Could clean industrial progresses and the rise of electricity demand foster the penetration of nuclear fusion in the European energy mix?

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The effects of the update of the EUROfusion TIMES Model (ETM) industrial sector to account for the introduction of low-carbon technologies is presented and discussed in this work. ETM is a minimum-cost energy system model aimed at investigating the conditions for the introduction of nuclear fusion in the future electricity mix. The most interesting ETM long-run scenarios (until 2100) must comply with stringent environmental targets to pursue the Below-2-Degrees objective, identified in the Paris Agreement, allowing wide commercial adoption of innovative production processes - currently under test or research - which would almost completely replace well-established fossil-based industrial techniques in the iron and steel, chemicals, non-ferrous metals, non-metallic minerals and pulp and paper sub-sectors. Among them, low-carbon and electrolysis-based processes could open the way to a considerable increase of electricity demand, requiring also clean resources not to undermine sectoral efforts in becoming more environmentally sustainable, and the same does the implementation of CCS technologies. The study shows that the industrial sector contributes to the energy mix decarbonization by relying on CCS technologies, when available, or new low-carbon technologies. The progressive electrification of the industrial sector turns into an increasing final electricity demand which is covered by renewables and nuclear when stringent climate policies are put in place. Despite technological constraints are likely to slow down fusion deployment in the future, a range of scenarios show that nuclear fusion could contribute to generation of carbon-free electricity in the future European energy system.

Keywords: energy scenarios; energy system model optimization; industry sector; nuclear fusion penetration.

1. Introduction

The role of modeling and planning, generally important for large investments, becomes crucial when dealing with a technology, such as nuclear fusion, that could ease the solution of climate change-related issues, but at the cost of enormous investments in terms of research and economic efforts.

The development of nuclear fusion in Europe [1] foresees the installation of a demonstration reactor (EU-DEMO) by 2050, with the aim of demonstrating the possibility to produce net electricity from nuclear fusion reactions. While the cost analysis of a nuclear fusion power plant (NFPP) is being investigated based on simplified models of the different physics, engineering and economical aspects [2], the EUROfusion Socio-Economic Studies Work Package (WPSES) is in charge of assessing the conditions at which fusion can be deployed – once it will be ready for the energy market – to produce electricity at a commercial scale. This fundamental step to drive research and development of fusion reactors is addressed using the EUROfusion TIMES Model (ETM) for scenario analyses [3]. Tools like ETM typically model the connection between supply and demand in a technologically explicit manner, also assessing the impact of the evolution of the production system on climate change-related issues. The peculiarity of ETM, with respect to other similar tools, is that it considers the availability of nuclear fusion in the electricity production mix. To keep the pace with the development and improvement of low-carbon energy-efficient technologies, such models require a periodic update of the technological stock. In this framework, the impact of the evolution of the industrial sector under environmental constraints in a TIMES model framework [4] is analyzed by the International Energy Agency (IEA) in its Energy Technology Perspectives (ETP) [5] and by the JRC-EU-TIMES Model [6]. Anyway, neither of them considers the possibility to have nuclear fusion power shares because of the shorter time horizon as compared to ETM, which instead looks at the global energy system evolution up to 2100. This paper discusses the possible future energy use in the European industry sector according to different storylines and scenarios, and analyzes if, and to what extent, the rise in the electricity demand could boost the penetration of fusion energy. It also allows performing, on the timescale to 2100, an assessment of the penetration of the new technology in the different industrial subsectors in Europe. The work presented here is part of a larger project intended to update the economic sectors of the ETM model according to the most recent literature on the current state of technologies and their possible future technical and economic development. Specifically, this paper follows the discussion about the evolution of the global [7] and European [8] transport sectors.

This paper is structured as follows. Section 2 briefly presents the main features of the EUROfusion TIMES Model, while Section 3 highlights the new structure of the industry sector in ETM, presented and discussed in detail in [9]. In Section 4, a range of energy scenario results are presented and discussed, while conclusions are addressed in Section 5.

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2. The EUROfusion TIMES Model

The EUROfusion TIMES Model is an economic model of the global energy system [10], based on the TIMES framework. It adopts an optimization strategy aiming to supply energy services at the minimum global cost (or equivalently, minimum loss of total surplus) [11], with a partial equilibrium approach over a long-term time scale, starting from 2005 (the so-called "base year") up to 2100. The global model is articulated over 17 world regions, grouping countries with comparable economic conditions and development assumptions, and outlined in Figure 1.

