a direct comparison between the scrap EAF technology and the HDRI-EAF technology is not entirely equitable, an effort was made to assess their competition. The minimum ratio of EAF-produced steel with respect to the total iron and steel demand was altered from 82% to 50%, keeping the BOF at 18% as a minimum level (these values refer to the constraints presented in Section 2.3.1*)*. This adjustment allowed the model to allocate the remaining 32% of steel demand between both technologies, according to the optimal choice. As expected, the scrap EAF technology was favored by the model, primarily due to its high efficiency and low emissions, compared to HDRI-EAF. This result underscores the need for a more comprehensive analysis of the scrap EAF technology and the distribution of steel types.

3.2 Ammonia and methanol

The results associated with ammonia and methanol production from hydrogen through electrolysis are presented together since they exhibit similar behaviors, likely for the same underlying reasons. In both cases, these technologies have zero penetration in the reference case (both in BAU and NET0 scenarios). For methanol production, the chosen technology is steam reforming of natural gas with CCS, while for ammonia, it's steam reforming of natural gas without CCS. Interestingly, the model appears not to be sensitive to variations in both efficiency and investment cost for these technologies, leading to the conclusion that production via electrolysis is unlikely to be a viable option in the context of this specific model.

It is important to note that these findings may not be readily generalized on a global scale. In the Italian energy system, where the production of such commodities within the industrial sector is very low, as well as their consequent CO_2 emissions are, these technologies have minimal impact in satisfying the emission limit imposed in the NET0 scenario. As a result, the model might not consider them as significant contributors to the overall decarbonization effort.

3.3 Domestic aviation

Figure 7 illustrates the model sensitivity to the efficiency of the hydrogen domestic aircraft. Under the efficiency value set in the model, hereafter denoted as ‘reference value’, the hydrogen aircraft is deployed for the entirety of the domestic aviation sector, accounting for 100% of the sectorial technology mix in 2050.

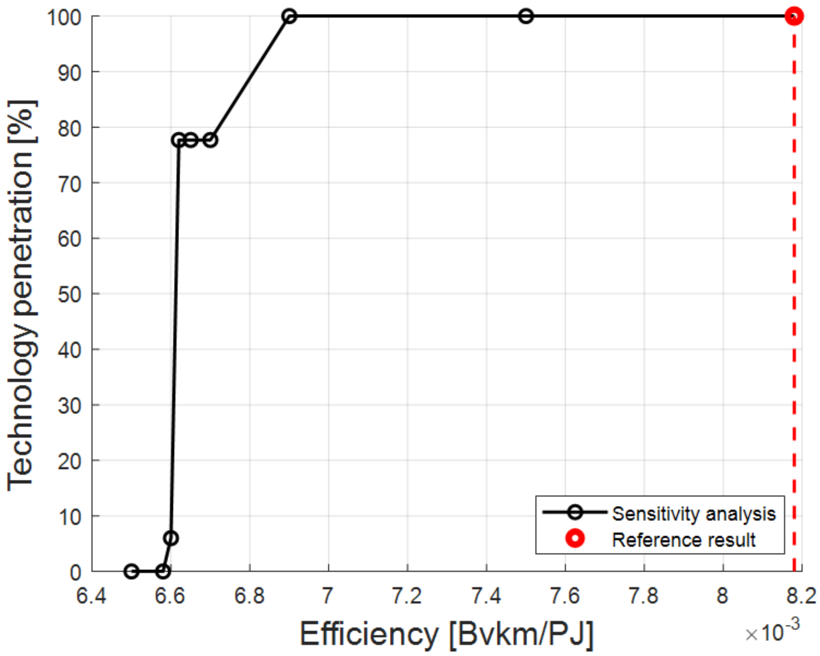

Figure 7. Sensitivity to the technology efficiency of the domestic hydrogen aircraft penetration within the domestic aviation sector in 2050, in the NET0 scenario.

The penetration of hydrogen-based planes declines when the efficiency reaches a value of 6.9×10^{-3} Bvkm/PJ, that is equal to a 16% reduction compared to the reference value of the efficiency. Subsequently, the penetration rapidly diminishes to zero with only a further 5% decrease in efficiency required.

The hydrogen plane is entirely replaced by the synthetic kerosene-fueled plane until the hydrogen plane's penetration reaches 77%. Beyond this point, after the efficiency threshold value of $6.7\cdot10^{-3}$Bvkm/PJ, the penetration drops to 6%, resulting in the domestic aviation sector no longer achieving complete decarbonization, as synkerosene only accounts for 85% of the total kerosene demand. This is consistent with the case of 0% hydrogen plane penetration, where the percentage of synkerosene remains the same. A summary of these results can be found in Figure 8.

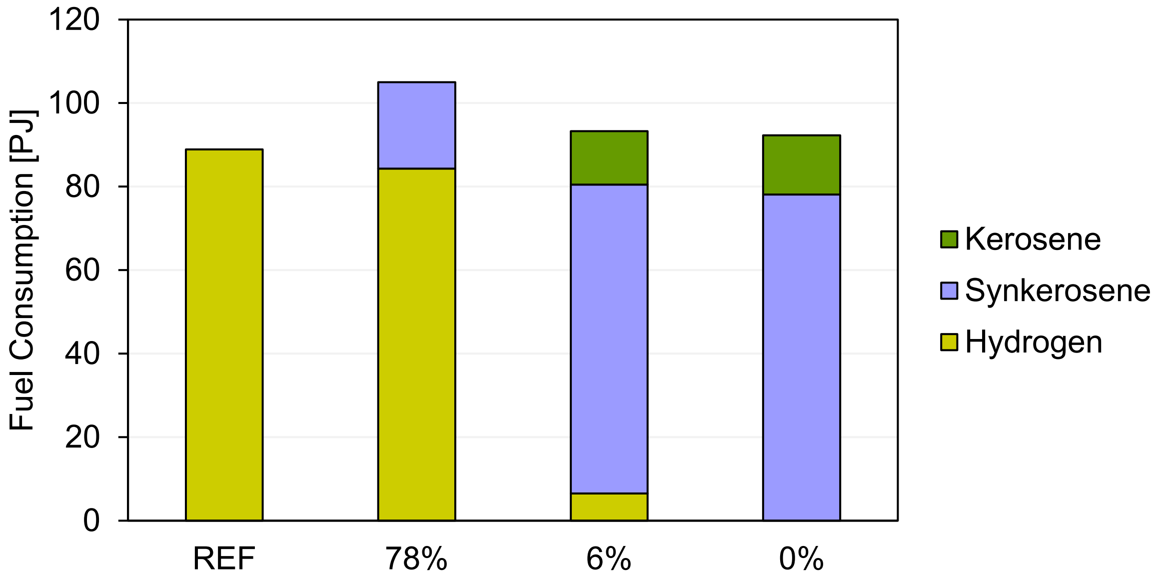

Figure 8. Fuel distribution in domestic aviation sector by hydrogen plane penetration in the sector. The reference (REF) case is confronted with three cases corresponding to 78%, 6%, 0% penetration of domestic hydrogen plane in the sector.

