SOCIO ECONOMIC PERSPECTIVES ON FUSION POWER FOR A SUSTAINABLE FUTURE ENERGY SYSTEM

[1,2 (a)]Bustreo, C., [3]Ben Ayed, N., [4]Biberacher, M., [5]Bongiovì G., [6]Börcsök, E., [7]Čadenović, R., [8]Cok, V., [9]Colucci, G., [10]De Marchi, E., [11]Dongiovanni, D. N., [12]Ferencz, Z., [13]Geysmans, R., [14]Giacometti, A., [15]Gracceva, F., [16]Jones, C. R., [17]Kembleton, R., [13]Kenens, J., [18]Lamut, U., [19]Lechon, Y., [9]Lerede, D., [20]Lopes Cardozo, [13]Meskens, G. [21]Müller, A.V, [6]Olahne Groma, V., [22]Oltra, C., [1,2]Orlando, M.T., [23]Povh, J., [22]Prades, A., [9]Savoldi, L., [24]Stankiewicz, P., [10]Trotta, A., [13]Turcanu, C., [7]Vitiello, S., [20]Ward, S. H.

[1]Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), Padova, 35127, Italy
[2]CNR (National Research Council) ISTP (Institute for Plasma Science and Technology), Padova, Italy
[3]Culham Centre for Fusion Energy, Culham, Oxfordshire, UK
[4]RSA FG Research Studio iSPACE, Salzburg, Austria
[5]University of Palermo, Department of Engineering, Palermo, Italy
[6]Centre for Energy Research, Budapest, Hungary
[7]European Commission Joint Research Centre, Ispra, Italy
[8]University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia
[9]MAHTEP Group, Department of Energy "Galileo Ferraris", Politecnico di Torino, Torino, Italy
[10]ENI S.p.A., Venice, Italy
[11]ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development), UTFUS-TECN, Frascati, Italy
[12]HUN-REN Centre for Social Sciences, Institute of Sociology, Budapest, Hungary
[13]Belgian Nuclear Research Center (SCK•CEN), Mol, Belgium
[14]University of Padova, Department of Philosophy, Sociology, Education and Applied Psychology, Padova, Italy
[15]ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development), Rome, Italy
[16]University of Portsmouth, Department of Psychology, Portsmouth, UK
[17]EUROfusion Consortium, Garching, Germany
[18]School of Advanced Social Studies, Nova Gorica, Slovenia
[19]CIEMAT (Research Centre on Energy, Environment and Technology), Energy Systems Analysis Unit, Madrid, Spain
[20]Eindhoven University of Technology, Eindhoven, Netherlands
[21]Max Planck Institute for Plasma Physics, Garching, Germany
[22]CIEMAT (Research Centre on Energy, Environment and Technology), CISOT (Socio-Technical Research Centre), Barcelona, Spain
[23]University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia
[24]Nicolaus Copernicus University, Institute of Sociology, Toruń, Poland

[(a)] corresponding author

Email: chiara.bustreo@igi.cnr.it

Abstract

In the global effort towards the mitigation of climate change, low-carbon electricity generating technologies play a pivotal role. Nuclear fusion stands as a highly promising option for carbon-free electricity generation in a sustainable, reliable, affordable and socially acceptable future energy system. The EUROfusion work package "Socio Economic Studies" (WPSES) on fusion conducts research aimed at identifying social and economic conditions that can effectively support fusion deployment in future energy markets. Placing nuclear fusion in the broader context of energy and climate issues, the SES research explores fusion as an energy technology contributing to sustainable energy production for the future society. Because of the cross-cutting nature of the research, SES studies can provide decision-makers with scientific evidence relevant for shaping appropriate strategies in favour of fusion. This paper aims to offer the scientific community a thorough overview of EUROfusion SES research, addressing a gap in the current literature.

1. INTRODUCTION

The pursuit of commercializing nuclear fusion is not merely a scientific and technological challenge. It is a multidimensional endeavour that requires a thorough consideration of many other critical factors, including social acceptance and economic feasibility. While the scientific community works towards overcoming technological issues, it is important to acknowledge that the success of fusion depends on its integration into broader socio-political and economic frameworks. In this sense, a comprehensive and in-depth analysis of the current global socioeconomic landscape is necessary. Diverse factors such as public and stakeholder attitudes, regulatory environments, market dynamics, and the potential economic impacts of fusion technology integration are worth to be explored. Indeed, anticipating challenges and opportunities, enables stakeholders to take actions for an effective integration of fusion into a more sustainable, equitable and prosperous society.