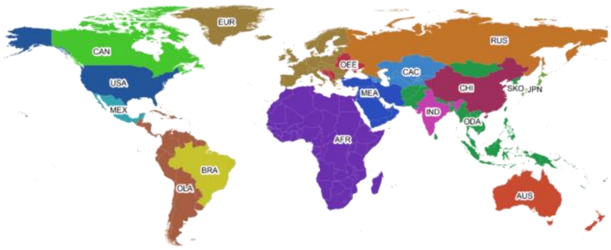

Fig. 1. ETM world regions [12].

Regional energy service demands throughout the ETM time horizon are calculated according to Eq. (1):

$$D_t = D_{t-1} \cdot [1 + (\delta_t/\delta_{t-1} - 1) \cdot e_{t-1}] \qquad (1)$$

where D is the demand, t the time step, δ the demand driver and e the elasticity of the demand to its driver. Elasticities are used to reflect possibly different patterns in energy service demands, changing in relation to socio-economic growth (i.e. the assigned driver for demand projection).

Here the service demands specifically correspond to the quantity of required end-use product in the industry sector [9]. ETM uses internally coherent trajectories for drivers (e.g. gross domestic product, population), taken from the US Energy Information Administration’s International Energy Outlook (2019 Edition) [13] for the latest available ETM update, or from other general equilibrium models like GEM-E3. The driver used for industrial energy service demand projections is the economic value added of end-use products.

3. The industrial sector reference energy system

In ETM, the structure of the industry sector includes five energy-intensive subsectors, which represent the bulk industrial energy consumption: the iron and steel subsector produces ferroalloys; the non-ferrous metals subsector produces aluminum, copper, niobium, tin, titanium and zinc; the non-metallic minerals subsector produces cement, ceramics, glass and lime; the chemicals sector produces ammonia, chlorine, high-value chemicals (HVC) and methanol; the pulp and paper subsector produces paper.

Each energy-intensive subsector contains the set of technologies, listed in Table 1.

Table 1. List of technologies considered in the ETM industry module.

Subsector	Product	Technology	Starting date
Iron and steel	Steel	Blast furnace-basic oxygen furnace (BF-BOF)	Base year
		Direct reduced iron-electric arc furnace (DRI-EAF)	Base year
		Steel from scrap-EAF	Base year
		Smelting reduction-BOF	2006
		BF-BOF with CCS	2030
		BF top-gas rec.-BOF with CCS	2020
		DRI-EAF with CCS	2030
		HIsarna-BOF	2025
		HIsarna-BOF with CCS	2030
		Hydrogen direct reduction-EAF	2030
		Ulcored with CCS	2030
		Ulcolysis	2030
		Ulcowin	2030
	Ferroalloys	Ferroalloys production	Base year
Non-ferrous metals	Alumina	Bayer process	Base year
	Aluminum	Hall-Héroult	Base year
		Secondary aluminum	Base year
		Hall-Héroult with inert anodes	2030
		Carbothermic reduction	2050
		Kaolinite reduction	2050
	Copper	Copper production	Base year
	Niobium	Niobium production	Base year
	Tin	Tin production	Base year
	Titanium	Kroll process	Base year
	Zinc	Zinc production	Base year
Non-metallic minerals	Clinker	Dry process	Base year
		Wet process	Base year
		Dry process with post-combustion CCS	2030
		Dry process with oxy-fuel combustion CCS	2030
	Cement	Cement blending	Base year
		Alkali-activated cement-based binders	2010
		Belite cement	2010
	Lime	Long rotary kiln	Base year
	Glass	Fossil fuel-fired furnace	Base year
		All-electric furnace	Base year
	Ceramics	Ceramics production	Base year
Chemicals	HVC	Naphtha steam cracking	Base year
		Ethane steam cracking	Base year
		Gas oil steam cracking	Base year
		LPG steam cracking	Base year
		Propane dehydrogenation	2010
		Naphtha catalytic cracking	2011
		Methanol-to-olefins	2015
		Bioethanol dehydration	2020
	Ammonia	Nat. gas steam reforming (NG SR)	Base year
		Naphtha partial oxidation	Base year
		Coal gasification	Base year
		Synthesis via electrolysis	2015
		Biomass gasification	2025
		NG SR with CCS	2025
	Methanol	NG SR	Base year
		Coke oven gas steam reforming	Base year
		LPG partial oxidation	Base year
		Coal gasification	Base year
		Synthesis via electrolysis	2015
		Biomass gasification	2025
	Chlorine	Mercury cell	Base year
		Diaphragm cell	Base year