It is interesting to understand why the aviation sector is not completely decarbonized when the penetration of the hydrogen plane drops to zero. Instead of producing the necessary amount of synkerosene to completely cut down the emissions by the sector, the model chooses to reduce natural gas imports by 16.0 PJ. This reduction is divided into 5.5 PJ in the residential sector, achieved through adjustments in space heating technology, while the remaining 10.5 PJ are saved in the power sector by transitioning from a cogeneration natural gas plant to a heat natural gas plant.

The analysis of the domestic hydrogen plane shows that its penetration in the sector does not vary when varying the investment cost. Indeed, even if the cost is increased by 50%, the hydrogen plane is still the only technology chosen in 2050. This means that efficiency is the key parameter for the competition between the hydrogen plane and the traditional plane with synthetic kerosene in the NET0 scenario.

As in the NET0 scenario the hydrogen plane is the most promising technology for the decarbonization of domestic flights, it was interesting to understand the competition between this technology and the fossil kerosene-based aircraft in a BAU scenario.

It is interesting to point out that in the BAU scenario, the model is quite sensitive to the plane cost while the efficiency variation does not provide any variation in the technology penetration.

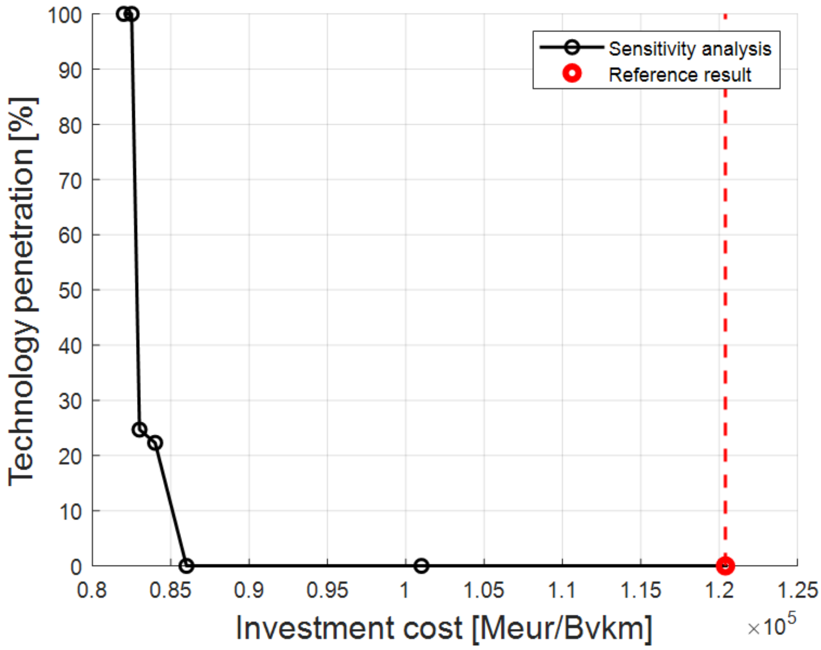

Figure 9. Sensitivity to the technology investment cost of the domestic hydrogen aircraft penetration within the domestic aviation sector in 2050, in the BAU scenario.

Figure 9 shows the sensitivity of the model to the hydrogen plane cost. With reference cost value, the hydrogen plane is not deployed by the model and the demand is completely satisfied by the fossil kerosene aircraft. The penetration starts to increase quickly with a cost decrease of 30% (86000 M€/Bvkm) reaching 100% with a decrease of 32%.

As the reference plane cost is 92000 M€/Bvkm the hydrogen plane is technically competitive only if its investment cost is less than the reference one.

It is important to underline that these results are achieved in a scenario without constraint on CO_2 emissions. In this scenario, hydrogen is produced by the reforming of natural gas which is the most cost-effective technology. Consequentially a green hydrogen plane would have higher fuel costs needing to further reduce its investment cost to be competitive.

3.4 International aviation

As for domestic aviation, the penetration of the hydrogen-based plane is sensitive only to the efficiency variation and not to the investment cost variation in the NET0 scenario. In Figure 10 the sensitivity to the technology efficiency is presented.

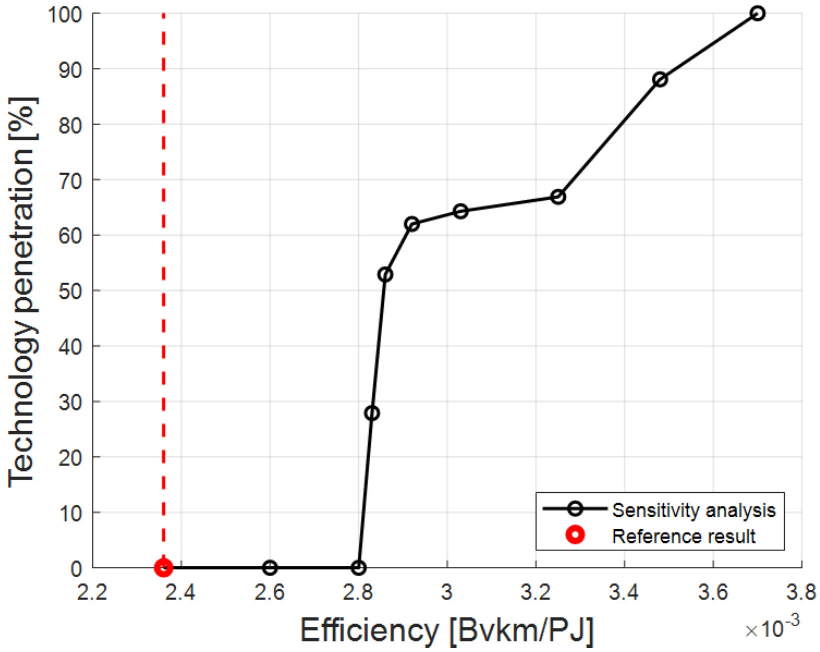

Figure 10. Sensitivity to the technology efficiency of the international hydrogen aircraft penetration within the international aviation sector in 2050, in the NET0 scenario.

With the reference value of efficiency, the international hydrogen plane is not used by the model that decarbonizes only 40% of the sectorial emissions through synkerosene, leaving 60% to fossil kerosene.

The hydrogen plane must increase its efficiency by at least 16% in order to become competitive, then the penetration sharply increases up to 60%, approximately, competing with the synkerosene-propelled alternative. An efficiency increment of 24% to 38% corresponds to a plateau, then an efficiency increment of 50% is needed for full penetration.

A possible explanation for the plateau resides in the fact that, until the penetration reaches 50%, the hydrogen plane is in competition with the synkerosene, while to further penetrate it must compete with other decarbonization technologies outside the international aviation sector (see Figure 11).