Studies on the socio-economic aspects of nuclear fusion in Europe have a 26-years long story, started with the recommendations by the Fusion Programme Evaluation Board, set up by the Commission in 1996, to perform an external assessment on the existing Fusion Programme and the prospect of fusion, with the ultimate goal of formulating recommendations for future strategies. The Board acknowledged "[…] that at the present stage of fusion development there is a need to complement the existing knowledge bases with an additional track, that of socio-economic research on fusion (SERF). Such research calls for a multi-disciplinary approach, bringing together researchers in the physical sciences, engineering and economic, social and environmental sciences." [1].

The first research programme on Socio-Economic Research on Fusion (SERF) was launched in 1997 under the coordination of the European Commission. The research addressed the direct costs of electricity production by nuclear fusion as well as fusion externalities, namely the monetization of the environmental impact of electricity generation. Studies aiming at the estimation of the electricity market share to be possibly covered by fusion were also carried out, by means of energy scenarios. In addition, the team initiated the monitoring of public opinion evolution regarding fusion in Europe through structured interviews, focus groups and evolution of the social impact of large fusion experimental facilities.

Still named SERF under the EFDA Technology Work Programme started in 2001, the program changed name into SER (Socio Economic Research) in 2007 and finally into SES (Socio Economic Studies) when the EUROfusion Consortium was set up in 2014. Despite the new name, the area of research and the scope of the project did not change. Indeed, the expertise of dozens of researchers in physical sciences, engineering and economic, social and environmental sciences has been brought together to identify the social and economic conditions that can effectively support fusion deployment in future energy markets and to provide scientific evidence relevant for shaping strategies in support to nuclear fusion.

The current SES research activities are split into two main branches, one dealing with the understanding of the public and the stakeholders' attitudes on fusion per se and in the wider context of energy supply; the other with the study of energy systems evolution from technical and economic perspectives. A bilateral connection between the two areas is established through outreach activities. These activities aim to engage with society through various communication means, providing a broader perspective on the societal approach to "*big issues*" and offering valuable data for both social and economic studies.

This paper is intended to provide the scientific community with a comprehensive picture of the EUROfusion SES research activities. Placing nuclear fusion in the broader context of energy and climate issues, the SES research explores fusion as an energy technology contributing to sustainable energy production for future society. The scientific literature is currently missing of such an overview, being the past results of the SES research published in separated papers or reported in restricted documents. The authors deem these updates for the community of outmost importance. Indeed, the unprecedented globally perceived urgency of taking effective and quick actions to mitigate climate change [2], whose impacts are becoming increasingly evident [3], together with the growing investments on fusion by private companies [4], leading to very aggressive time schedules for the commercialization of fusion, more than ever ask for a comprehensive overview on these themes for reference, comparison and discussion.

In the following sections, the main results of the EUROfusion research on SES are presented. Specifically, section 2 goes through the most recent studies on public attitudes towards nuclear fusion in Europe. Section 3 reports on the research activities concerning both the development and the understanding of energy scenarios for the exploration of the role on fusion in future decarbonized energy systems. Section 4 puts the SES workprogram in the context of the Prospective R&D research in EUROfusion.

2. RESEARCH ON SOCIAL STUDIES

Facing the grand challenge of fusion as a component of a sustainable energy market requires a thorough understanding of societal attitudes and a more robust integration of social science than previously attempted. The fusion community is striving to deliver advancements and technological innovations that extent beyond energy production and can impact various sectors of society. Understanding public attitudes towards fusion and engaging citizens in discussions and decision-making processes related to energy scenarios is vital.

The EUROfusion social research activities have primarily focused on identifying the factors that influence public and stakeholder acceptance of fusion, both in its current research phase and as a potential future energy source in Europe. Our three primary areas of investigation are stakeholder engagement, public attitudes, and media analysis. To the best of the author's knowledge, the EUROfusion program on social studies on nuclear fusion is still the most comprehensive, extensive, and detailed initiative globally.

To get a complete and exhaustive picture of the societal perception of fusion, complementary analyses based on both qualitative and quantitative approaches and addressed to different segment of society are carried out.