		Membrane cell	Base year
Pulp and paper	Pulp	Mechanical pulping	Base year
		Semi-chemical pulping	Base year
		Kraft process	Base year
		Sulfite process	Base year
		Recycled fiber pulping	Base year
	Paper	Paper production	Base year

In order to calculate the sectoral energy demand over the model time horizon, all energy producer/consumer technologies in ETM are split into two classes:

- Base year technologies, used to model demand and energy use at the beginning of the time horizon (year 2005). The base year demand is calculated by combining the total sectoral energy consumption from IEA statistics [1] with calibration parameters representing efficiencies and fuel use. Note that the existing technological characteristics of the production stock in the base year is not reproduced exactly, but the energy use breakdown is estimated in order to reproduce the actual consumption;
- New technologies, to model energy use throughout the time scale, are added to the base year technological stock.

Together with the energy-intensive subsectors, the ETM industry sector includes also "minor industries" (textile, food, drink, tobacco, etc.) and micro-CHP industrial plants.

The general structure of any energy-intensive industrial new technology, with its inputs and outputs, is reported in Figure 2. In some subsectors, energy-intensive intermediate materials may be needed for production of the final material. This happens with alumina, used for aluminum production with some technologies, clinker, used as primary material for a cement production process, and pulp, used as primary material for paper production. New technologies in the energy-intensive industrial subsectors, characterized in detail using data from the available literature, include 66 existing or upcoming production processes, see Table 1, which can be chosen by the model to satisfy the prescribed demand for end-use goods. Note that, due to the relatively long lifetimes of industrial plants, the energy use contribution coming from base year technologies may last up 2035.

Each energy-intensive industrial technology is characterized by 5 parameters:

- Starting date for the availability of the technology, i.e. the first year at which the technology can enter the energy system during the model time-horizon;
- Availability factor, i.e. the amount of time for which the plant is able to operate to produce the demand commodity over a year, [%];
- Lifetime of the plant, in [years];
- Investment cost, in $\$/t_{product}$;
- Fixed O&M cost, accounting for the price of raw material, labor and maintenance per quantity of the produced demand commodity, in $\$/t_{unit\ capacity}/year$.

The variable O&M cost (i.e. cost of energy) is the result of the partial equilibrium model, where the price of each commodity is computed endogenously. Since industrial production statistics are available in all subsectors at least until 2015, actual elasticities are indeed calculated in ETM, and not assumed, to reflect real demand trends from 2005 to 2015. After then, elasticities are assumed to evolve according to three different growth levels (medium, low, high), corresponding to the ETM built-in storylines, see below.

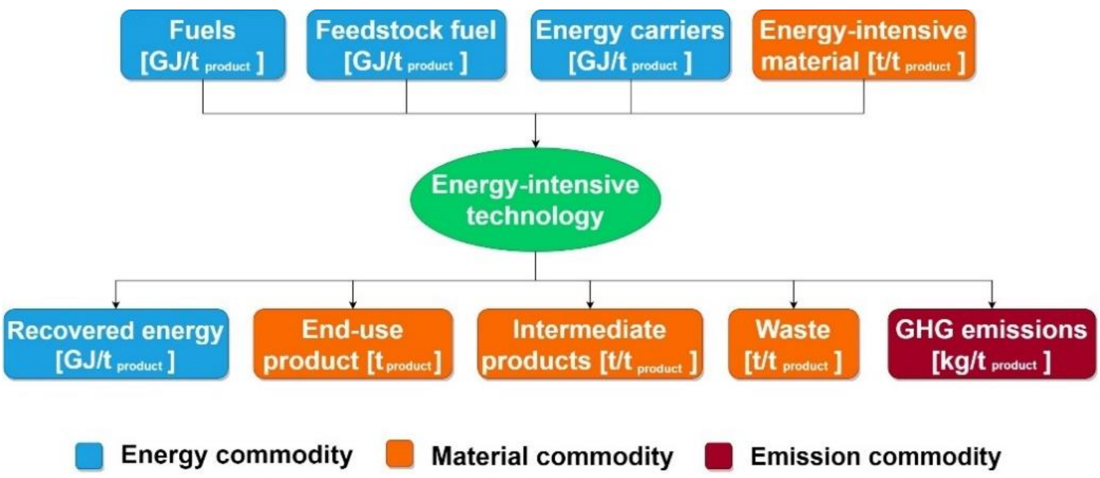

Fig. 2. General structure of any technologies for energy-intensive industrial subsectors.