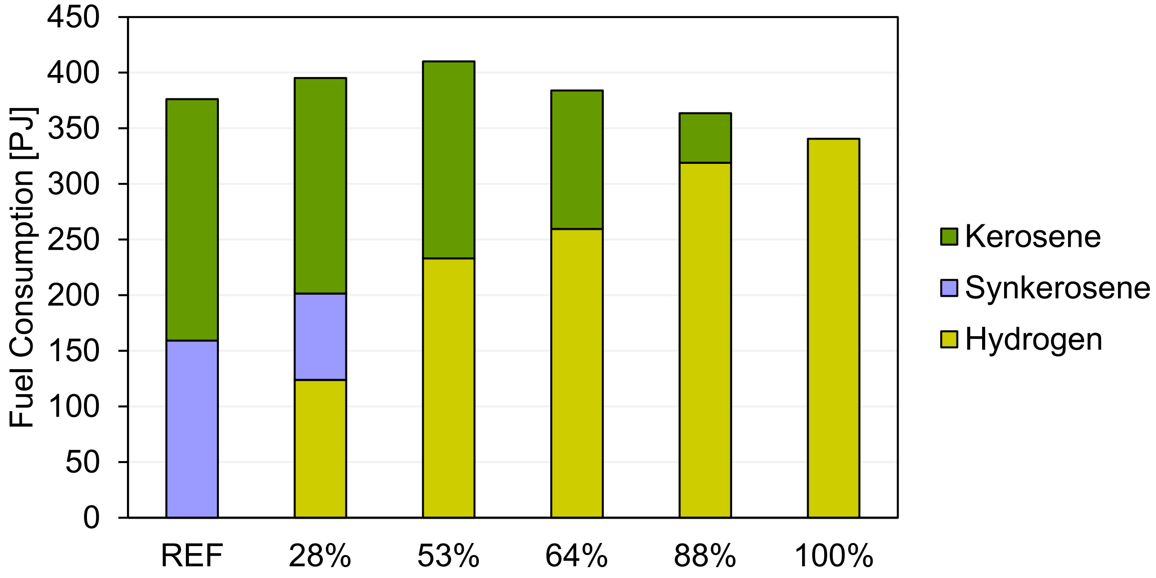

Figure 11. Fuel distribution in international aviation sector by penetration of hydrogen based international plane. The reference (REF) case is confronted with five cases corresponding to 28%, 53%, 64%, 88% and 100% penetration of international hydrogen plane in the sector.

However, with penetration values above 70%, the deployment of the international hydrogen plane implies a decrement of the hydrogen domestic plane penetration. Eventually, the model does never decarbonize the entire aviation sector, since when the hydrogen-based international plane is used for international flights, all the domestic planes are fueled by fossil kerosene.

It's worth noting that the model employs two main technologies for hydrogen production: biomass gasification with CCS and solid biomass steam reforming. As depicted in Table 12, there is a correlation between the production of synfuels and the source of hydrogen. When more synfuel is produced, hydrogen generation shifts towards biomass gasification. Conversely, if hydrogen is directly used for aviation, the portion produced by biogas steam reforming increases.

Table 12. Hydrogen production from biomass by synkerosene share of the total kerosene consumed in the aviation sector.

Synthetic kerosene as a percentage of total kerosene	Biomass gasification [PJ]	Biomass steam reforming [PJ]
50%	255.3	40.6
40%	233.0	81.4
30%	190.0	118.4
0%	146.0	160.0

The biomass steam reforming option has higher efficiency and lower costs compared to biomass gasification. However, in the reference case (associated with 0% hydrogen-based international plane and 100% hydrogen-based domestic plane), it is less utilized. The primary advantage of gasification lies in its carbon capture capability, making it a negative emission technology. This is due to biofuels being modeled with an emission factor of zero, assuming their impact on climate change is negligible [38]. The captured carbon dioxide is then partially stored and utilized as input for the hydrogenation of synthetic kerosene.

For those reasons, understanding the impact of carbon storage on the competition between synthetic kerosene and hydrogen was crucial. Therefore, a sensitivity analysis on the efficiency of the hydrogen-based plane was conducted considering alternative levels of CO_2 storage cost and maximum capacities, with respect to those detailed in Section 2.4.

The investment cost variation of the carbon dioxide storage had no impact on the sensitivity analysis even if it was doubled. On the contrary, the results of changing the maximum CO_2 storage capacity are shown in Figure 12.

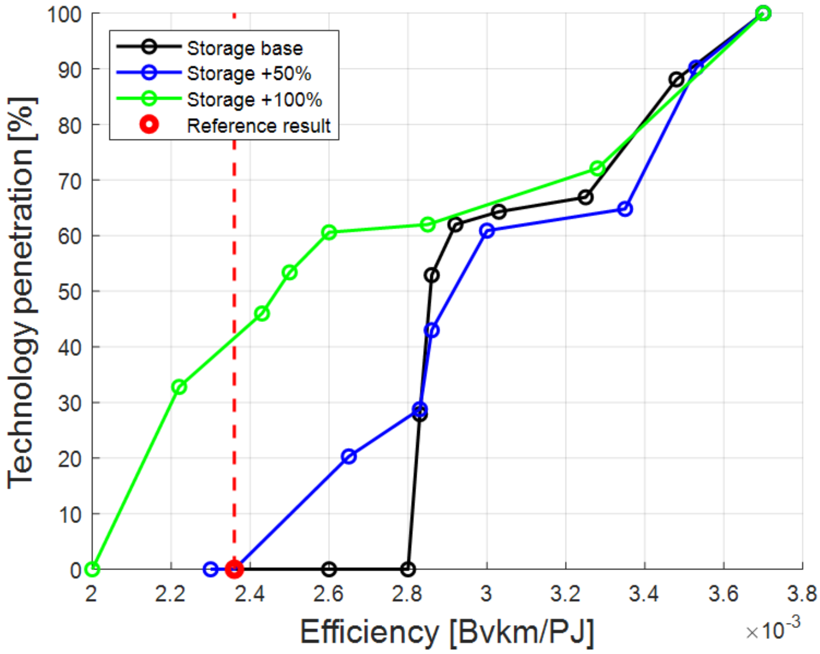

Figure 12. Sensitivity to the technology efficiency of the international hydrogen aircraft penetration within the international aviation sector in 2050, in the NET0 scenario, under different levels of CO2 maximum on shore storage.

The base case is compared to a scenario in which the maximum onshore storage capacity is increased by 50%, as well as another scenario with a 100% increase in storage capacity. As a result, synkerosene becomes significantly less competitive compared to hydrogen-based planes. In the case with a 100% increase in storage capacity (54 Mt/year in 2050), the penetration of hydrogen-based planes reaches approximately 40% when considering the reference efficiency value.