Qualitative social research in SES aims to establish a direct dialogue with citizens and stakeholders (such as energy experts, NGO representatives, policy makers) through focus groups, interviews, deliberative workshops and other means. The aim is to gather views, interpretations, concerns, doubts and expectations from society and the public regarding fusion, energy, and climate issues, and to better understand the underlying dimensions of public attitudes towards fusion. The first qualitative research based on focus groups was conducted in Spain and the UK in 2008 [6,7]. It showed that fusion was generally poorly understood. Indeed, a minority of participants admitted some familiarity with the word *fusion*, but were unable to describe its main characteristics or make any sense of it at the start of the research. In this context of very low awareness, fusion was conceived as a “promising” energy source: abundant, alternative to current energy sources and “almost” renewable. The unknown and long-term side effects, the waste and the high level of investment emerged as the main concerns in the participants' discourses on fusion. In terms of general attitudes towards fusion, participants tended to have ambivalent attitudes after receiving information about fusion from a variety of sources (as people were exposed to conflicting opinions and details about the risks and benefits of fusion energy). Towards the end of the group sessions, as participants acknowledged the benefits of fusion, that tended to be replaced by *conditional acceptance*. Indeed, participants wanted reassurance that any risks would be mitigated and managed and that investments in renewable energy would not be undermined.

Similar results emerged from more recent qualitative research carried out in Slovenia, Spain, Italy, Hungary and Belgium. Citizens were invited to discuss fusion with energy and fusion experts [8]. The aim of the research was to explore people's views on fusion energy and monitor any evolution through the years. A method called World Café was used, involving small groups of participants (around 10 to 25 people per country). These participants were given balanced information about fusion and then discussed its potential benefits, risks and drawbacks. The discussions were recorded and analyzed. The results showed that although people in these countries had limited knowledge of fusion, they were generally supportive of its development. However, this support was cautious because of unresolved questions about the feasibility and implications of the technology leading to an ambivalent perception of fusion energy. There were some differences in the specific issues discussed in each country, but the main themes were quite similar. A common concern was that fusion technology hasn't yet been proven to work on a commercial scale. These findings shed light on the mixed feelings people have about fusion and have important implications for how the fusion community should approach public engagement on this technology.

Complementary to qualitative assessments, surveys were also conducted to gather quantitative evidence on societal acceptance at a broader national and European level. In 2018, the first EUROfusion European survey on fusion was conducted. The survey was the first-of-its-kind, as it marked the first dedicated assessment of public attitudes towards fusion. Twenty thousand Europeans from 21 countries responded to an online questionnaire, providing the basis for a comparative analysis of cross-country and other group differences in self-reported measures of perceived benefits and costs, positive and negative affect, attitudes, acceptance and support for fusion energy research. The results showed, among others, that almost one out of two of the respondents had heard of fusion energy before taking part in the survey. Overall, the majority of respondents considered the development of fusion energy to be acceptable: more than 65% of the population surveyed considered the development of fusion to be “acceptable” or “totally acceptable”; 24% were unsure or undecided and less than 10% considered the development of fusion to be “unacceptable”. Differences were found across Europe, with public acceptance of fusion ranging from 54 % in Austria and Belgium to 80 % in Romania, Ukraine, Bulgaria or Finland, confirming that public engagement programs should be adapted to reflect these differences [9]. The survey showed (Fig.1) a general neutral opinion of Europeans towards the technology and confirmed the conditional acceptance previously assessed.

The second edition of the survey, planned for 2023, will build on the results of the first edition. The survey will track the evolution of public attitudes towards fusion energy in the same European countries as in the first edition. Additionally, it will provide insights into the role of fusion in relation to climate and energy issues as well as the energy trilemma. As in the first edition, the survey will be conducted among a representative sample of citizens in each European country. The survey will collect data on a range of topics, including: public awareness of fusion energy; public attitudes towards fusion energy; public perceptions of the risks and benefits of fusion energy; public views on the role of fusion energy in addressing climate change and the energy trilemma. Beside monitoring the evolution of public opinion on fusion energy in Europe in light of the recent major shocks by the COVID pandemic and the war in Ukraine, the results will also provide a basis to improve public outreach and engagement efforts on fusion energy.

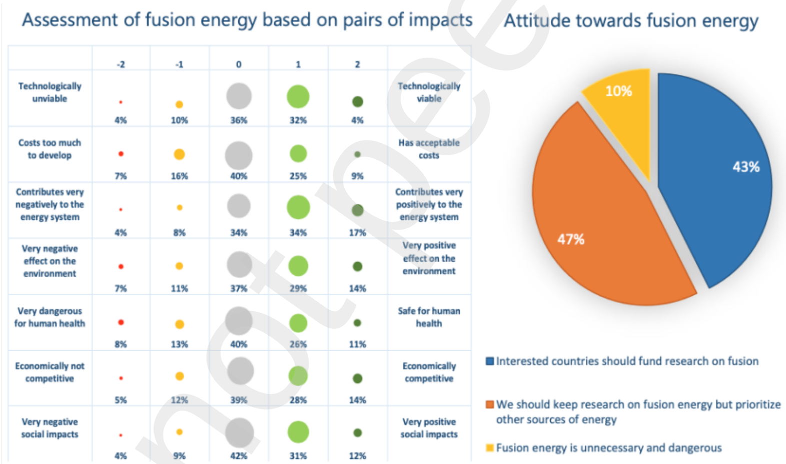

FIG. 1: Results from the EUROFUSION-SES European Survey (2018-2019) (N=19970)