Table 2. Summary of the main features of ETM storylines.

Features \ Storyline	Paternalism (P)	Harmony (H)	Fragmentation (F)
Environmental responsibility	Strong (RCP 2.6)	Strong (RCP 2.6)	Weak (RCP 6)
Investment policy	Medium-term (medium discount rate)	Long-term (low discount rate)	Short-term (high discount rate)
Demand elasticity	Medium	Low	High
Cooperation between countries	Moderate	High	Very low

4. ETM storylines and scenarios

ETM storylines – named "Paternalism" (**P**), "Harmony" (**H**) and "Fragmentation" (**F**) – depict the broad outlines of socio-economic development and define the degree of environmental responsibility according to the Representative Concentration Pathways (RCP), adopted by IPCC [15], assigning yearly constraints for the global maximum greenhouse gases (GHG) emissions and concentrations until 2100 to reach different environmental targets. Table 2 reports a summary of the main features of ETM storylines. In each storyline, the computed end-use energy service demand evolves according to Equation (1) as reported in Figure 3a for steel, ferroalloys and non-ferrous metals, in Figure 3b for non-metallic minerals and chemicals, and in Figure 3c for paper. Due to the formulation of Equation 1, when the demand shows a decreasing trend (steel and non-ferrous metals, see Figure 3a), the effect of the high level of elasticity in **F** (Table 2) is reflected in a steeper decrease with respect to the production in the other subsectors.

Within the three storylines, a set of scenarios can be defined, which differ according to the availability of fusion (assumed here starting from 2050 for all scenarios), the availability of CCS (starting from 2030 for some scenarios, see Figure 4a), the low or high level of fission deployment, and the fast or slow development of the fusion technologies. The technical and economic features of the fusion power plants adopted in this work are summarized in Table 3: four types of commercial fusion plants are considered, namely two basic plants, the first one available starting from 2050 on, and two advanced plants, the first one available from 2070 on. All plants are based on the EU-DEMO concept. They mainly differ for their investment cost [2], decreasing as technical progress is achieved throughout four decades, and for electrical efficiency, set at 42 % for basic plants and 60 % for advanced plants.

Table 3. Technical and economic characterization of fusion power plants in the current analysis [16].

Type of plant	Start year	Investment cost [$/kW]	Fixed O&M cost [M$/GWa]	Var. O&M cost [M$/PJ]	η [%]
Basic plant A	2050	5910	65.8	2.2	42
Basic plant B	2060	4425	65.8	1.6	42
Adv plant A	2070	4220	65.3	2.1	60
Adv plant B	2080	3255	65.3	1.6	60

4.1 Scenario analysis

In the energy consumption projections of the industrial sector, shown in Figure 4b, 4d and 4e, the same scenario (s01 as from the scenario tree in Figure 4c) is analyzed throughout the three storylines, which has the following peculiarities:

- Carbon capture and storage (CCS) is available starting from 2030;