These results suggest that the competition between synkerosene planes and hydrogen planes is strongly influenced by the availability of CO_2 storage. When CO_2 storage options are limited, the CO_2 captured during hydrogen production must be utilized, which enhances the competitiveness of synfuels (consuming CO_2 for their production). However, in scenarios with greater CO_2 storage capacity, there is no longer a need to produce synfuels to accommodate the CO_2, making hydrogen planes more competitive. In general, the impact of the Italian CO_2 storage potential seems to play a relevant role in the model in decarbonization scenarios and should be carefully investigated by future studies.

3.5 Heavy trucks

In the reference case, the fuel cell heavy-duty truck is used by the model to satisfy around 10% of the heavy-duty demand, while the other 90% is covered by the electric truck. The model is sensible to both the investment cost and the efficiency of the technology but in different ways.

For what concern the investment cost sensitivity analysis shown in Figure 13, the reduction of the cost is linked to a penetration increase: in particular, a 50% decrease in the total cost corresponds to a 26% penetration. The cost increment was explored until reaching the 2025 value, as it is not reasonable to assume that the truck would cost more in 2050 than in 2025, but the penetration remained constant at 11%.

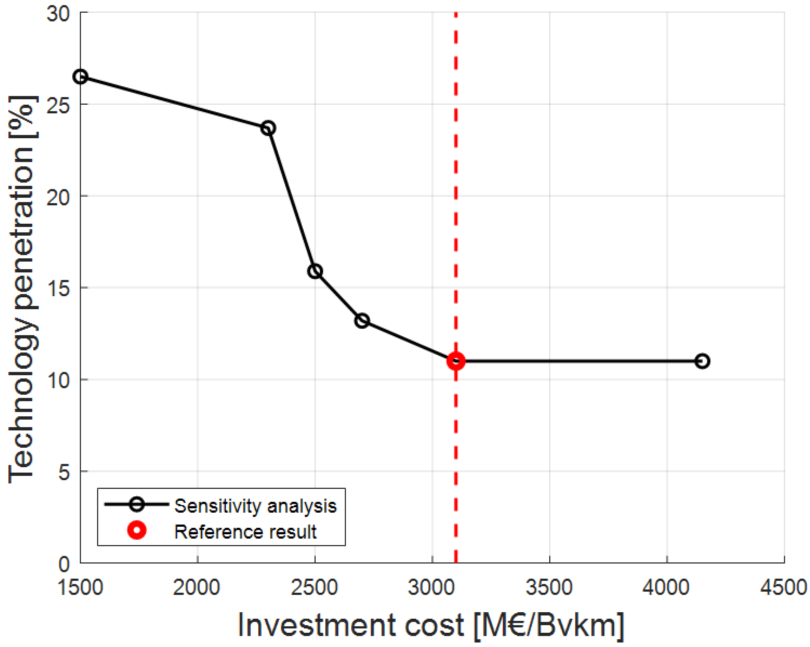

Figure 13. Sensitivity to the technology investment cost of the fuel cell heavy truck penetration within the heavy-duty trucks sector in 2050, in the NET0 scenario.

In the heavy trucks sector, the primary competitor to the fuel cell truck is the electric truck, as no other technologies are deployed. An increase in the penetration of fuel cell trucks directly leads to a decrease in the adoption of electric trucks. However, the impact of increased fuel cell truck usage extends beyond the heavy-duty sector. The reduction in electric truck usage results in decreased utilization of synthetic fuels in the aviation sector. Simultaneously, there is a rise in the adoption of electric buses over plug-in hybrid buses in the bus sector.

The model is much more sensitive to the efficiency of the fuel cell truck as it is shown in Figure 14.

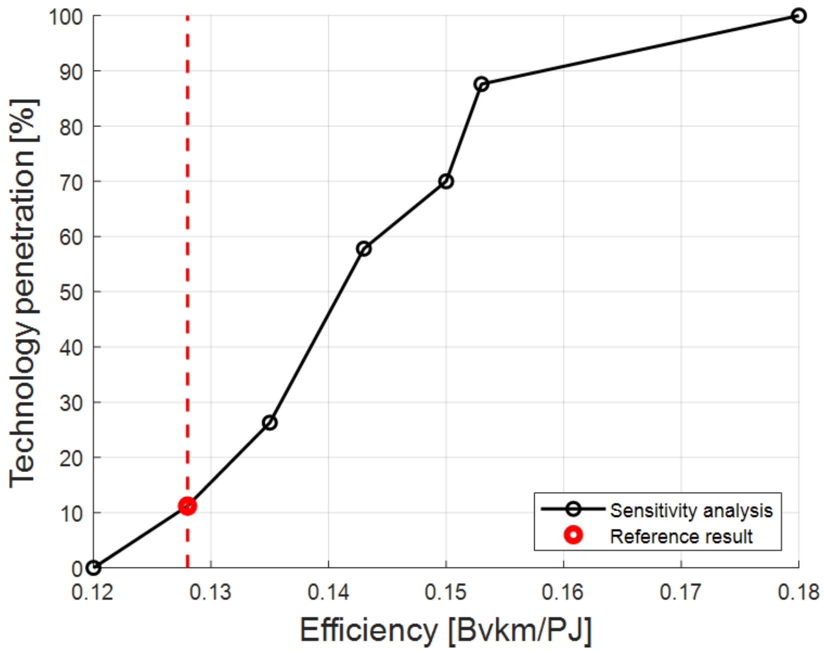

Figure 14. Sensitivity to the technology efficiency of the fuel cell heavy truck penetration within the heavy-duty trucks sector in 2050, in the NET0 scenario.

A penetration close to 90% is easily reached with an efficiency increment of 17% even if the full penetration is reached only for an increment of 50%. However, the model is also very sensitive to efficiency decrement as an efficiency reduction of 6% corresponds to zero penetration.

Due to high uncertainty surrounding the efficiency value in 2050, there is room for more exhaustive research on the fuel cell heavy-duty characterization in order to understand its true future potential. The increment of penetration of the hydrogen truck is reflected in the model as for the case of cost decrement: reduction of the direct competitor (electric truck), increment of electric buses, and reduction of synthetic kerosene for aviation.

3.6 Medium trucks

In the reference case, the penetration of the hydrogen medium truck is zero and the demand is completely satisfied by the electric truck. The model is not sensible to the cost, but it is to the efficiency. The results of the sensitivity are shown in Figure 15.