To understand how society views and evaluates fusion energy, also media analysis of both traditional news outlets and social media platforms is carried out. The scope is to identify: how media portray and frame fusion energy; how this influences public awareness and understanding of fusion as both a scientific endeavor and a potential major contributor to the future energy system. In 2012, an international comparison of media coverage of fusion and fission energy in three countries (Germany, Spain and Portugal) and in English-language newspapers [10] was conducted. Positive statements about fusion prevailed in all areas, especially in Portugal (72%), Spain (62%) and in transnational print media (60%), and less so in Germany (48%), where a significant but not predominant number of datasets (34%) presenting fusion in a negative way were found. In 2013, an investigation into the nature of the content of information on fusion energy on the internet was carried out [11]. Through a content and thematic analysis of a sample of English, Spanish and Portuguese web documents, the structural characteristics of the web was analyzed to characterize the representation of nuclear fusion, and to study the associations with nuclear fission as well as the main benefits and risks associated with fusion technology on the web. The results showed that online information on fusion comes from a variety of sources. In addition, almost half of the content examined provided relevant technical insight into fusion. The majority of the web material analyzed presented a favorable view of fusion energy, positioning it as a clean, safe and powerful energy technology. There was also a dominant narrative that presented fusion as a potential solution to global energy problems, a central scientific endeavor, and a superior replacement for nuclear fission. In 2019 a content analysis of Tweets related to fusion energy was conducted using traditional coding methods and automatic sentiment analysis. The study covered five languages (English, German, Spanish, Italian, Polish, Portuguese) and showed that fusion remains a scientific topic, more than an economic or political one. Fusion is more often portrayed as positive than negative, but neutral messages are the most common of all.

3. ECONOMIC STUDIES

Achieving fusion energy is more than a technological endeavour. Indeed, many factors will concur to fusion success such as, among others: society and economy evolution, climate change and climate policies, fusion material resource availability, fusion supply chain readiness. Energy scenarios are the most powerful means to explore how the future could unfold in the decades to come. Pictures of alternative global socio-economic layouts can shed light on the challenges that lie ahead for fusion deployment and provide key elements for a timely implementation of effective strategies to support fusion.

3.1. GLOBAL SES SCENARIOS

The SES energy scenarios are developed from the EUROfusion TIMES Model (ETM), a multi-regional partial-equilibrium model of the global energy system. Like other models of the TIMES family, ETM is a bottom-up, cost-optimization model that identifies the least-cost energy system configuration under a set of environmental and socioeconomic assumptions and constraints for a given time horizon. The ETM database encompasses more than a thousand of energy technologies for all the supply (electricity and heat generation, and upstream) and demand (industry, transport, residential, commercial and agriculture) sectors of the energy system. Since its beginning in 2004 [12], ETM has undergone continuous updates to accurately reflect the development of energy technologies, the increasing ambition of energy policies to address climate change, and the growing interest of private companies in fusion. Dozen scenarios, all extending up to the end of the century, have been developed to explore what conditions are most favourable for a successful deployment of nuclear fusion.

As a result of a joint activity with the Social Research team and a collaboration with external experts, as part of the stakeholder's engagement activity, alternative storylines were formulated on the basis of different assumptions on the identified critical factors related to the future penetration of fusion technology, namely: public acceptance, GDP, technology advancements, climate change and energy costs. Based upon these storylines, the scenarios published in 2017 [13] were developed. The study proved that under moderate/stringent carbon emissions limits, fusion can have a place in the future global energy mix and its deployment would start as soon as it becomes available. The scenarios showed that the highest fusion share in the global electricity production in 2100 - 14% of the total production and equivalent to about 750 GW - would be reached under the assumption of a world with strong environmental responsibility, stringent carbon emissions targets and cooperation among regions. Of course, due to the explorative nature of the scenarios as well as the intrinsic limitations of any model due to the complexity of the system dynamics to be replicated, and the uncertainties affecting such a long-time frame, scenario results cannot be generalized. In fact, they are usually valid within their specific context only. The abovementioned installed capacity of fusion is an example. The rapid and large fusion technology deployment showed in the SES scenarios would be viable provided that a large support by a new fusion-nuclear industry was available and tritium was produced at a rate high enough to start-up many power plants almost simultaneously. In these regards, further SES assessments estimated that the number of power plants in operation at the end of the century could not exceed 200 under conservative assumptions relative to the tritium cycle. Specifically, it was assumed that tritium was produced by fusion power plants only, the doubling time was 5 years long and tritium requirement for start-up ranged from 4 to 20 kg. For comparison, 438 fission power plants (394 GW) are in operation today and 58 are under construction. Nuclear fission power has a 50-years long story, started in the '70s, as long as that fusion could have experienced in 2100 if it were commercialized by the mid of the century.