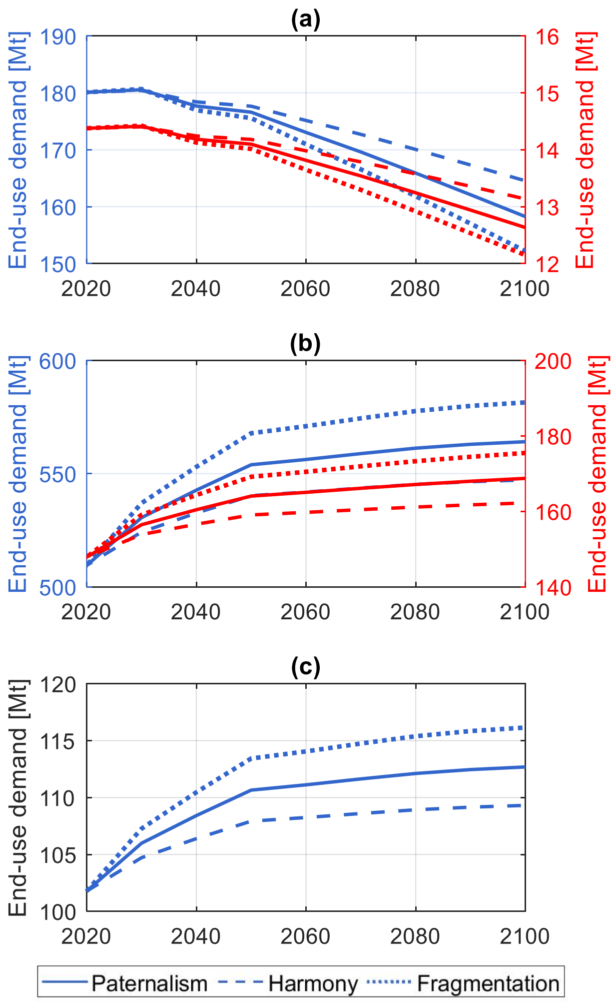

Fig. 3. Evolution of European industrial end-use product demand in the ETM storylines: iron and steel (a, left axis), non-ferrous metals (a, right axis), non-metallic minerals (b, left axis), chemicals (b, right axis) and pulp and paper (c).

- Progressive phase-out of nuclear fission (up to 1/5 of the current European capacity);
- Nuclear fusion power plants are available for electricity production from 2050 on, with technical and economic features showed in Table 3. It is assumed that, on the basis of the estimated future availability of tritium [17], the maximum possible installed fusion capacity is constrained to 1 GW in 2050 and up to a maximum of 15 GW in 2100 in Europe. This picture corresponds to the "slow development" of fusion technologies, while the fast one allows for a maximum of 71 GW in 2100, starting from the same maximum capacity in 2050, and constrained mainly by the industrial readiness of the fusion technology.

It is worth recalling that the scenario considered is not meant to be a forecast, but rather the picture of one of the possible evolutions of the current European energy system.

In particular, a significant increase in carbon-free electricity penetration is computed in both storylines **P** and **H** to displace the use of fossil fuels, reaching the ~ 50 % of total energy use. Anyway, fossil fuels are not phased-out until the end of the century, especially due to the application of CCS in technologies that use carbon-rich fuels, mostly in the iron and steel subsector. Indeed, that is the subsector where CCS is identified as the best solution for decarbonization, despite the presence of other carbon-free options, such as hydrogen direct reduction and electrolysis-based technologies (Ulcolysis and Ulcowin), which are not considered by the TIMES optimization algorithm due to their high cost [9]. Note that, according to model results, also cement and ammonia production take advantage of CCS adoption (not shown). In **H**, hydrogen and biomass are computed to give a quite higher contribution to the energy consumption by the end of the century, with respect to **P**.

A different evolution is computed in the storyline **F**, where fossil fuels consumption increases until 2060, showing then a slow decrease until 2100. Electricity use in 2100 reaches the 35 % of the consumption mix (while the power sector does not undergo any attempt of decarbonization), and the use of coal is even higher than in 2020. The total energy demand has the same level in 2100 as in 2020, even though it reaches a peak of $\sim 360\ Mtoe$ in 2050, mainly due to a large employment of natural gas in the mid-century periods.

The detail of the electricity production share in 2100 throughout all the scenarios analyzed for the storyline **P** is reported in Figure 4c. The electricity production sources are grouped into six categories: 1) nuclear: fission and fusion power plants; 2) solar: photovoltaic and concentrated solar power (CSP) plants; 3) wind plants; 4) other RES: hydroelectric, biomass and geothermal plants; 5) fossil fuels: coal, oil and gas plants; 6) CCS-equipped oil and gas power plants. Although the different scenarios do not correspond exactly to the same total electricity consumption, Figure 4c shows a clear pattern: renewable sources, and mostly wind power, dominate the mix, with the contributions of nuclear energy quite different, driven by the different features of the scenarios (see Figure 4a). The role of fusion over the total nuclear production is only remarkable in scenarios assuming fast fusion deployment and fission phase-out (s04 and s08, where fusion covers 68 % of the total nuclear production).