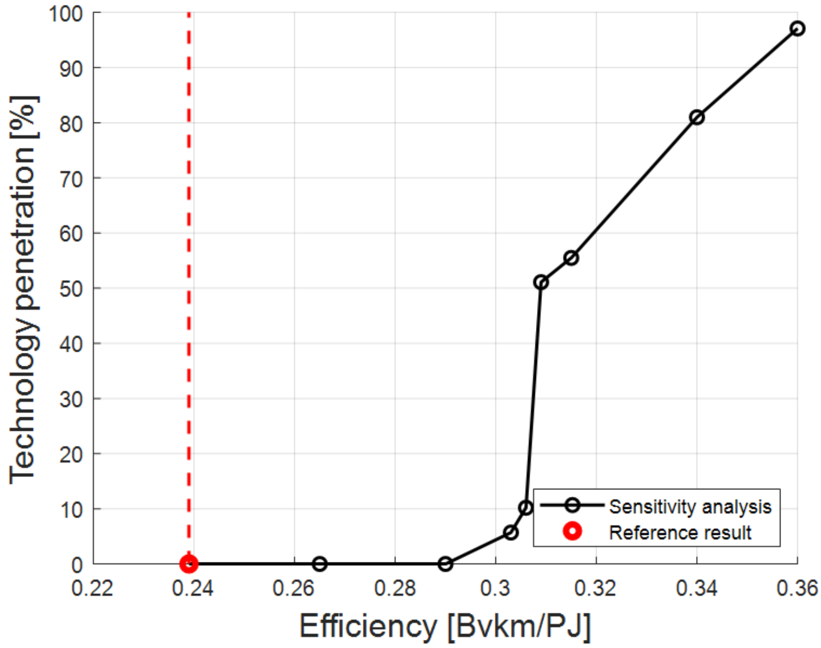

Figure 15. Sensitivity to the technology investment cost of the fuel cell medium truck penetration within the medium-duty trucks sector in 2050, in the NET0 scenario.

The penetration starts to increase with an efficiency increment of 20% and it presents three different trends: from an increment of 20% to 28% the penetration increases by 10%, then the penetration level of 50% is reached fast, with an increment of 30% while, after that, the trend is slower, and the maximum penetration reached with an efficiency increment of 50% is 97%.

It was interesting to compare the model sensitivity of the heavy-duty truck to the medium one to understand and compare the behaviors. The sensitivity to the hydrogen vehicle efficiency levels in the two subsectors is shown in Figure 16.

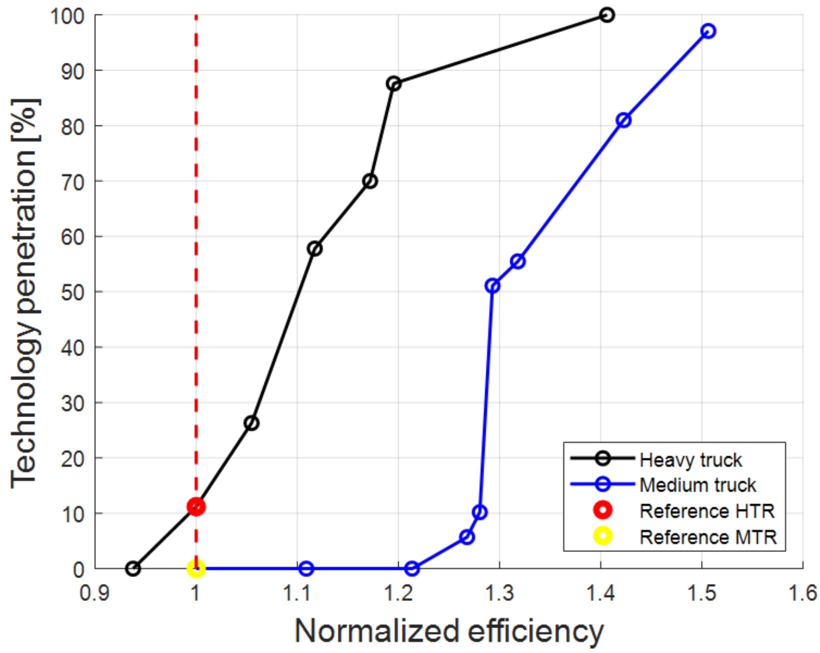

Figure 16. Comparison of the sensitivity to fuel cell heavy and medium trucks efficiency, normalized with respect to the reference value, of the penetration of both technologies within their respective sectors in 2050, in the NET0 scenario.

On the x-axis, the efficiency has been normalized for the reference value of both heavy and medium trucks to allow an easier comparison. As a result, it is possible to see that hydrogen penetration is higher in the heavy truck sector for any efficiency increment percentage. This was expected since the fuel cell heavy truck was deployed by the model even with the reference efficiency value.

3.7 Cars

This section eplores the sensitivity of the hydrogen fuel cell car in the cars subsector associated with the techno-economic characterization. With the reference efficiency and investment cost values the technology is not deployed by the model and the car transport demand is satisfied by the plug-in hybrid car for 70% and the other 30% by the electric car in 2050 in the NET0 scenario.

The model is sensible to both the investment cost and the efficiency variation. For what concern the investment cost, the results are shown in Figure 17.

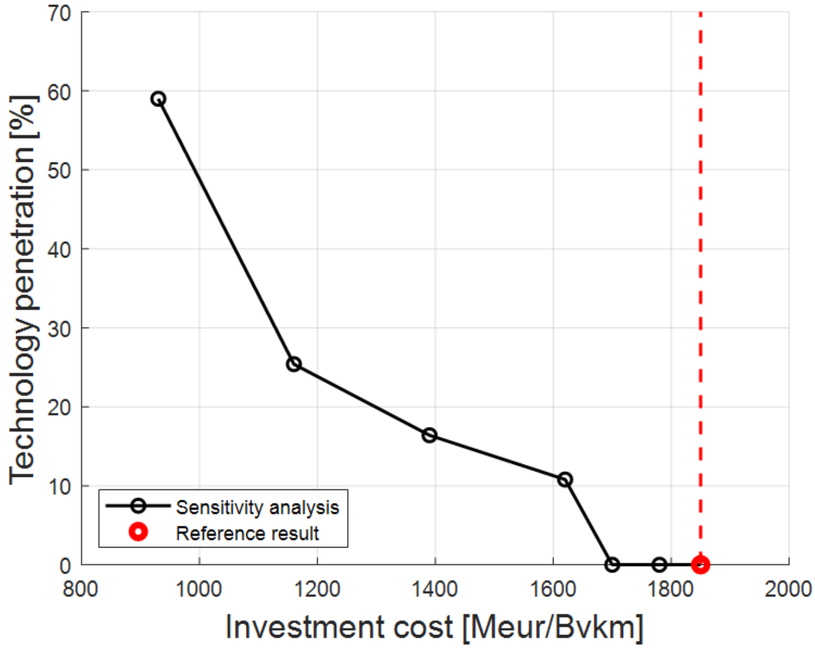

Figure 17. Sensitivity to the technology investment cost of the fuel cell car penetration within the cars sector in 2050, in the NET0 scenario.

The technology starts to be used when the investment cost decreases by 9%, the penetration steadily increases until the value of 60% is reached for a cost decrease of 50%.

It is interesting to notice how at first the technology substituted is the fully electric car while the activity of the plug-in one remains the same, only after a cost decrease higher than 40% the plug-in car starts to be challenged.

Even if with a small cost decrease the fuel cell car starts to be used, it must be said that the initial cost was already quite optimistic, being 6% lower than the electric car and 20% lower than the plug-in one in 2050.

