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Analysis of the possible contribution of different nuclear fusion technologies to the global energy transition

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ABSTRACT

Despite the huge uncertainties related to the possibility of a quick development of nuclear fusion technologies - being disputed that it may come too late to effectively contribute to emission mitigation - research is focusing on a wide set of options for fusion reactors. This paper presents a global scenario analysis using the energy system optimization model EUROfusion TIMES to analyze the possible future role of fusion according to three different technologies and using capacity curves based on historical trends for the electricity sector. The analyzed fusion options are based on ARC, EU-DEMO and Asian-DEMO reactor concepts, characterized in terms of techno-economic features according to publicly available literature and considering a set of educated growth rate for their penetration. Results concerning installed capacity trends and contribution to the electricity mix are presented up to 2100 in three socio-economic storylines and for different scenarios considering either the availability of competing technologies or delays in the development of fusion plants. Despite not contributing at all to the energy transition in Europe and the US, fusion may gain share in contexts characterized by highly growing electricity demand, contributing to satisfy stringent environmental constraints together with other low-carbon technologies in the second half of the century.

1. Introduction

Climate change is the most important challenge that the global community must face in the next decades [1]. Today the energy sector represents a key contributor to climate change, accounting for more than two-thirds of global greenhouse gas (GHG) emissions [2], considered as the main responsible for global warming in the post-industrial age [3]. The fight to climate change-related issues requires efforts for both mitigation and adaptation strategies [4]. In the context of mitigation in the energy sector, technological advancement to enhance and support the adoption of existing low-carbon options across supply and end-use sectors must go on to achieve a transition towards a cleaner and more sustainable energy system [5]. The development of renewable energy technologies is an ongoing process, especially in the electricity generation sector [6], whereas the peak in global GHG emissions from the power (electricity and heat) sector was just reached in 2018 [7], mainly due to a large reliance on fossil sources, still accounting for the bulk of power generation (more than 60% in 2019 [8]). Besides renewable energy technologies, two innovative options are gaining increasing interest in the electricity generation sector: plants equipped with carbon capture and storage (CCS) [9] and nuclear fusion [10]. While some plants already exist envisaging the adoption of the former technology (almost 30 power plants equipped with CCS were commissioned between 2020 and 2021) [11], that would allow substantial reduction of emitted CO_2 emissions in plants relying on fossil fuels, the feasibility of the latter still has to be demonstrated, despite considerable progress in recent years and a growing number of projects contributing to make fusion energy achievable [12].

The research on magnetic confinement nuclear fusion (which is the most-promising option among the different fusion alternatives) is mainly focused on the tokamak configuration, notwithstanding few running projects concentrating on spherical tokamaks [13] and stellarators [14]. In this framework, the ITER reactor [15] is under construction in France. ITER is an international program gathering China, the European Union, India, Japan, South Korea, Russia and the United States in a 35-years collaboration to demonstrate an energy gain (i.e., the ratio of fusion power to thermal power absorbed by the plasma [16]) for fusion (equal to 10) [17] and the capability to sustain the fusion reaction for long periods of time (hundreds of seconds). The potential success of the research project will lead to the design, construction and

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operation of demonstration (DEMO) reactors to lay the foundations for commercialization of nuclear fusion power plants in the second half of this century expected in Europe [18], China [17], Japan [19] and South Korea [20] – the final design and construction of such machines is then postponed after the ITER exploitation. Differently, in the USA, the ARC project [21] is also based on the tokamak configuration but targeting a compact machine at higher magnetic field than DEMO. The aim is the realization of an affordable, robust, compact (ARC) fusion reactor, able to produce three times the electricity required to operate the machine. ARC would rely on high-temperature superconducting magnets [22] in place of ITER's low-temperature superconducting magnets [23] allowing comparable performances with reduced plant dimensions (thus lower construction effort). Note that, being largely decoupled from the ITER successful exploitation, the target pretended for ARC's commercial availability is in 2035, thus at least 25 years before the ITER-based commercial reactors, according to the aggressive timeline set out in Ref. [24] to put fusion electricity in the grid in the 2030s. Despite being highly disputed in the scientific community, the possibility that the target will be met cannot be ignored when studying future energy scenarios on the long run. Note that the ARC project is the most developed among an increasing number of fusion projects coming from private companies flourishing in many countries and promising the commercial kWh from fusion even starting from 2025, although most realistically in the next 15 years [25].

The main challenge for nuclear fusion is to achieve a positive balance between the energy injected into the plasma and the heat emitted by that, necessary to produce steam and – by way of turbines and alternators – electricity. Nuclear fusion is deemed as a game changer mainly due to being a zero-carbon and dispatchable electricity source, therefore joining the strong benefits of renewable energy technologies, but with the possibility of a (quasi-)continuous operation [24]. Note, however, that the target energy gain for the experimental reactor ITER is significantly reduced with respect to the nominal target if the energy actually consumed by the plant is accounted for, while the plasma ignition that guarantees self-sustained fusion reactions would imply an infinite gain [26]. Moreover, despite being considered a fully clean and sustainable technology itself, issues regarding the life cycle of nuclear fusion-related materials, their availability, and the activation of components at the end of life of the reactor are still to be fully clarified. From the environmental point of view, the CO_2 footprint of fusion materials (steel, cement, lithium, copper and vanadium, among others) is generally shown to be low if compared to renewable technologies, especially in the case of compact reactor concepts (i.e., ARC) [27]. Nonetheless, the construction of fusion reactors requires a huge amount of steel and cement. Low-carbon alternative options (e.g., based on electrolysis) are supposed to be available on the commercial scale soon [28], and widely adopted until the commercialization phase of fusion machines. In any case, such materials are widely required for the majority of energy supply and demand facilities and for this reason the impact associated to their production is not only peculiar of fusion plants. Considering reserves of crucial materials for fusion, deuterium is abundant in seawater, while the limited and uneven availability of lithium (required to breed tritium) and rare earths, among others, may cause equity issues, especially for the first generation of fusion reactors, when some industrial chains will not be fully developed [27]. From the safety point of view, the absence of a chain reaction guarantees the impossibility of catastrophic accidents [29]. Concerning radioactive wastes or residues, an appropriate selection of the material and the adoption of accurate procedures for management and disposal should limit the generation of activated waste to a low or very low level [30], and the technologies already developed for the nuclear fission plants could easily cope with them. The plans for the decommissioning of the ITER reactor, relying on the French expertise in the decommissioning of nuclear fission plants, go indeed in that direction.

The study of the possible penetration of new energy sources and technologies in the future energy mix is usually performed at the macroscale with Energy System Optimization Models (ESOMs) [31]. Those models require a proper description of the energy system under analysis and the development of the so-called Reference Energy System (RES), including a lumped techno-economic characterization of the possible future technologies. The aim of ESOMs is to produce least-cost configurations of the energy system over a medium-to-long-term time scale [32]. ESOMs can present results based on different scenarios, representing plausible descriptions of how the future may develop [33] generated according to a set of key inputs and parameters for socio-economic development, ranging from projections concerning population and gross domestic product (GDP) to expectations about the deployment of specific technologies [34].

Concerning the study of possible penetration of nuclear fusion in the energy mix using quantitative models, some studies have been carried out throughout the last two decades using different quantitative models.