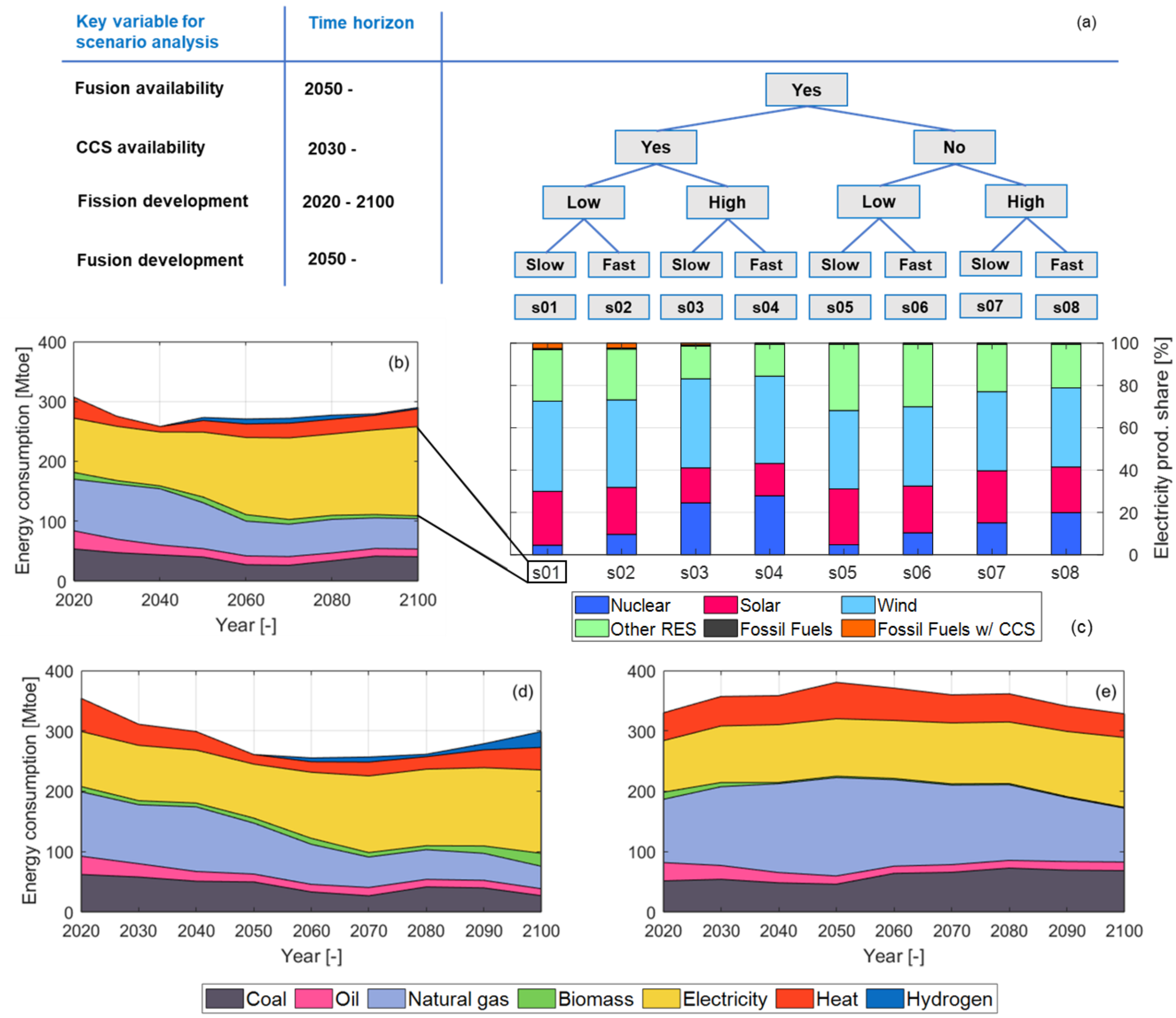

Fig. 4. (a) ETM scenario tree. Industrial energy consumption for scenario 1 in the three storylines **P** (b), **H** (d) and **F** (e), respectively. The detail of the electricity production mix in 2100 is also presented (c) for the analyzed scenarios where fusion is available starting from 2050 on.

On the other hand, in scenarios where fission is phased-out (s01, s02, s05, s06) the growth of fusion is limited by the imposed technological constraints only (tritium availability and/or industrial readiness for fusion fast deployment).. Indeed, it reaches the maximum possible penetration in all scenarios, which demonstrates that, under the assumptions considered in this study, nuclear fusion does provide a contribution to the production of carbon-free electricity in an end-of-the-century European decarbonized energy system.

The time evolution of the composition of the electricity mix is detailed in Figure 5 for scenario s01 from the scenario tree in Figure 4c (the same described in Section 4) in the three storylines. Electricity production is at least doubled with respect to the current European production (~ 3000 TWh) in all the storylines. In **F**, electricity production becomes lower than in **P** and **H** moving towards the end of the century, and it is mostly dominated by fossil fuels. Instead, renewables are the most relevant electricity source in **P** and **H**, especially approaching the end of the time horizon considered in ETM. Solar energy shows a remarkable increasing trend from 2050 on in **P** and **H**, along with the use of CCS in the mid of the century, to comply with stringent decarbonization targets. Instead, in Fragmentation, CCS is never used, although it is available, and renewables represent only the 23 % of total electricity production at the end of the century. In 2100, fusion covers one third of the total nuclear production in the three storylines (~ 100 TWh in **P** and **H**).