The reference investment cost assumed in the study was 7000$\$_{2015}$/kW for the *Basic* technology available from 2050 and 5000$\$_{2015}$/kW for the *Advanced*, available 20 years later. However, sensitivity analyses were performed to deal with the uncertainties on investment costs. The results showed that a 30% decrease of investment costs determines almost the same increase of fusion power share in the energy market. In addition, other studies proved that the internalisation of external costs of electricity generation turns into higher shares of fusion electricity, whatever the storyline, due to the low external costs of fusion (~0.5 $cEur_{2015}$/kWh).

More recent SES studies have focused on the assessment of feasibility, challenges and costs of deep decarbonisation strategies. Indeed, national climate goals have progressively become more ambitious, as a result of the perceived urgency of taking actions to combat climate change and its impacts. More challenging and more rapid decarbonisation pathways have been proposed and legally-binding net-zero emissions targets have been set in many countries. As an example, in 2021 the European Climate Law writes into law the goal set out in the European Green Deal for Europe's economy and society to become climate-neutral by 2050, with the additional intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels.

To reflect these changes, since 2021 the SES scenarios have been developed from a new set of storylines, corresponding to the IPCC Shared Socio-economic Pathways (SSP1, SSP2 and SSP5 [14]) and many carbon emission reduction pathways have been explored, ranging from an allowed global temperature increase of 1.5 to 5°C.

SSP1 represents a world in which there is a gradual shift towards a more sustainable path. Consumption is oriented towards low material growth and lower resource and energy service intensity; incentives are given for investment in efficient energy/environmental technologies; different world regions cooperate to minimise the costs of achieving environmental goals. SSP2 represents instead a "middle path" in which social, economic and technological trends do not deviate significantly from historical patterns; emerging economies follow the resource-intensive development model of industrialised countries; technological development proceeds without specific incentives to invest in more efficient technologies; slow progress towards global cooperation to achieve sustainable development goals. Finally, SSP5 depicts a world in which the rapid growth of the global economy leads to resource- and energy-intensive lifestyles around the world, with few incentives to invest in avoiding their environmental impacts and little global cooperation to do so.

As technologies will underpin the transition to a low-carbon economy, their availability, cost and performance will have a strong influence on the economic costs of alternative mitigation targets, and even on their actual feasibility. The EUROfusion SES scenario tree architecture proposed in 2022 (Fig. 2) addressed this issue by analysing the relative importance of availability, cost and performance of three key mitigation technologies: nuclear fission, carbon capture and storage and nuclear fusion.

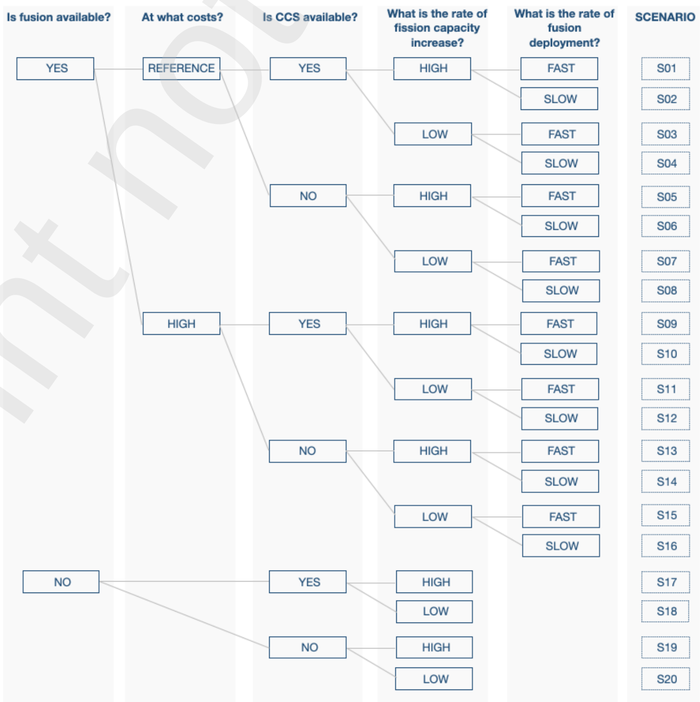

FIG. 2: EUROfusion SES scenario tree from 2022. "Reference" overnight costs of fusion are 7000$\$_{2015}$/kW for the Basic technology available from 2050 and 5000$\$_{2015}$/kW for the Advanced, available 20 years later. "High" costs of fusion correspond to a 30% increase compared to the reference. If CCS (Carbon Capture and Storage technology) is not available,