- In Ref. [35], the PLANELEC-Pro global electricity system model is used by the Swiss Federal Institute of Technology to assess the global potential for the development of fusion power elaborating 6 multi-regional electricity market scenarios until 2100. No details are given concerning the technical and economic parameters adopted to characterize nuclear fusion power plants (NFFPs).
- In Ref. [36], the World-TIMES multiregional global energy system model is adopted by the GERAD Research Center (Canada) to compute results in two scenarios with different CO_2 concentration levels by 2100 (450 ppm and 550 ppm). In both cases, nuclear fusion achieved considerable installation levels despite the high installation costs. Fusion is considered as available starting from 2048 considering a cost of ~6–9 M$ per MW based on estimates dating back to 1998 [37], while technical parameters are not provided. Nonetheless, lithium to breed tritium is considered as the only input commodity leading to electricity generation.
- The analysis presented in Ref. [38] is one of the most recent examples of quantitative assessment analyses to study the possible role of fusion in view of the climate prescriptions of the Paris Agreement. The authors of the Research Institute of Innovative Technology for the Earth (Japan) [38] use the Dynamic New Earth 21+ (DNE21+) global multi-regional nonlinear least-cost optimization energy system model [39] and develops 3 socio-economic development pathways analyzed in 4 global emission pathways and considering scenarios dealing with the uncertainty in fusion energy development. DNE21+ is also a bottom-up energy model involving the characterization of about 300 technologies to explore their possible role in climate change mitigation. Concerning nuclear fusion, it only considers a single nuclear fusion technology representative of the Compact Reversed Shear Tokamak (CREST) [40] and SlimCS [41] reactor concepts, both based on the developments of the ITER project and considered as economically and engineering viable small-size fusion technology options. The only technical parameters provided are represented by the annual capacity factor and the operational lifetime of the plant, while constraints for the development of fusion technologies are based on the same trajectory depicted by historical data for nuclear fission capacity, despite being that unequivocally influenced by the low social acceptance due to well-known severe accidents [42].
- Two other major projects using ESOMs to deal with nuclear fusion are the EUROfusion TIMES Model (ETM), a multi-regional global ESOM instance developed by the WorkPackage for Socio-Economic Studies (WPSES) within the framework of the EUROfusion Consortium to evaluate the perspectives of development of a EU-DEMO-like fusion reactor [43], and the TEMOA-Europe [44], currently under final development at PoliTO, which represents the fully open-source counterpart of ETM but just focuses on the European region, developed in an open-source framework [45,46] to allow easy third-party verification and to enhance the capabilities of energy system models in a very high-level and widespread

programming language like Python. Both models work on a time scale up to 2100 and consider, apart from economic parameters derived from recent literature, a technical characterization including lithium consumption (considering again lithium as a primary input commodity to breed the tritium participating to the fusion reactions), besides capacity factor and lifetime.

This paper discusses the possible future role of fusion energy in the global (with a multi-regional perspective) electricity mix considering a set of three different fusion technologies, including not only the European DEMO (as already done in ETM) and the CREST and SlimCS technologies, as done in DNE21+, but also, for the first time, the ARC-like reactor in the dataset of an energy system optimization model (ETM, in particular). In Section 2, the structure and the parameters for the fusion module in the database of the ETM model are presented, along with a study to derive constraints for the future adoption of fusion energy. In Section 3, the scenarios adopted to study the penetration of fusion in the global mix are presented, along with results from energy system optimization via ETM in Section 4. Section 5 presents the conclusions of the work.

2. Techno-economic characterization of nuclear fusion technologies for electricity generation

This section presents the techno-economic characterization [23] of nuclear fusion technologies (including the ARC reactor [21]) for use in energy system optimization models.

The main technical and economic features of a nuclear fusion power technology are lumped in the following parameters, see also Table 1.

- **Lithium consumption**
- **Yearly operation time** (capacity factor)
- **First year of availability of the technology**
- **Lifetime** (and construction time)
- **Investment cost**
- **Fixed O&M cost**
- **Variable O&M cost**

Table 1
Comparison of techno-economic description of the EU-DEMO-, the Asian-DEMO- and ARC- based nuclear fusion reactors.

Parameter		EU-DEMO	Asian-DEMO	ARC
Lithium consumption [kg of ^{6}Li/PJ$_e$]		14 (2060) 7 (2080)	9	14 (2035) 11 (2050)
Yearly operation time [h/year]		~ 6000	~ 6000	~ 6000
First year of availability		2060	2060	2035/2060 (depending on the scenario)
Lifetime [years]		40	40	40
Construction time [years]		10	10	5
Investment cost [B$/plant]		3.0 (in 2060) 2.2 (in 2080)	4.3	1.0 (in 2035) 0.7 (in 2050)
Investment cost [M$/MW$_e$]		5.9 (in 2060) 4.2 (in 2080)	8.5	5.3 (in 2035) 2.8 (in 2050)
O&M cost [M $/plant/year]	Fixed	~ 33	~ 33	~ 20[a] (in 2035)
	Variable	~ 23 (in 2060) ~ 17 (in 2080)	~ 23	~ 14 (in 2050)

[a] Preliminary rough estimation, starting from the estimation considering that the O&M cost for a European Pressurized Reactor (EPR) corresponds to 3.3% of the investment cost and reducing that value to the 2% of the investment cost for ARC, as nuclear fission fuel requires more complex management than in a fusion plant.

Being the optimization process performed with ESOMs generally driven by an economic paradigm (aiming at producing the minimum-cost energy system in the examined scenario), the economic parameters (costs) play a crucial role to establish the optimal technology mix. The work in Ref. [35] does not show any data used for the characterization of nuclear fusion power plants in the PLANELEC-Pro, while in Refs. [36,38] some detailed information about the adopted data for the Asian-DEMO reactor encompassing the features of both CREST and SlimCS reactors are reported. Specifically, the starting availability dates, lifetimes and investment costs show good agreement in Refs. [36,38], even though the two works were developed 12 years apart. In particular, nuclear fusion availability starts in 2048 in the World-TIMES [36] and in 2050 in ITER-participating countries in the DNE21+ [38]. The assumed lifetime is 40 years in both models, while investment costs range from 8820 $/kW in Ref. [36] to 8500 $/kW in Ref. [38]. Such data is considered for the first year of availability of the plants, while a physiological cost decrease is progressively accounted for in both World-TIMES and DNE21+. In addition, DNE 21+ considers one basic and one advanced versions of the technology based on the Asian tokamak concepts, accounting for a 22% cost reduction between the two types of plants. Concerning the fixed and variable operation and maintenance costs, the study in Ref. [36] is the only document reporting data adopted in the World-TIMES model, which considers 77 $/kW and 0.36 $/GJ for them, respectively. On the other hand, the annual capacity factor is only quoted in Ref. [38] to be 90%, as adopted in the DNE21+.

Two technologies were already included in ETM to represent two different stages of development of a reactor based on the EU-DEMO concept, the first available starting from 2050 (Basic EU-DEMO-based concept), the second available starting from 2070 (Advanced EU-DEMO-based concept) [47]. The costs for those fusion technologies are computed according to the fusion reactor cost estimation performed by means of the PROCESS code [48], which aims to minimize the cost of electricity, accounting for constraints on engineering, physics and materials of the NFPP [49] and arbitrarily increased by 30%. In this work, a single technology is considered for the EU-DEMO-based commercial NFPP accounting for a shift in the starting date for the availability of the technology due to the most recent adjustments to the EUROfusion Roadmap towards commercial NFPPs [18] placing commercial fusion power starting from 2060. Specific lithium consumption and cost reductions are prescribed starting from 2080 (instead of 2070 as in the previous ETM-based analyses).

Concerning ARC, it has been added to the ETM and made available starting from 2035, as claimed in Ref. [21] despite the several technical and economic criticalities concerning nuclear fusion for electricity production. Given the huge uncertainty associated to the actual availability of ARC in 2035, other scenarios are studied in this work (including 2060 as the first year and a scenario without ARC among the technology options), as explained in Section 4.1. The techno-economic parameters representing the EU-DEMO-like plant considered for this work are reported in Table 1 and compared with those assumed for an ARC-like plant. In particular, it is highlighted how the compact nature of ARC allows to consider a shorter construction time (5 years) than the EU-DEMO-based reactor concepts (10 years). However, construction time has not a relevant role when an ESOM, as ETM is, is run in perfect foresight (i.e., each agent has perfect knowledge about future market parameters over the entire modeling horizon) rather than myopic foresight.