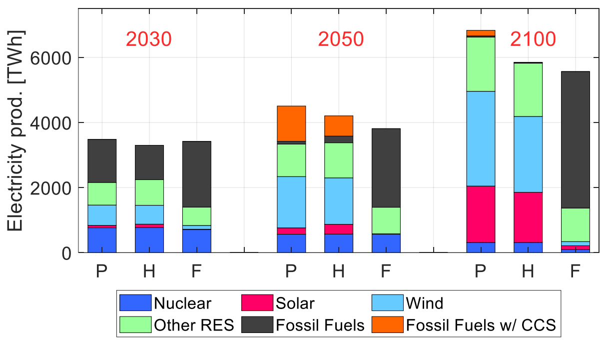

Fig. 5. Computed electricity production shares in Europe from 2030 to 2100 in scenario s01 in the three storylines.

Finally, Figure 6 shows the evolution of the resulting CO_2 emissions in the industrial sector. In both **P** and **H**, CCS is a key technology to lower emissions, as it can be seen from the trajectories for s01. On the other hand, in **F** direct emissions from the industrial sector are slightly lowered from the initial levels (−20 % from 2020 to 2100) mainly due to the application of CCS, that is only developed in the chemical sector for ammonia production by the end of the century.

When CCS is not available, even in the storyline **P**, zero emissions cannot be reached, even if the reduction from 2020 CO_2 emissions levels is massive (−74 %). This is not in contradiction to the storyline emission constraint, which is given at a global, as opposed to sectoral and regional, level.

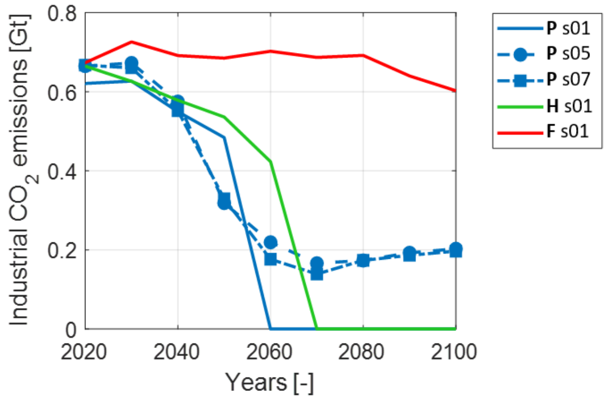

Fig. 6. CO_2 emissions computed for the industrial sector.

4.2 Industrial technology assessment

The trends of industrial CO_2 emissions (shown in Figure 6) of the scenarios in the storyline **P** can be explained by the evolution of the technology shares to meet energy service demands, and in particular by the steel (see Figure 7), cement (see Figure 8) and chemicals (see Figure 9) production, respectively. They represent in fact the portions of the industrial sector where innovative technologies are largely available (see Table 1), so they have a great influence in determining the evolution of the whole sector, mostly in terms of emissions.

In the following, three scenarios (s01, s05, s07) are discussed being representative of the scenarios where CCS is available (s01) or not (s05, s07).

In s01 (Figure 7) the process BF with top-gas recovery-BOF (BF-TGR-BOF), which relies on CCS and is highly efficient, gains a larger and larger role in the decarbonization of the iron and steel subsector (25 % share in 2100). Its role is almost totally balanced by the recycling of scrap steel when CCS is not available (s05 and s07), where also hydrogen gains a remarkable role, even though the traditional BF-BOF process, highly inefficient and coal consuming, is not phased-out. On the other hand, HIsarna-BOF, a highly efficient coal-based process, plays a dominant role in s01.

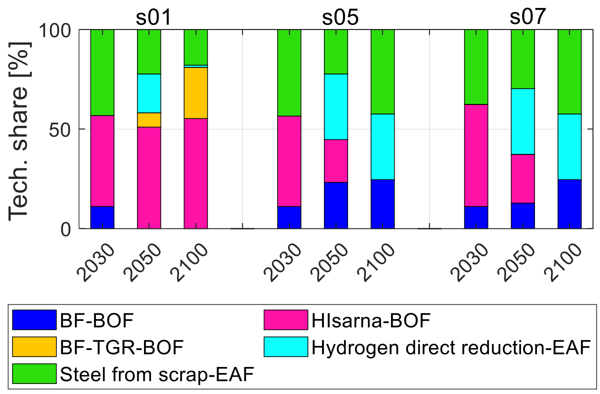

Fig. 7. Technology share computed for steel production in the storyline **P**, for scenarios s01, s05 and s07 at selected time steps.