only afforestation is used for carbon sequestration. The "high" rate of fission capacity increase corresponds to a capacity increase by 5 times compared to today, while the "low" to a power plant turn-over leading to a constant total operating capacity until the end of the century. The "fast" fusion deployment corresponds to the rate of capacity increase as experienced by nuclear fission up 1985, the "slow" to a 5-years doubling time, which is allowed if the amount of tritium required for power plant start-up is in the range of 4-20kg.

Combining the three SSPs, five representative concentration pathways (RCP1.9 to RCP8.5) and two extreme scenarios in terms of technology combinations (S01 and S20), the SES project has analysed 24 different possible climate scenarios. Fig. 3 shows the cost increase of the global energy system in the scenarios analysed relative to the baseline, that best represents the world trajectory in the absence of climate policy. Some sceanarios are "infeasible", which means that no solution could be found. In these cases, any allowed energy system configuration fails to meet the energy demand.

Representative Concentration Pathway	STORYLINES					
	SSP1		SSP2		SSP2	
	S01	S20	S01	S20	S01	S20
RCP 8.5 (~ +5°C)					BASELINE	BASELINE
RCP 6.0 (less than +3.5°C)			BASELINE	BASELINE	+2%	+10%
RCP 4.5 (less than +3°C)	BASELINE	BASELINE	+2%	+2%	+6%	INFESIBLE
RCP 2.6 (less than +2°C)	+3%	+5%	+10%	INFESIBLE	INFESIBLE	INFESIBLE
RCP 1.9 (less than +1.5°C)	+9%	INFESIBLE	+20%	INFESIBLE	INFESIBLE	INFESIBLE

FIG. 3: EUROfusion SES scenario matrix in 2022 showing the cost increase of the global energy system relative to the "Baseline", that best represents the world trajectory in the absence of climate policy. If a scenario is infeasible, no solution could be found, that is none of the allowed energy system configurations can meet the energy demand. (RCP stands for Representative Concentration Pathways; the global long term temperature increase corresponding to each RCP is also specified.)

The new scenarios show that the achievement of climate goals is generally more affordable if nuclear power and Carbon Capture and Storage systems are available (S01 vs S20 under the same RCP). Some of the scenarios which rely on renewable power to a significant extent and, to a lesser extent, on nuclear fission power, result infeasible (S20). Moreover, the scenarios show that the most ambitious climate targets, such as limiting the global temperature increase to less than 1.5°C, can be achieved only if carbon emission reduction is treated as a global endeavor, thus possibly departing from the current stated policies at national level.

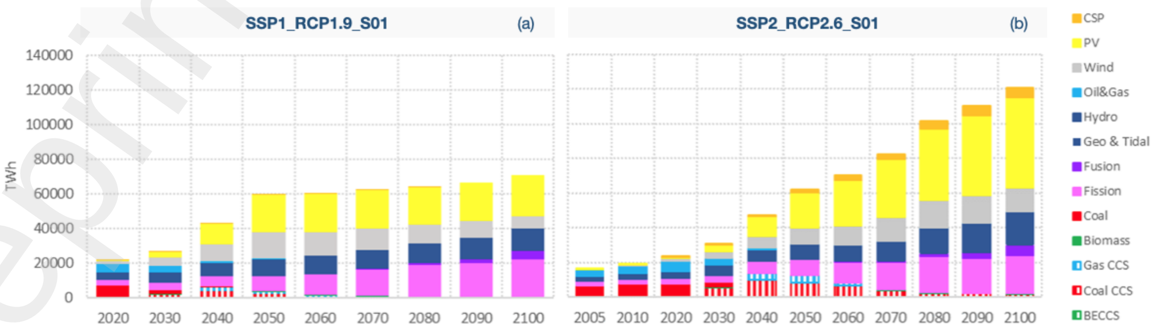

FIG. 4: Electricity production by source in the SSP1_RCP1.9_S01 (a) and SSP2_RCP2.6_S01 (b) scenarios.