Also, the Asian-DEMO-based reactor, in the wake of the approach adopted in Ref. [38] has been added to the ETM technological database as representative of a family of NFPPs also including the K-DEMO, considering a single technology available starting from 2060. The same investment cost as in Ref. [38] is taken into account for the Asian-DEMO (more than 40% higher than for the 2060 version of the EU-DEMO-based reactor), while fixed and variable operation and maintenance costs are assumed as comparable to those of the EU-DEMO-based NFPP.

Lithium consumption is taken into account as a parameter contributing to the economic optimization in ETM [32]. However, while its cumulative availability, attested at 12 Mt [50], makes it essentially inexhaustible, the extraction process contributes to the total cost of the system with 93 k$/t [50], which remains small when compared to the total NFPP cost, for all the technologies considered here. All in all, such a parameter is expected not to have a considerable influence on the choices made by the model.

The lithium consumption is estimated on the basis of the expected declared tritium consumption for all the reactors considered here and reported in Table 1. The tritium consumption for the EU-DEMO is estimated at 0.38–0.76 kg/day for 1.5 GW_e, corresponding to 92.4–184.9 kg/year for 1 GW_e full power year and, approximately, to 7–14 kg of $^6Li/PJ_e$ [51]. For the Asian-DEMO-based reactor, the estimation of 123 kg of tritium per GW_e per year performed in Ref. [20] for the K-DEMO is considered to be applied, corresponding to $\sim$ 9 kg of $^6Li/PJ_e$.

As no data concerning tritium consumption for ARC could be found in the literature, the 14.1 MeV neutrons being stopped in the blanket were taken as starting point to estimate the tritium (thus lithium) requirement. Considering the ARC fusion power (525 MW) [52], a fusion frequency of $2.32 \cdot 10^{20}$ s^{-1} and the tritium mass, the tritium consumption can be estimated. The obtained requirement is 0.10 kg/day, equivalent to 36.5 kg/year for the rated net electric power to the grid at a first development stage of 190 MW_e [52], returning 192.1 kg/GW_e. The final estimations for ^6Li consumption per PJ_e for ARC are reported in Table 1. A further development is accounted for the ARC-based reactor technology in 2050, with a shift to a higher electrical power output of 250 MW_e, expected in Ref. [21] and to a lower specific lithium consumption (starting from the same fusion power of 525 MW).

Table 1 also highlights how ARC would represent the least expensive NFPP concept in terms of single plant costs (construction, operation, and maintenance) [53]. On the other hand, the costs for the EU-DEMO and the Asian-DEMO are computed on the basis of a reactor expected to provide 500 MW_e to the grid, and that would make ARC's initial investment cost per MW_e (2035) just the 10% lower than the initial EU-DEMO cost (2060), expressed in $\$_{2010}$. However, the economic advantage of ARC for this analysis becomes evident when, in 2050, it would provide 250 MW_e electricity to the grid with a cost per MW_e more than 50% lower than EU-DEMO in 2060.

Nevertheless, costs reported in Table 1 may be highly disputable due to the strong uncertainties related to the research progresses and to the development of fusion technologies. For instance, costs for the ITER project have been already significantly revised upwards [54] and research and development costs for fusion (as in all the other sectors of the whole economy) may be affected by the current framework of generally high inflation and issues to the [55] supply chain. For this reason, a parametric analysis to assess the dependence of the results on the technologies cost was performed and presented in Section 4.1.1. Note that no constraints on the availability of tritium have been adopted in this analysis.

Besides technical and economic features, ESOMs may also require constraints to ensure a credible development of energy technologies. Concerning fusion, targets have been set for the development of ARC capacity by Dr. Mumgaard, CEO of Commonwealth Fusion Systems, the company aiming to build a compact fusion power plant based on the ARC tokamak power plant concept. It has been claimed that 2 TW of electricity from fusion are expected to be developed by 2050, supposedly starting the operation of the first ARC in 2035 [53]. That would mean having 8000 reactors delivering 250 MW net electrical power each (as from Table 1). Roughly speaking, that target means to consider, in average, slightly more than 500 reactors per year entering into operation, thus more than one per day. If considering a simple exponential development as in Equation (1) (where *P* is power and *t* represents time), the target of 2 TW_e by 2050 may be reached with a doubling time (time needed for capacity to double in value) slightly higher than 1 year, as technology adoption usually follows an exponential law in the first development stages [56]. Note that currently, the only source to have achieved doubling times lower than 2 years in the initial development phase is solar PV, with slightly more than 1.4 years-doubling time [42].

$$P_t = P_{t-1} \cdot 2^{\frac{1}{doubling\ time}} \quad (1)$$

Fig. 1 shows what such a high development speed would mean when compared against the historical development of other power technologies in the last two decades, considering data provided by the U.S. Energy Information Administration [57], the International Renewable Energy Agency for wind [58] and solar energy technologies [59] and the REN21 Project [60]. From a first look, the fifteen-year CFS target appears too ambitious if compared to, e.g., the twenty-year development of solar PV and wind offshore which, at a certain point, experienced a bend in their growth that slowed down their development, as shown in Ref. [42]. With such a trend, nuclear fusion capacity would surpass the current installation of both nuclear fission and hydropower plants, getting close to the current levels of fossil fuels installed capacity (around 4 TW in 2019).

In particular, the trend targeted by CFS is definitely much faster than the development experienced by solar PV and wind technologies throughout the first 15 years for which data about installed capacity are available. Note that the size and technological complexity of NFPPs with respect to either solar PV panels or wind turbines makes the target capacity growth rate quite unbelievable, especially in a very limited time frame.

As far as the constraints on installation of fusion capacity already adopted in other studies, ETM takes into account a constraint for the maximum global cumulative EU-DEMO-based technology capacity development based on tritium availability [61], but that does not account for the readiness of industry to manufacture components for fusion reactors on a large scale. Regarding the Asian-DEMO-based technology, the study in Ref. [38] assumes that the reactor is available in the countries participating to the ITER endeavor starting from 2050 (and in some other regions of the world starting from 2070), and that installed capacity cannot grow by more than 2 GW/year in every region. Note, however, that the growth rate there is not substantiated by any specific study in support of it.

On those premises, a new set of three alternative constraints for fusion deployment is developed and adopted here, based on the classical development trends of power technologies relying on the suitable development of industrial chains that could support the construction and commissioning of new power plants.

In [62], it is observed that the historical development of capacity for

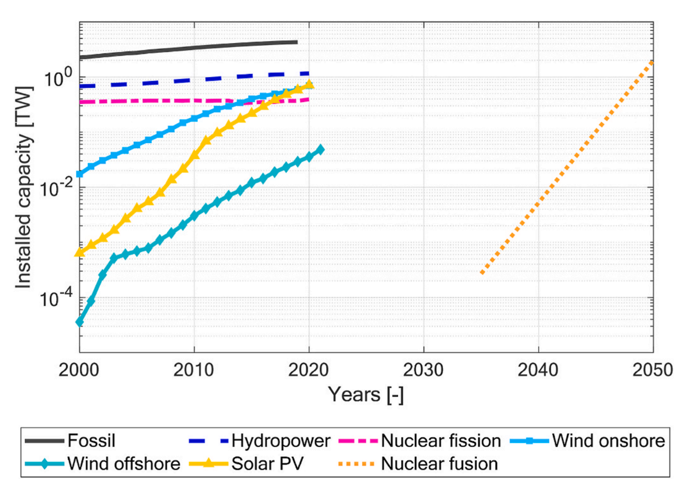

Fig. 1. Historical capacity development of fossil, hydropower, nuclear fission, wind and solar PV technologies against nuclear fusion according to the CFS target of 2 TW by 2050, following a trajectory computed according to a simple exponential growth deployment.

power generation sources follows a recurring trend, and the observations are put in numbers in Ref. [63], characterizing three different phases.