Concerning cement production in Figure 8, CCS is not considered an attractive option in all the three represented scenarios, while innovative cements (Belite and Alkali-activated cement binders) gain the whole market by 2100, even if with different shares. In s05 Belite represents the first choice to substitute traditional cement production due to its lower cost. On the other hand, it requires larger quantities of carbon-rich sources, thus it is deemed as a secondary choice in s01 and s07, where it is not adopted, being not considered as recommended to respect emission constraints.

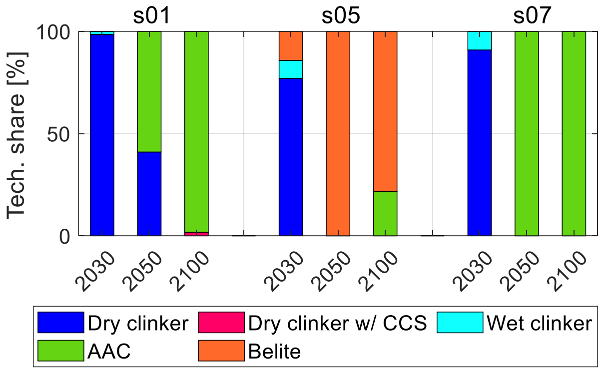

Fig. 8. Technology share computed for cement production in the storyline **P**, for scenarios s01, s05 and s07 at selected time steps.

Finally, Figure 9 shows the evolution of the technology share for the chemicals sector. Here, the situation is complex due to the co-presence of four different products (HVCs, ammonia, methanol and chlorine), but the three selected scenarios highlight evident patterns. While fossil-based routes keep their large role in all the scenarios, CCS gains a remarkable role in ammonia production in s01, especially in the mid-century (ammonia steam reforming is the only possible technological option for CCS application in the whole chemicals sector). In s05 and s07, instead, for which CCS is not available, it is substituted by electrolysis, as it does not involve any direct emissions and can be considered as a clean technology (provided that hydrogen is produced via low-carbon routes).

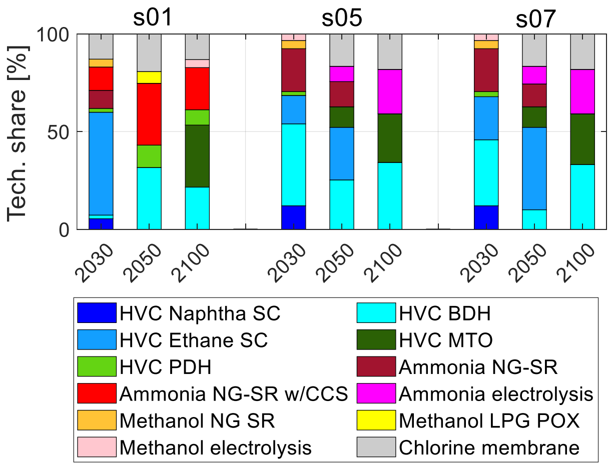

Fig. 9. Technology share computed for chemicals production in the storyline **P**, for scenarios s01, s05 and s07 at selected time steps.

5. Conclusions

The role of energy system modeling and planning, generally important for large investments, becomes crucial when dealing with a technology like nuclear fusion, involving huge economic efforts but a significant environmental-friendly energy production potential.

This work comes after a massive update of the ETM industrial module, and is meant to show how different innovative technological options could gain a significant role or not in the future energy mix. Different storylines are presented, with a set of different scenarios.

The results shown in this paper highlight the rise of electricity demand during time, and the environmental benefits obtained through the introduction of innovative clean technologies in the industrial sector. The computed technological mix in the industrial subsectors shows that CCS can be an important instrument to reach ambitious climate goals. Nevertheless, in the analyzed scenarios where CCS is not available, important CO_2 emissions reduction targets can be reached anyhow, albeit other innovative low-carbon technologies are not able to lead to net-zero emissions.

The raise in the European electricity demand allows some penetrations of fusion energy in the electricity mix. The fusion penetration is bounded by the imposed capacity limits, which can be imagined today due to technical and material availability constraints for EU-DEMO-derived reactor concepts currently implemented in ETM.

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