The role of nuclear fusion was assessed in two of the scenarios previously mentioned, namely the SSP1_RCP1.9_S01 and SSP2_RCP2.6_S01 scenarios, as they are the main scenarios underlying the IPCC's 6th

Assessment Report. The first scenario (Fig.4a) shows a world transitioning from fossil fuels (coal and gas) in the first half of the century to a mix of nuclear and renewables after 2050. CCS technologies play a limited role in this transition. After mid-century, it shows low and stabilized electricity demand thanks to relevant improvements of energy efficiency. In the second scenario (Fig.4b), electricity demand is much higher and grows linearly until the end of the century. CCS technologies enter the system after 2030 to enable the transition to a system also composed of nuclear and renewable technologies, with solar PV playing a dominant role.

As shown in previous studies, the new scenarios show that nuclear fusion enters the system soon after it becomes commercially available, and that the stricter the constraints on carbon emissions reduction, the higher the share of fusion in electricity generation with a maximum penetration of around 5-6% of total electricity production. Further studies are ongoing to explore, among others, the effects of an early commercialization of nuclear fusion, compliant with the timelines declared by private companies [4].

3.2. SOFT LINK BETWEEN ETM AND JRC PLEXOS-EU MODELS

Global energy scenarios provide indications on national energy systems evolutions to ensure the achievement of global climate targets. However, due to the size of the problem and the consequent computational burden, the technical feasibility assessment of each national power system cannot be performed in this environment. Therefore, since 2018 the activity on energy scenarios has been complemented by feasibility assessments of the European power system resulting from the SES global scenarios, by means of a commercial software for power market simulation, PLEXOS (https://energyexemplar.com). The logic is shown in Fig. 5. The activity has been carried out in cooperation with the EU Joint Research Centre (DG JRC) [15].

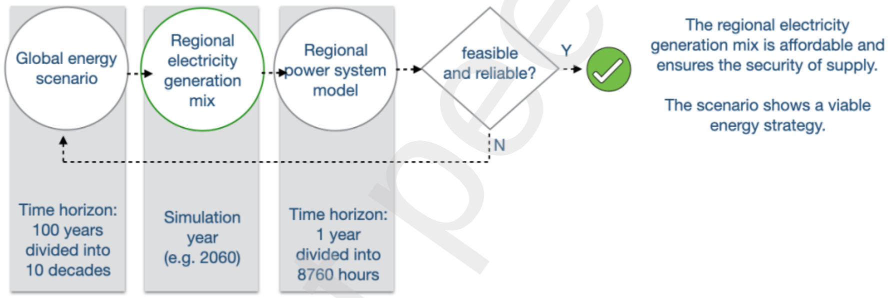

FIG. 5: The logic process of the soft-link between the global ETM model and PLEXOS, a regional power system model.[16]

This kind of studies provides insights into the actions needed to ensure the security of supply. The operation of the European electricity generation mix resulting from the SES global energy scenarios is tested with an hourly resolution and national detail. Generally, the time horizon does not extend beyond 2060 to ensure consistency with the planned development of the European transmission grid.

In order to ensure consistency between the ETM scenarios and the JRC PLEXOS-EU model [17], several modelling assumptions are made. Firstly, the generation capacity resulting from the ETM scenarios is allocated among European countries based on the ENTSO-E TYNDP 2020 and 2022 database [18]. This allocation takes into account the national trends for generation capacities in 2040 and the grid in 2050, with adjustments made to align with the ETM scenarios. For example, if the total wind capacity in ETM is twice as large as in ENTSO-E NT 2040, each country's wind capacity is multiplied by two. If nuclear capacity in the ETM scenarios is larger than in ENTSO-E NT 2040 scenario, the difference in capacity is distributed among countries based on their share of fossil-fired power plants. However, certain countries that have no plans for nuclear energy or are keen to phase it out, such as Italy, Austria, Belgium, Germany etc., are not included in this distribution. The modelling assumptions also include specific characteristics for each type of power plant, such as ramp-up and ramp-down times, minimum on/off times, minimum stable operation power, probability of generator failure, and maintenance rates. The power system configurations in PLEXOS and ETM are aligned in terms of installed capacity per technology, but power system operation patterns can differ due to factors like minimum up/down time and minimum stable factors that are not accounted in ETM. As a result, the power generation mixes between the two models may differ, with potential impact on the total carbon emissions.