1) exponential growth with doubling of installed power every 2 ÷ 4 years. In this phase, described by Equation (2) the technology is taken from laboratory scale to a level of visibility in the global energy mix (identified as "materiality" state [62]), supposed to be reached at 0.1 ÷ 1% of the contribution to total energy supply (TES);

$$P_t = P_{sat} \cdot \frac{\tau_{exp}}{\tau_{life}} \cdot \left[exp\left(\frac{t - t_{trans}}{\tau_{exp}}\right) - exp\left(\frac{t - t_{trans} - \tau_{life}}{\tau_{exp}}\right)\right] \text{ for } t < t_{trans} \quad 2$$

where P_t is the electric power at time t, P_{sat} is the asymptotic capacity level in the saturated state, τ_{exp} is the characteristic time of exponential growth, computed according to Equation (3), τ_{life} is the characteristic lifetime of the power generation plants and computed according to Equation (4), t_{trans} is the time at which the transition from the exponential to the linear phase occurs.

$$\tau_{exp} = doubling\ time \cdot (1 + 1 / e) \quad 3$$

$$\tau_{life} = plant\ lifetime \cdot (1 + 1 / e) \quad 4$$

2) linear growth with a constant growth rate, described by Equation (5).

$$P_t = P_{sat} \cdot \frac{\tau_{exp}}{\tau_{life}} \cdot \left[1 + \frac{t - t_{trans}}{\tau_{exp}} - exp\left(\frac{t - t_{trans} - \tau_{life}}{\tau_{exp}}\right)\right] \text{ for } t_{trans} \leq t \leq t_{sat} \quad 5$$

Note that, despite the definition of "linear" phase provided in Ref. [62] and in Ref. [63], Equation (5) actually includes also a non-linear term.

3) saturation phase when the growth is stopped and the capacity level remains fixed, as described by Equation (6).

$$P_t = P_{sat} \text{ for } t > t_{sat} \quad 6$$

The model in Ref. [63] is able to work when a target is set for P_{sat}, and in the case of nuclear fusion that will be set here at 2 TW installed capacity. The capacity curves are computed according to three different doubling times up to 2100: the lower and the upper limits are set to identify the exponential phase mentioned above (2 and 4 years), while the value of 1.43 years corresponds to the fastest doubling time in the exponential phase, as identified in the set of historical data reported in Fig. 1 and belonging to solar PV [42]. In all cases, the lifetime for fusion technologies is set to 40 years, thus strongly influencing the duration of the linear growth phase, attested at 55 years as from Equation (4).

Fig. 2 shows the results of the application of the three-phase model described by Equations (2), (5) and (6): when considering the fastest experienced growth in the exponential phase by other power technologies (doubling time of 1.43 years), the installed capacity in 2100 almost reaches 2 TW, thus very close to the targeted saturation capacity. This implies that only a maximum of 134 GW can be installed by 2050. On the other hand, with a 2 years-doubling time, the maximum achievable capacity results in 1.8 TW in 2100. In that case, the installed capacity achieved by 2050 is just slightly below 30 GW. When considering instead a more reasonable doubling time of 4 years, the installed capacity development is far slower in the exponential phase (with a duration of 40 years) and the final installation level in 2100 is slightly above 1 TW, with only 2.6 GW installed by 2050.

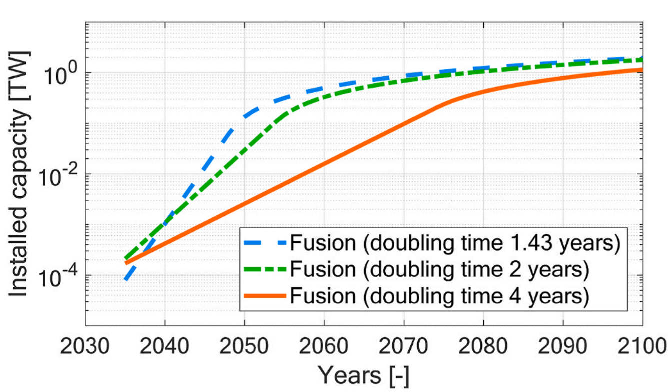

Fig. 2. Installed capacity trends for nuclear fusion computed according to 1.43, 2 and 4 years-doubling times and constraint applied to EU-DEMO based on tritium availability.

In the following scenario analysis, the maximum capacity constraint for cumulative fusion capacity is selected to follow the super-optimistic "fastest growth" (1.43 years-doubling time) curve in Fig. 2 and both the EU-DEMO-based and the Asian-DEMO-based reactors will be possibly installed starting from 2060, thus when fusion capacity is already possibly at 500 GW. Note that, since the constraints for capacity development are strongly influenced by the assumption made on the first year of availability of the first NFPP, a parametric study is also performed to assess its influence on the development of the role of nuclear fusion in the energy mix.

3. Scenario definition

The integration of nuclear fusion in ETM is currently studied according to three storylines – named "Paternalism", "Harmony" and "Fragmentation". Storylines are used to.

- Consider different elasticity levels to drive the growth rates for end-use demands (e.g., yearly driven distance by road vehicles; production of industrial goods like steel, cement, paper, etc.; demand for space heating in buildings) and different technology-specific discount rates, depicting different broad outlines of socio-economic development. Demand elasticities are considered in ETM to reflect changing patterns in energy service demands in relation to socio-economic growth. These are assigned with a different value for each demand category and region throughout the whole considered time horizon, but generally allocated on three levels: keeping Paternalism values as reference, they are reduced by 30% in Harmony, leading to lower demand levels, and increased by 30% in Fragmentation, leading to higher demands. Conservatively, elasticities generally are assumed not to decrease further in the long term, to avoid an excess of optimism about the growth of future demand. On the other hand, discount rates are used to evaluate investment policies: the higher the discount rate, the lower the value we assign to future savings in today's decisions [64]. Therefore, taking as reference Paternalism values, they are doubled in Fragmentation and halved in Harmony to reflect short-term and long-term investment policies, respectively.
- Define the degree of environmental responsibility according to three Representative Concentration Pathways (RCP) [65], assigning yearly constraints for maximum greenhouse gases (GHG) emissions and concentrations until 2100 to reach different environmental targets, according to the trajectories in Fig. 3. Summarizing, Paternalism and Harmony expect great efforts for CO2 reduction for the whole duration of the considered time scale (RCP 2.6), reaching very low emission levels in the second part of this century, and getting close to net-zero emissions starting from the 2080s, while the peak of CO2 concentration is set in 2080 in Fragmentation (RCP 6), and efforts for emissions reduction are undertaken only starting from that point in time on.

Within the three storylines, the analyzed scenarios differ according to the degree of technological advancement, or the application of specific policy measures or constraints, as shown in Table 2.

The scenarios analyzed in the present work differ according to the

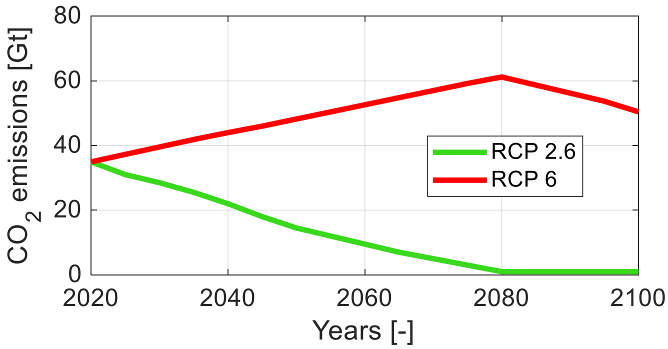

Fig. 3. CO_2 Emission trajectories implemented in ETM to reproduce the RCPs 2.6 and 6 [65].