The sensitivity analysis to the efficiency is shown in Figure 18.

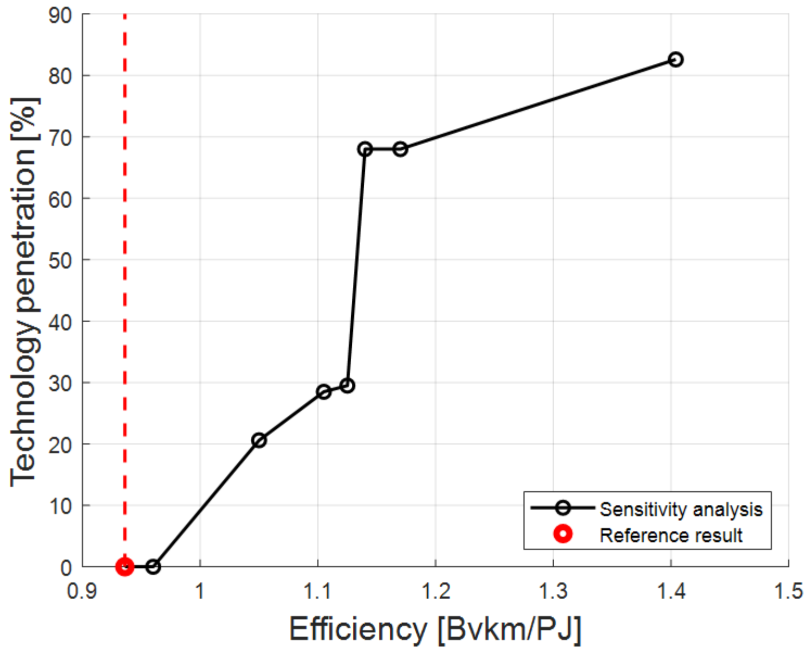

Figure 18. Sensitivity to the technology efficiency of the fuel cell medium truck penetration within the cars sector in 2050, in the NET0 scenario.

Like the cost, the efficiency increase needed for the technology to start to be used is quite small, being only 4%. Then the penetration level of 70% is reached with an efficiency increase of 20%, while the full penetration is not reached for increments below 50%.

The step from a penetration of 30% to 70% corresponds to the point when the fuel cell car becomes competitive with respect to the plug-in hybrid car.

It is interesting to compare the results found with the efficiency of the Toyota Mirai, one of the main fuel cell cars on the market today.

The efficiency of the Mirai is stated to be 1.10 Bvkm/PJ on its technical sheet [60], this would mean that if the 2050 hydrogen car efficiency was the same as the Mirai the penetration would have been around 30%, being the competing technologies efficiencies confirmed. Even if the lower efficiency value of 1,04 from the US Department of Energy [61] is chosen, the technology will still be used in the model.

3.8 Aggregated results

This paragraph presents aggregated data on hydrogen production and consumption in different sensitivity cases, as well as a summary of the sensitivity analysis results on all the technologies investigated.

Table 13 presents the results for efficiency variation.

Table 13. Results concerning sensitivity analysis on efficiency.

Technology investigated	Original penetration [%]	Minimum penetration reached [%]	Maximum penetration reached [%]	Efficiency variation for the minimum penetration [%]	Efficiency variation for the maximum penetration [%]
Domestic plane	100	0	100	-22	-16
International plane	0	0	100	+16	+50
Heavy truck	11	0	100	-6	+50
Medium truck	0	0	97	+20	+50
Fuel cell car	0	0	82	+4	+50
Direct reduction iron	100	0	100	-30	-20

The sensitivity of the model to the efficiency is remarkable. For all the technologies investigated (besides ammonia and methanol as explained in Section 3.2), a variation of ±20% is sufficient to impact the model output.

Specifically, when considering technologies that were either not used or partially used by the model in the reference case, the results suggest that all of them hold promise. The fuel cell car, in particular, emerges as a technology with considerable potential. However, it's important to underscore that none of these technologies will be the sole solution within their sector. That is because the efficiency variation corresponding to the maximum penetration for all these emerging technologies reaches a relatively high value of 50%.

One case has been chosen for each technology to display aggregated data on hydrogen production and consumption. These cases focus on sensitivity to efficiency, specifically considering efficiency variations of 20-30%.

Efficiency-related sensitivity cases were chosen because all the technologies investigated exhibit varying penetration levels when their efficiency changes (unlike investment costs). The magnitude of the variation depends on the technology, and the smallest variation that corresponds to a significant increase or decrease in penetration has been selected.

In Figure 19 the aggregated results for the hydrogen production technologies are presented.