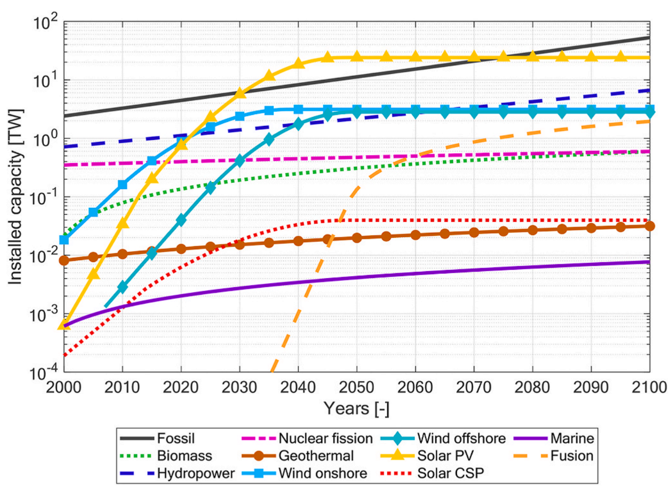

Fig. 4. Maximum installed capacity constraint as implemented in ETM at the global level.

development of CCS technologies: in the scenario “W/CCS”, CCS is available starting from 2030 both in the power generation and the industrial sector (steel, cement, and chemicals production), as expected in Ref. [66], while in the scenario “W/O CCS”, CCS-equipped technologies are not available at all.

Note that the constraints for the future development of electricity generation technologies other than fusion are based on the trajectories depicted in Ref. [42]. In particular, the mentioned trajectories are not driven by any hypotheses about trends compliant with a transition towards a decarbonized energy system, but just computed according to historical trends about capacity building coupled with the concept of S-curves for technology adoption [56]. The maximum installed capacity constraints for the different technologies are illustrated in Fig. 4. In particular, the maximum possible globally installed capacity level is reached by fossil fuel generation plants (almost 53 TW) and solar PV (24 TW), while nuclear fission (including Gen IV reactors), biomass, geothermal, solar CSP and marine energy capacity are forced to stay below 1 TW. Note that constraints for maximum capacity deployment are implemented at the global level alone without assigning different trajectories at regional level.

Secondly, two additional scenarios are considered to deal with the uncertainties related to the parameters for the characterization of nuclear technology, and especially about the starting date for the availability of ARC-like commercial reactors: in the first one (from here on called “ARC-2060” scenario), the ARC-based NFPP is considered to be available starting from 2060 (as it happens for both the DEMO-based reactors), while in the second one (from here on called “NO-ARC” scenario) ARC is not available at all. In both these scenarios, the selected

Table 2
Summary of the main features of the three storylines and the investigated scenarios.

Storylines	Demand elasticities	Discount rates	Emission limits	Scenarios	
Paternalism	Baseline	Baseline	RCP 2.6	W/ CCS	ARC-2035 ARC-2060 NO-ARC
				W/ O CCS	ARC-2035 (CFS trajectory doubling times 6 months, 1.43 yrs, 1 yr, 2 yrs, 4yrs) ARC-2060 NO-ARC
Harmony	−30% with respect to Paternalism	−50% with respect to Paternalism	RCP 2.6	W/ CCS	ARC-2035 ARC-2060 NO-ARC
				W/ O CCS	ARC-2035 ARC-2060 NO-ARC
Fragmentation	+30% with respect to Paternalism	+100% with respect to Paternalism	RCP 6	W/ CCS	ARC-2035 ARC-2060 NO-ARC
				W/ O CCS	ARC-2035 ARC-2060 NO-ARC

constraint for the development of fusion coming from Fig. 4 is simply shifted by 25 years (while the other ones are preserved), leading to slightly more than 1 TW by 2100 (against almost 2 TW possibly reached when starting fusion capacity installations in 2035).

While the ETM dataset currently considers a broader spectrum of scenarios [67], when related to fusion development, they all refer to the availability (or not) of the EU-DEMO technology, considering also the supposed availability of tritium. In this work, for the first time, different technologies for NFPP have been introduced and confronted, together with a capacity growth constrained according to well-established technology adoption models for power technologies.

4. Results

4.1. Scenarios ARC-2035 (W/and W/O CCS)

Results presented in this section first compare the development of fusion energy capacity and the development of the power sector until 2100 in the scenarios W/and W/O CCS described above for each of the three ETM storylines (Paternalism, Harmony and Fragmentation with their characteristic maximum emission trajectories and service demand growth levels).

In all the three storylines, the optimization process returns a development of fusion technologies in the scenario W/O CCS. On the other hand, when CCS is available starting from 2030 (scenario W/CCS) with an investment cost that is lower than the one considered for fusion for all the different options, fusion is only developed (and at its maximum capacity growth) in those storylines with considerable demand growth levels, namely Paternalism and Fragmentation. ARC is the only cost-effective fusion technology according to the least cost compositions of the energy system depicted by ETM.

In particular, looking at Fig. 5, installations of fusion power plants start from 2050 in Paternalism and Fragmentation, when just ARC is available at a cost of 0.7 B$/plant (equivalent to almost 3 M$/MW$_e$ when considering a plant producing 250 MW$_e$). Note that the current

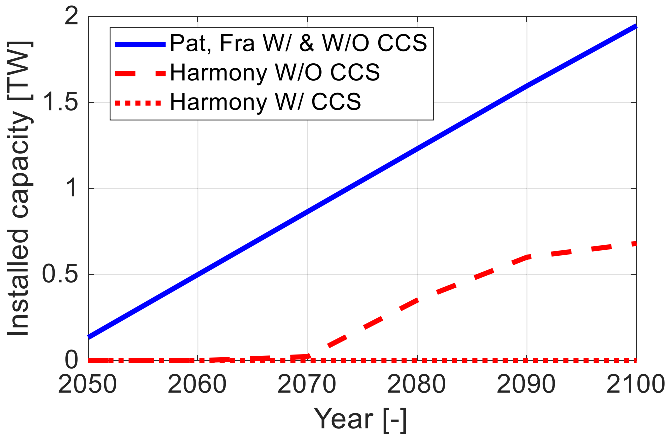

Fig. 5. Results for nuclear fusion (ARC) capacity development in scenarios W/ and W/O CCS 2 for the three ETM storylines.

ESOM approach does not usually consider the application of technology learning algorithms [68] (and the same is true for this work), so that it is possible to observe cost decrease even when no capacity is previously installed. Fusion capacity perfectly retraces the trajectory in Fig. 4 starting from 2050 both in scenarios W/and W/O CCS for the Paternalism and Fragmentation storylines. This would be also the case if less optimistic growth rate assumptions would be made for fusion installed capacity. Harmony scenario W/O CCS requires a lower fusion capacity to comply with the imposed emission targets (the same as in Paternalism, but coupled with lower demand growth), up to ~ 700 GW by 2100. Indeed, in this scenario, fusion integration would require even lower costs to compete against other low-carbon technologies as decarbonization is also possible just relying on the deployment of less expensive alternatives. On the other hand, Harmony scenario W/CCS does not require any fusion capacity installation, meaning that fusion cannot contribute anyhow to any decarbonization of the energy system, that is already achieved deploying CCS.

Shifting towards regional results, when developed, fusion capacity is not deployed at all in Europe and America (except for a low fusion development in Mexico in the Paternalism W/CCS scenario, up to 2090), which mainly rely on renewable sources to decarbonize the power sector. On the other hand, fusion is always required in developing regions of the world (mainly located in the Far East). In particular, Table 3 gives more details about the computed location and installed power of nuclear fusion plants in the different regions of the model in all the scenarios where fusion is developed. China, India and Southeast Asian Countries (including Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, the Philippines, Singapore, Thailand, and Vietnam) are those mainly relying on fusion energy, although to different extents in the different scenarios. That means that mainly those developing regions experiencing a robust reliance on fossil fuels for electricity production [8], especially in the last decades of economic boom, would require fusion, among other low-carbon technologies, to comply with stringent decarbonization targets.

All in all, the development of fusion (and ARC in this particular case) with the features adopted as inputs for this work, does not significantly depend on the deployment of other "competing" technologies like CCS (even though its development is not limited to the power sector), but is mostly influenced by high levels of end-use demand (therefore electricity, as electrification of end uses is the main alternative to the reliance on fossil fuels). This is highlighted especially in the results from the Harmony scenarios, where low demands are reflected in the absence of fusion when CCS is also available and in a lower deployment when CCS is not an available option.

Fig. 6 shows the results in terms of electricity generation mix for the two scenarios in the three ETM storylines. As a first result, the total electricity generation is generally slightly higher when CCS is not available at the end of the time scale, as carbon removal must be substituted with a larger electrification of end uses to comply with the environmental constraints. Nevertheless, the difference (within the same storyline) is never much higher than 5% (Fragmentation). That leads to a total electricity production around 110 PWh in Paternalism scenarios (see the "Pat" values in 2100 in Fig. 6a and b, with an increase of almost 5 times with respect to current levels [8]). The two Harmony scenarios require between 64 (scenario W/CCS) and 67 PWh (scenario W/O CCS), while the difference is slightly more marked between Fragmentation scenario W/CCS (~90 PWh) and scenario W/O CCS (~95 PWh). Therefore, an important result is that the electrification of end uses, in a context of considerably growing demand (Paternalism), requires no dramatically larger electricity consumption than a scenario with very high demand growth in spite of emission reduction (Fragmentation).

Fig. 6 also shows a comparison against electricity production levels as computed with ETM analyses and by the International Energy Agency (IEA) in Ref. [69]: the economic optimization algorithm on which ETM relies on considerably underestimates the results of the IEA Net-Zero Emissions by 2050 (NZE2050) scenario (even above 70 PWh) and the Announced Pledges Scenario (APS), reaching 60 PWh. Note, however, that in Ref. [42] it is claimed that the electricity generation potential inferred from the historical data shall result in a deployment of electricity production technologies that appears sufficient to meet the expected power sector requirements until 2050. On the other hand, the results computed with ETM for Europe and the USA are in line with IEA projections. This calls for a review of the input data for the other regions of the model, as most of the data to characterize the technologies

Table 3
Computed location of ARC-based fusion capacity (in GW) in the analyzed ETM scenarios.

Storyline	Scenario	Region	2050	2060	2070	2080	2090	2100
Paternalism	W/CCS	India	30	150	230	450	680	850
		Southeast Asia	40	300	470	690	830	11,060
		China	0	44	81	81	81	32
		Mexico	3	8	8	8	4	0
	W/O CCS	India	100	320	400	400	700	980
		China	30	180	470	830	890	970
Harmony	W/CCS	–	0	0	0	0	0	0
	W/O CCS	China	0	0	0	280	510	510
		Central Asia	0	0	2	23	37	100
		Japan	0	0	21	50	52	54
		South Korea	0	0	0	0	0	14
Fragmentation	W/CCS	India	130	500	870	1200	1600	1900
		Africa	0	0	0	12	21	21
	W/O CCS	India	130	500	870	1200	1600	1900
		South Korea	0	0	0	0	0	29

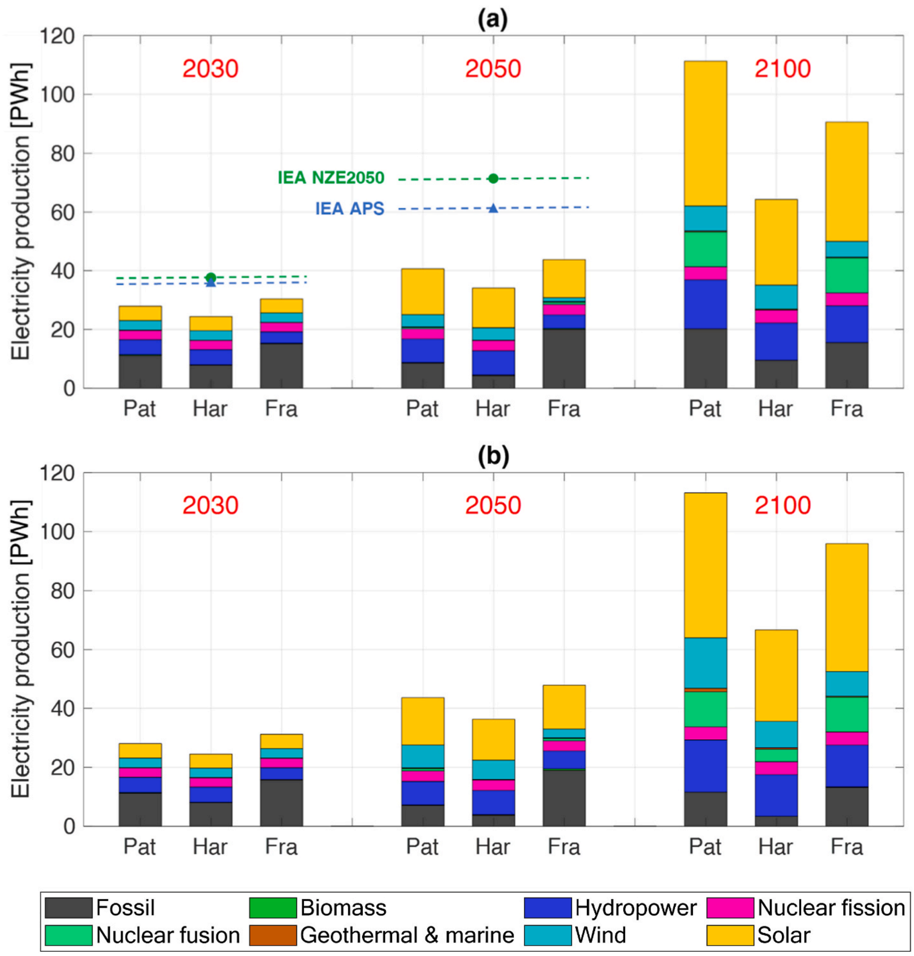

Fig. 6. Electricity generation mix evolution in the three storylines in scenarios a) W/CCS and b) W/O for the three different storylines (Paternalism, Harmony and Fragmentation).

included in the ETM database are taken from the European and American literature.

The electricity mix at the end of the century in scenario W/CCS (see Fig. 6a) does not differ dramatically among the three storylines. They all envisage the largest contribution from solar energy (~45%) and hydropower (close to 15% in Paternalism, and Fragmentation, 20% in Harmony), with fossil fuels still accounting for 15 (Harmony) to ~20% (Paternalism and Fragmentation) of total production, especially due to a growing contribution of gas power generation throughout the analyzed time horizon. Fusion share is shown to reach no more than ~15% (Fragmentation) contribution to total electricity production, with ~10% in Paternalism. Fusion represents a contribution comparable to hydropower and larger than wind, and well above nuclear fission (close to 5%). On the other hand, fusion is not developed in Harmony scenario W/CCS especially due to the far lower electricity demand, highlighting how fusion power plants are not an option for decarbonization in a context of low development of consumption levels (the missing share from fusion is taken by wind power, attested at ~ 15% in 2100). Note that CCS is available in this scenario, but that it is not developed in the power sector as it represents an expensive alternative with respect to the other electricity generation alternatives; indeed, the electricity mixes depicted in Fig. 6a and b are almost identical. On the other hand, the presence of CCS in other sectors leaves the floor to a considerable presence of fossil fuels in the electricity mix at the end of the century, also due to the implementation of the maximum capacity constraints in Fig. 4. In all the cases, as mentioned above, the contribution of electricity from fusion is negligible in 2050.