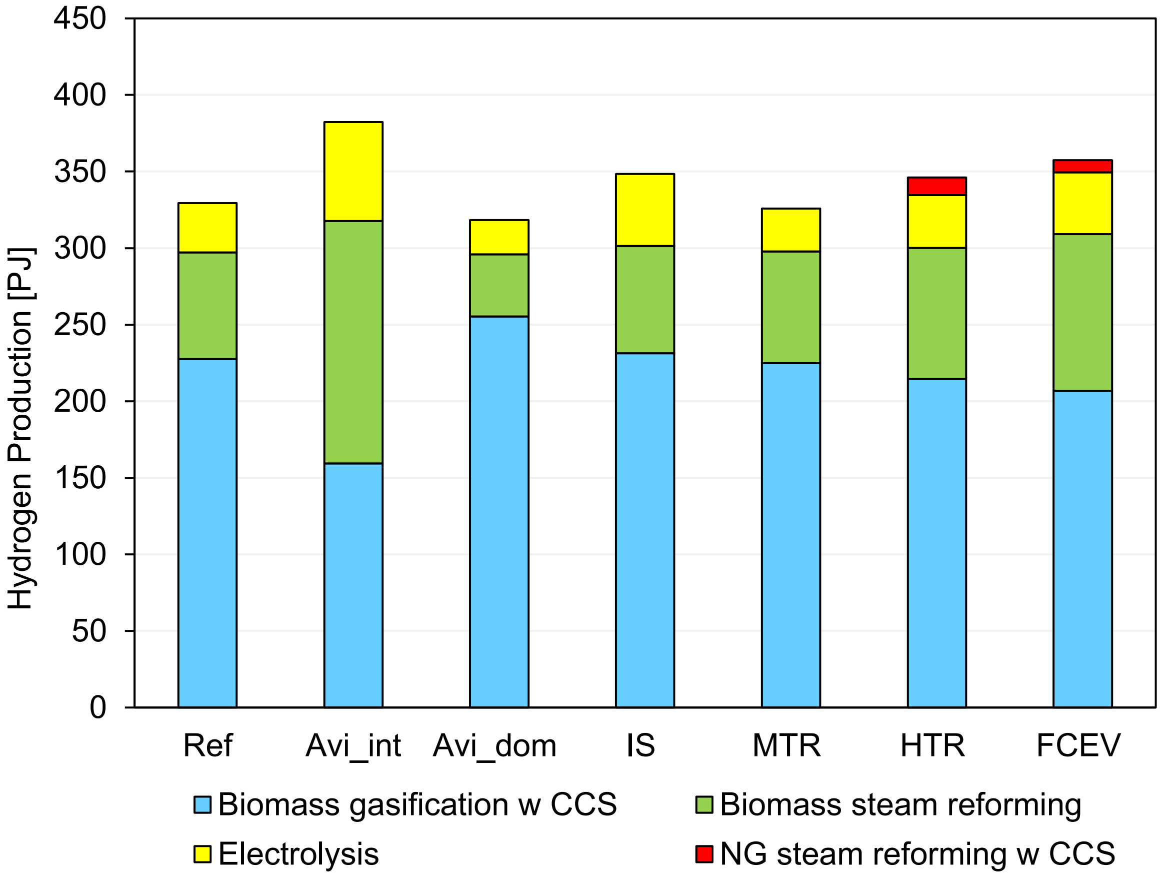

Figure 19. Hydrogen production by source in different sensitivity cases. The cases are: 20% efficiency increment for hydrogen based international planes (avi_int); 20% efficiency decrement for hydrogen based domestic planes (avi_dom); 30% efficiency decrement for HDRI-EAF (IS); 30% efficiency increment for fuel cell medium trucks (MTR); 20% efficiency increment for fuel cell heavy trucks (HTR); 20% efficiency increment for fuel cell cars (FCEV).

In the model, hydrogen is produced in three main ways, with the addition of a fourth in some cases. The three main technologies are biomass gasification with CCS, biomass steam reforming, and electrolysis, while the fourth is methane steam reforming with CCS.

In the base case, 90% of hydrogen is produced from biomass, and in general, in all sensitivity cases, this is the most important source. Hydrogen production from biomass stays quite constant at around 300 PJ due to the fact that the biomass input is limited by the constraint on the biofuels potential (see Section 2.4) so, when the demand increases with respect to the reference case, hydrogen production increment is carried out mainly by an increase in production by electrolysis.

It's worth noting that while the total hydrogen production from biomass remains relatively constant, the distribution between gasification and steam reforming varies, depending on technology penetration. This phenomenon is particularly evident when considering a higher penetration of hydrogen-based international planes. The underlying reason for this behavior is the interconnection of synfuels production with hydrogen production. As previously discussed in the analysis of the aviation sector, synfuel production is linked to hydrogen production through biomass gasification. The CO_2 captured in this technology is utilized in the generation of synfuels. Consequently, when synfuel production decreases, the proportion of hydrogen produced by biomass steam reforming increases.

The results concerning the end-use technologies are reported in Figure 20. In the base case, most of the hydrogen (80%) is consumed by the aviation sector, both in the form of synfuel and direct hydrogen. The steel sector is the second most important, followed by the blending of natural gas and hydrogen for road transport.

The consumption sharply increases with the higher penetration of the hydrogen-based international plane because the plane has a lower efficiency than the synthetic kerosene plane that is substituted.

For what concerns the relationship between different hydrogen uses in different sensitivity cases, it can be seen how the higher or lower technology penetration always cause a reduction or an increment in the synfuel use, while the other sectors remain relatively stable. This observation underscores the significant interdependence between the potential utilization of synfuels in the future and the competitive viability of hydrogen end-use technologies within individual sectors. In contrast, the performance of specific hydrogen end-use technologies in different sectors tend to exhibit relatively isolated characteristics and responses, with their success being determined by sector-specific factors rather than inter-sector dependencies.

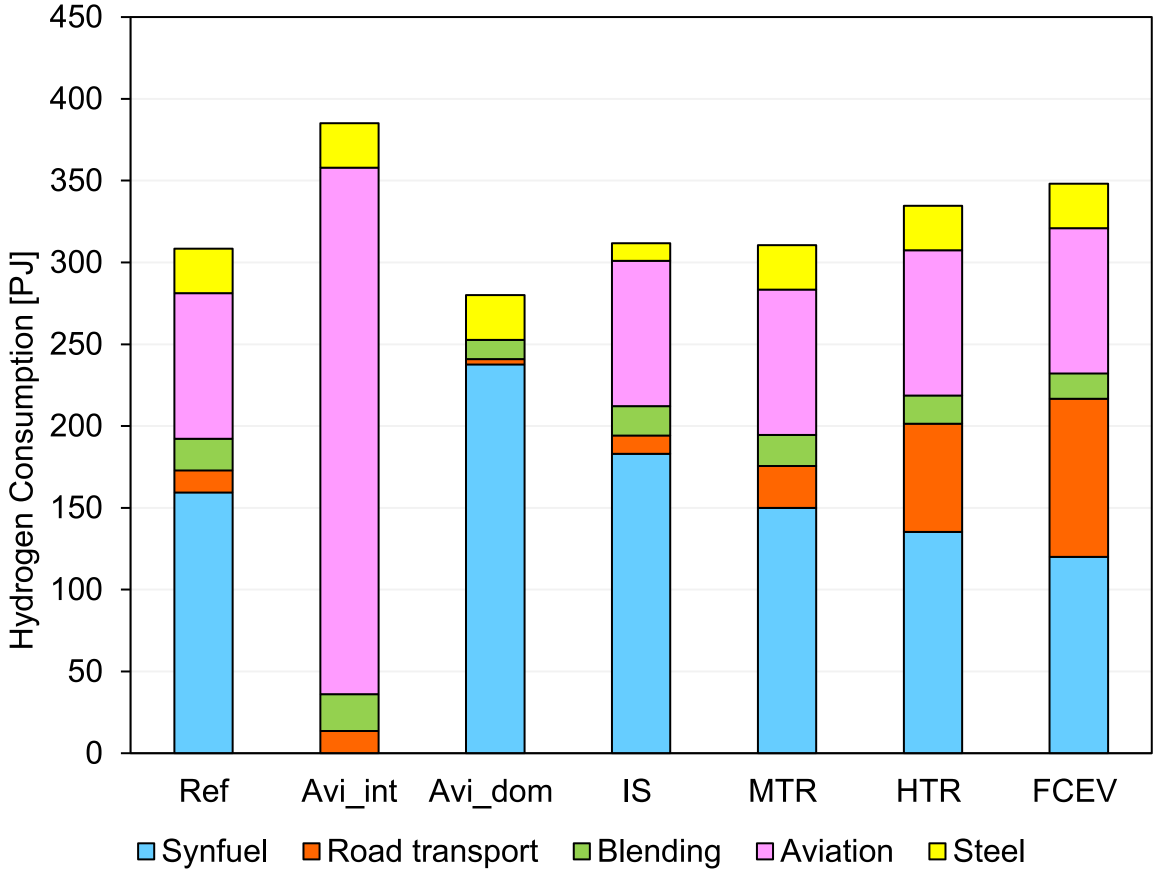

Figure 20. Hydrogen consumption by sector in different sensitivity cases. The cases are: 20% efficiency increment for hydrogen based international planes (avi_int); 20% efficiency decrement for hydrogen based domestic planes (avi_dom); 30% efficiency decrement for HDRI-EAF (IS); 30% efficiency increment for fuel cell medium trucks (MTR); 20% efficiency increment for fuel cell heavy trucks (HTR); 20% efficiency increment for fuel cell cars (FCEV).