In scenario W/O CCS (see Fig. 6b) the situation is different in specific but interesting aspects, mainly because the absence of CCS forces a more effective fossil fuels phase-out. The fossil fuel contribution is reduced by ~40% in Paternalism, 65% in Harmony and 15% in Fragmentation with respect to scenario W/CCS in 2100 (in Fragmentation no dramatic efforts are constrained to reduce carbon emissions). In particular, fossil fuels for electricity production represent about 10% of total electricity generation in Paternalism scenario W/O CCS in 2100, the ~15% in Fragmentation and just the 5% in Harmony. Solar energy, with shares close to 50% in all the storylines represents the major source of electricity in scenario W/O CCS. Wind and hydropower represent considerable shares of the electricity production mix in all the three storylines, with contributions ranging from 15% each in Paternalism, ~15% (wind) to ~ 20% (hydropower) each in Harmony and ~10% (wind) to 15% (hydropower) in Fragmentation. Fusion electricity accounts for around 12 PWh in Paternalism and Fragmentation scenarios W/O CCS (with a share close to ~ 10%) and 4 PWh in Harmony.

With respect to the high contribution by renewable and intermittent energy sources in all the studied scenarios, it should be noted that the modeling approach usually adopted in ESOMs does not include operational dispatchment aspects. Therefore, the characteristic intermittence of such sources usually only reflects in lower (and evenly distributed across the year) capacity factors and capacity credits with respect to baseload plants. This is an approach focused on the macroscale, and it typically requires further analyses of results with proper dispatchment models. For the purposes of this work, these aspects are neglected; note that including them would penalize renewables against a non-intermittent energy source such as fusion.

4.1.1. Parametric analyses

To identify whether fusion is a necessary power generation technology according to the model and constraints used here regardless of cost, the constraint for the fastest fusion capacity development (according to a doubling time of 1.43 years in the exponential phase) has been relaxed considering different hypotheses, spanning from those reported in Fig. 2 to some more unrealistic values down to the CFS exponential trajectory up to 2 TW by 2050 as from Fig. 1 ("CFS target") and saturated capacity until 2100 (fixed at 2 TW). Five additional cases have been analyzed in Paternalism scenario W/O CCS, as reported in Fig. 7: 1) CFS exponential trajectory up to 2 TW in 2050 as from Fig. 1 ("CFS target") and saturated capacity until 2100 (fixed at 2 TW); 2) 6 months-doubling time ("6 mths-dt"); 3) 1 year-doubling time for fusion in the exponential phase of the fastest growth method described in Section 2 ("1 yr-dt"); 4) 2 years-doubling time for fusion in the exponential phase of the fastest growth method described in Section 2 ("2 yrs-dt"); and finally 5) 4 years-doubling time for fusion in the exponential phase of the fastest growth method described in Section 2 ("4 yrs-dt"). The implementation of different constraints does not influence the technology of installed reactors: the ARC-based NFPP characterized in this work is the only fusion technology selected for the installation during the optimization (not shown). As expected, fusion capacity is higher when the CFS target of maximum 2 TW by 2050 is implemented as constraint. Fig. 7 shows, indeed, how doubling time, and thus the industrial capacity deployment rate, is the only limitation for fusion penetration once investment cost is below a certain threshold. The share of fusion capacity installed in the different regions of the model is not different from those reported in Table 3 for Paternalism scenario W/O CCS. Therefore, in the conditions established by that scenario, fusion is only required to meet the electricity demand in China and India.

On the other hand, the investment cost is a discriminant before mid-century as no fusion reactors are installed until the unitary cost for ARC-based plants is set at 1 B$, as reported in Table 1 (roughly corresponding to 5 M$/MW$_e$), i.e. before 2050. It is also important to understand the investment cost at which NFPPs would be attractive even before 2050. The analyses performed in ETM have shown that NFPPs would be competitive with respect to the other alternatives in the power sector, under the maximum trajectories for capacity deployment in Fig. 4, starting from 3.8 M$/MW$_e$ – which would be slightly below than 750 M$ for a 190 MW$_e$ plant. This is true in all the storylines and scenarios, even though Harmony scenarios keep showing low reliance on nuclear fusion due to the lower electricity demand. On the other hand, fusion is required at any cost after 2050, in scenarios with growing demands (and electricity consumption as a consequence) and given that the deployment of the other electricity generation technologies is limited by the capacity growth in Fig. 4.

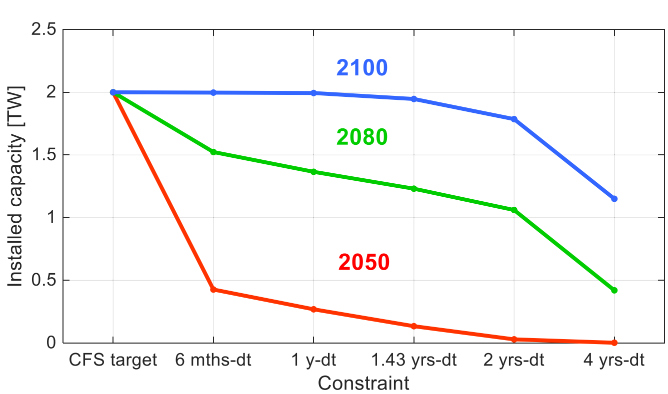

Fig. 7. Fusion development curves obtained for parametric runs according to different constraints for fusion deployment in ETM in Paternalism scenarios W/O CCS.

4.2. Scenarios ARC-2060 and NO-ARC

Given the large disputability about the possibility to develop any fusion reactor in the next few decades, two scenarios (ARC-2060 and NO-ARC, as described above) were also analyzed. In scenario ARC-2060, ARC-based NFPPs are available starting from 2060 and investment cost data in Table 1 are moved forward so that a 190 MW$_e$ costs 1 B$ in 2060 and a 250 MW$_e$ plant costs 0.7 B$ in 2080 (thus again less than the EU- and Asian-DEMO based technologies in the same time periods). In that scenario, ARC is developed anyway at the maximum possible capacity growth rate (doubling time of 1.43 years) contributing to 6 PWh electricity generation in Paternalism and Fragmentation. Nonetheless, it has to be considered that the prescribed unitary cost per unit of installed capacity for the ARC-based plant (5260 $/kW$_e$) would be higher than for the EU-DEMO-based NFPP (5910 $/kW$_e$) in 2060. The lower construction time for ARC, as from Tables 1 and is not a decision variable as ETM was run in perfect foresight. Again, CCS is not deemed as a cost-effective alternative in the power sector.

Fusion is developed at its maximum possible capacity anyway in both ARC-2060 and NO-ARC scenarios of the Paternalism and Fragmentation storylines starting from 2060, i.e., as soon as fusion is available (as in scenarios W/and W/O CCS, the availability or not of CCS-equipped technologies is not a discriminant for the penetration of fusion). Being the maximum installed capacity strongly influenced by the first year of availability of nuclear fusion and on the methodology adopted to derive the growth curve (see Section 2), this study shows how, on the basis of the techno-economic parameters adopted, nuclear fusion can be economically competitive with other power technologies in the analyzed long-term scenarios.