4 Conclusions and perspectives

In this study, a preliminary assessment of the TEMOA-Italy model sensitivity to the efficiency and investment cost of various hydrogen end-use technologies was conducted within the framework of a decarbonization scenario. The primary objective was to discern how variations in these key parameters influence the model technology adoption and, subsequently, their potential role in achieving decarbonization goals. Several sectors, including automotive, heavy-duty trucks, aviation, and the industrial sector, were scrutinized, revealing notable insights and implications for the transition to hydrogen-based technologies.

The findings of this research underscore that, across most sectors, the TEMOA-Italy model exhibits a more pronounced sensitivity to changes in technology efficiency rather than investment cost. In many cases, variations in investment cost yielded negligible alterations in technology penetration, while efficiency proved to be a critical determinant. These results emphasize the significance of improving the efficiency of hydrogen technologies to enhance their competitiveness in decarbonization efforts as well as highlighting the relevance of tracing high reliability of input data especially for this specific parameter, to obtain robust output model results.

The automotive and heavy-duty truck sectors emerged as particularly sensitive areas of the model, even if with some differences. For instance, the fuel cell heavy-duty truck displayed an initial 10% penetration, but it required only a 6% decrease in efficiency to be excluded from the model optimal solution. Given the substantial uncertainty surrounding efficiency values for 2050, this outcome necessitates further research and uncertainty assessments to ascertain the true potential of such trucks. Conversely, fuel cell cars were not initially considered by the model, yet a minor efficiency increment of 4% rendered them viable. Given the existence of fuel cell cars with significantly higher efficiency values in the market, their potential role in automotive sector decarbonization should be investigated more comprehensively.

In the aviation sector, both domestic and international hydrogen-based planes exhibited sensitivity to efficiency changes, with a minimum efficiency variation of around 20% required to trigger shifts in technology penetration. However, the extent of these variations remains challenging to interpret, primarily due to the limited data availability for hydrogen-based plane efficiencies and costs, coupled with the low TRL.

Conversely, the industrial sector, specifically methanol and ammonia technologies, displayed limited sensitivity, with the model failing to adopt these technologies despite substantial parameter variations. In contrast the HDRI-EAF technology showcased robust adoption potential, even when confronted with worst-case efficiency estimates. This reaffirms HDRI-EAF's significance in the decarbonization of the industrial sector.

However, it's essential to recognize that these results are influenced by the chosen sensitivity analysis method and the unique characteristics of the TEMOA-Italy model. Notably, the "one at a time" method does not capture the interplay between various parameters, such as costs and efficiencies, which may have complex, interconnected effects on technology adoption.

Furthermore, the specific constraints of the decarbonization scenario used in this analysis likely played a pivotal role in shaping the model's sensitivities: for example, renewable and biofuel potentials were fully exploited. This situation could potentially explain why the model is more sensitive to changes in efficiency than to variations in investment costs.

This study paves the way for future research aimed at gaining a deeper understanding of the model's sensitivity to hydrogen end-use technologies and, more broadly, identifying the most promising sectors for hydrogen integration. Here are some prospective areas of exploration:

- Advanced Uncertainty Assessment Methods: it is advisable to employ more sophisticated uncertainty assessment methods that go beyond the "one at a time" approach. Techniques such as robust optimization or alternative scenario modeling could be applied to the most promising sectors identified in this study. This would allow for a more comprehensive analysis of how different parameters affect the adoption of hydrogen technologies.
- Constraint Analysis: further investigation is warranted regarding constraints like maximum CO_2 storage capacity and steel type ratios. Understanding the impact of these constraints on sectors like aviation and steel demand is essential. This research would provide valuable insights into the feasibility and limitations of hydrogen integration in these industries.
- Integration of excess renewable electricity: since the adopted version of the TEMOA-Italy model is mainly suitable for capacity expansion problems, enhancing the model to suitably account for excess electricity production from

renewable sources would be significant. This adaptation would make the production of hydrogen through electrolysis more economically viable and aligned with the goals outlined by governing authorities.

In summary, this study contributes valuable insights into the potential of hydrogen-based technologies in a decarbonization scenario. It underscores the importance of improving technology efficiency and highlights the need for more advanced sensitivity analysis methods and robust data to navigate the uncertainties associated with emerging technologies. These findings can inform future policy decisions and investment strategies aimed at achieving sustainable decarbonization objectives.

Data availability

The TEMOA source code is available at [62], while the TEMOA-Italy model is available at [33]. The input and output databases associated with all the sensitivity cases studied in this thesis are available at [63].

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Appendix A: Pre and post update data comparison

Table 14. Pre and post update data comparison

	Specific consumption pre update	Specific consumption post update	Investment cost pre update	Investment cost post update
Kerosene-based domestic aviation	120.8 MJ/km	127.0 MJ/km	1000 M€/PJ	115000 M€/Bvkm
Hydrogen-based domestic aviation	120.8 MJ/km	122.3 MJ/km	3100 M€/PJ	160000 M€/Bvkm
Kerosene-based international aviation	71.9 MJ/km	298.5 MJ/km	1000 M€/PJ	92000 M€/Bvkm
Hydrogen-based international aviation	71.9 MJ/km	423.7 MJ/km	31000 M€/PJ	120000 M€/Bvkm
Heavy truck (2025)	13 MJ/km	9.8 MJ/km	5400 M€/Bvkm	4150 M€/Bvkm
Heavy truck (2050)	9.5 MJ/km	7.8 MJ/km	4189 M€/Bvkm	3100 M€/Bvkm
Medium truck (2025)	5.7 MJ/km	5.7 MJ/km	4980 M€/Bvkm	4980 M€/Bvkm
Medium truck (2050)	4.2 MJ/km	4.2 MJ/km	3860 M€/Bvkm	3860 M€/Bvkm
Fuel cell car (2025)	1.6 MJ/km	1.6 MJ/km	3370 M€/Bvkm	2760 M€/Bvkm
Fuel cell car (2050)	1.1 MJ/km	1.1 MJ/km	2920 M€/Bvkm	1850 M€/Bvkm
Direct reduction iron	10.2 MJ/t	14.5 MJ/t	763 €/t	763 €/t
Ammonia synthesis via electrolysis	40.3 MJ/t	24.3 MJ/t	104.0 €/t	156.0 €/t
Methanol synthesis via electrolysis	24.0 MJ/t	24.0 MJ/t	44.0 €/t	44.0 €/t