On the other hand, Harmony scenario ARC-2060 does not develop fusion when it is not available before half-century, as larger shares of gas and solar electricity contribute to the decarbonization of the power sector in a framework of low electricity demand with respect to the other storylines. After 2060, the higher costs for fusion due to the delay in its first availability does not allow the penetration into the energy system. Also, the electricity demand is so low that it does not meet the capacity growth constraints for the power technologies. Also, in the NO-ARC Harmony scenario, fusion is not required to comply with the environmental constraints: again, fusion comes too late to effectively contribute to the decarbonization of a power system subject to low demand.

Note that the quantitative outcomes in terms of installed capacity are strongly influenced by the input data and the large uncertainty about them suggest that the outcomes of this work should not be considered as forecasts.

4.3. Discussion

Eventually, also considering a very optimistic constraint implemented for the deployment of fusion capacity, the results of this work confirm how fusion may represent in the second half of the century a game changer in the energy transition towards a decarbonized energy system, in context of growing demand for energy consuming services mainly for developing, energy- and carbon-intensive economies in Asia.

In [35], the analysis carried out via the PLANELEC-Pro electricity system model considers given fixed pathways for the evolution of the electricity demand (differently from ESOMs, where electricity demand is a consequence of the optimized least-cost configuration of the energy system). It envisages two alternative fusion reactors with an investment cost of 8500 $/kW$_e$ in case of a "Conventional R&D" or 6600 $/kW$_e$ in case of advanced R&D (therefore considering higher costs than for the ARC and EU-DEMO based technologies presented here). The analysis in Ref. [35] considers two possible scenarios depending on the levels of fusion installations starting from 2040. First, a "Moderate Introduction of Fusion" scenario envisages fusion power plants of 1.5 GW$_e$ capacity each to be put in operation during the period 2040–2060 in North America, Europe, Japan and South Korea, up to 330 GW$_e$ by the end of the century; then, a “Massive Deployment of Fusion” scenario with 27 GW_e already installed by 2060 up to 950 GW_e by 2100. In both cases, fusion reaches the maximum possible capacity, in accordance with the results of this work. Note, however, that the constraints on the maximum installed capacity at the end of the century are very different in the two studies.

Also, the results obtained in Ref. [36] using the World-TIMES Model forecast fusion to penetrate in the energy system. A capacity even above 1.5 TW is reached by 2100 considering higher investment costs with respect to this analysis, albeit in less stringent scenarios from the point of view of the reduction of carbon emissions never leading to full decarbonization, following RCP 4.5 and RCP 6. Therefore, as it also happens in Fragmentation in this work, environmental targets and high costs are not a discriminant for the adoption of fusion as an electricity generation alternative.

In [38], the analysis carried out via the DNE21+ model represents the most recent investigation concerning the role of fusion in the future energy mix. While the costs related to fusion technologies are in line with those considered here for the Asian-DEMO (close to 9 M$/MW$_e$), the most stringent scenario from the environmental point of view follows RCP 4.5. Considering those inputs, the installed fusion capacity is never above 600 GW in a wide range of analyzed scenarios, despite the results being in line with the outcome also obtained here considering fusion as a low-carbon alternative mainly for developing, energy- and carbon-intensive economies like China and India.

5. Conclusions and perspective

Capturing the groundbreaking potential as zero-emissions technology for electricity production, nuclear fusion is becoming a topic addressed not only by public, but also by many several private companies despite being subject to huge concerns about its feasibility.

Relying on the available techno-economic characterization, different fusion technologies, including ARC-like reactors, the EU-DEMO- and the Asian-DEMO-based reactors, have been considered for the first time in this paper within a single framework and implemented in the power sector of the global energy system using the EUROfusion TIMES Model, based on the most recent set of techno-economic data available in literature. The aim of the study was to investigate which is the set of (optimistic) constraints under which electricity from fusion could be relevant for the energy mix worldwide. An upper bound for the overall installed capacity from fusion technologies has been derived considering the fastest possible growth historically experienced in the power sector (by solar PV technologies), envisaging a capacity deployment curve which was never implemented before in scenario analyses concerning nuclear fusion. A capacity doubling time of $\sim$ 1.4 years in the first phase of commercialization of nuclear fusion reactors, starting from 2035 with ARC, has been derived in this study, based on the historically observed fastest power technology development (much slower, however, than the public expectations expressed by the CEO of CFS, one of the leading companies in the development of fusion reactors – ARC, in the specific case), bringing to maximum 2 TW installed capacity by 2100. With this constraint, different storylines and scenarios have been analyzed up to the end of the century, considering different broad outlines of socio-economic and environmental development of the future world, and the presence or absence of CCS in the power and industrial sector.

The main outcome of the analysis is that even in the most optimistic conditions nowhere nuclear fusion represent a feasible decarbonization option before 2050, in view of the negligible capacity installed in the first (exponential) phase of the capacity growth, even in the case ARC-based NFPPs would become available starting from 2035. With the highest possible capacity doubling time already experienced by the technology with the fastest growth rate, i.e. solar PV, from one side, Europe and America do not need nuclear fusion for a transition towards a clean energy system by 2050, while the lower demand levels in Africa do not generally justify large investments in fusion. On the other side, the large industrial development in Asian regions, relying on a massive use of fossil fuels to sustain economic growth, may require a wider set of decarbonization alternatives, also including nuclear fusion due to the need for a fast and effective decarbonization.

At the end of the century, the ARC technology, when available, could be competitive with conventional power technology at their maturity in all the analyzed scenarios, substituting large portions of fossil plants in the electricity generation mix and achieving non-negligible contributions in all the presented scenarios in the absence of CCS, regardless of the environmental targets, the investment policies, and the projected electricity demand. Moreover, larger electricity demands correspond to larger fusion shares in the power sector. The DEMO reactors as defined in this study do not result economically competitive if compared to the ARC-like reactors, giving the hint that a significant cost reduction should be addressed in the design of such reactors. Only in the case the ARC-based is not available, the DEMO-based reactors are considered in the energy mix. Note that the presented results are inevitably related to the adopted optimistic constraint for fusion capacity deployment, which is the only limiting factor identified here for the penetration of fusion in the global energy system. A parametric analysis showed that fusion plants may find a place in the energy mix before 2060 only provided that the investment cost falls below 3.8 M$/MW$_e$ as highlighted especially in the results from the Harmony scenarios (where the lower electricity demand, despite the strong decarbonization requirements, limits the development of very expensive technologies). Therefore, the capability of industrial actors to set the suitable environment for a massive deployment of a fusion plant fleet at a cost well below the current expectations is crucial for research efforts in the last and next decades not to be vain.

In this study, no specific constraints coming from the fuel (tritium) availability have been considered, which could further limit the adoption of fusion technologies than the capacity curves applied here. Beside the continuous efforts to improve the techno-economic characterization in all the sectors of the energy system model adopted here, particularly in the power sector) and to rejuvenate socio-economic trajectories on the basis of the most recent projections, in the framework of fusion modeling there is a special need to better characterize in perspective the fusion chain, especially evaluating the role and consumption/cost figures of materials directly involved in electricity generation from fusion (e.g. tritium, lithium, superconducting materials, stainless steel, helium used as cryogen). Moreover, the results may be strongly biased by the very low maturity of fusion technologies. Therefore, the analysis presented here should be periodically reviewed based on the progresses towards the development of commercial fusion reactors and is not intended to provide a deterministic forecast for the deployment of fusion capacity.

The possible benefits coming from alternative/additional uses of fusion energy (considering for instance the production of heat for, e.g., industrial processes), beside accounting for other alternative fusion technologies such as the stellarator configurations, could also be explored as a way to attract more funds and public consensus on this “nuclear” technology.

Author statement

Daniele Lerede: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Visualization; Writing - original draft; Writing - review & editing. Matteo Nicoli: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Visualization; Writing - original draft; Writing - review & editing. Laura Savoldi: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Validation; Writing - review & editing. Antonio Trotta: Conceptualization; Funding acquisition; Project administration; Resources; Supervision; Validation; Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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