Fig. 6 shows an illustrative example of the results of the soft link. While ETM and PLEXOS exhibit alignment in terms of electricity generation, the power system analysis conducted in PLEXOS reveals that the power mix resulting from ETM is insufficient to fully meet the demand. Specifically, in this energy scenario, the final electricity demand in Europe is met by importing some energy from other countries. However, the power system analysis in PLEXOS shows a notable amount of unserved demand, amounting to approximately 10% of the total demand or 627 TWh. This can be attributed to the fact that the available electricity for consumption is lower than the final demand. In fact, the excess generation from renewables, particularly wind, surpasses the demand during many hours of the year, and the excess energy cannot be stored for later use when generation falls short. Consequently, approximately 15% of the total generation, equivalent to 830 TWh, is wasted.

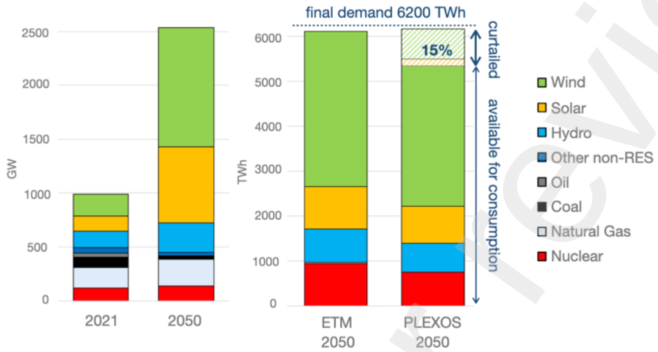

FIG. 6: On the left, installed capacity per technology in Europe in 2021 and 2050 as resulting from the scenario derived from global ETM model. On the right, the corresponding electricity generation per technology as resulting from the ETM global model and from the dispatch model PLEXOS.

Despite the minor role that fusion can play by then even under very optimistic deployment scenarios, the power system evolution up to the mid of the century deserves particular attention. Indeed, nuclear fusion success might be compromised if the power system development does not allow space for large base-load electricity generation in the next decades. Due to the higher level of geographical and temporal details, issues related to the management of over-generation and under-generation events emerge. As a consequence, indications on the required size of energy storage systems, transmission grid enhancements and flexibility measures can be derived. These studies also give proof that covering the electricity demand with decarbonized generation is likely to be very challenging in countries that currently rely on a large baseload generation, ranging from 50% to 85% of the total generation and generally provided by fossil fuels. This remains true even when assuming significant improvements in interconnection capacity and the deployment of extensive energy storage systems. Of course, those are the countries where an early deployment of nuclear fusion would be a game changer in the decarbonization process and would lighten the burden related to the implementation of measures to ensure the security of supply.

3.3. COMPLEMENTARY RESEARCH

Many complementary research activities have been carried out to address aspects not directly covered by the research on energy scenarios. The results of these studies are intended to complete the picture on the benefits and hurdles related to fusion deployment. They are listed and shortly commented in the following. Reference to published papers are given for further details where possible.

In 2020, to assess the socioeconomic implications of investing in a fusion power plant built in Europe in the countries involved in both the supply chain and plant construction, the Multiregional Input Output methodology was applied [19] through four sustainability indicators (total good and services production, value added creation, employment generation and $CO2$ emissions). Indeed, the positive socioeconomic effects in terms of economic growth and employment strongly depend on both the location of the plant (host country) and the country involvement in fusion manufactures production. United States and European Union resulted as the best options in terms of GDP growth. European Union, China and India, the most benefited countries in terms of employment, instead.

Additionally, a new methodology for providing policy makers with tools for taking more informed decisions based on energy scenarios has been explored. As described in [20], the Multicriteria Analysis method has been applied on the European road transport sector as resulting from SES scenarios. Further applications of the methodology are under exploration to link the development of energy scenarios in Europe to country-specific technical, economic, environmental, and social criteria. A first ranking of criteria was determined by historical energy production and demand data series on a national level [21]. The weights of evaluation criteria, resulting from model calculations, can indeed provide valuable guidance in the development of long-term scenarios when compared with the results of social science surveys.

Also, a multi-year project has been carried on the assessment of fusion material availability and depletion issues. A wide study encompassing the estimation of a DEMO-like fusion power plant material inventory, the component lifetime and replacement rate, the feasibility of in-situ re-use or recycling procedures, the existence of competitive markets (such as industries for lithium batteries) aims at estimating the maximum the size of the fusion nuclear fleet at the end of the century, compliant with the deployment rates applied in the scenarios studies. The work focuses on materials like lithium, beryllium, lead, and tungsten, used in plasma-facing components, as well as on helium and niobium used in superconducting magnets. Indeed, all can potentially be critical either because of scarcity of reserves and mine production (e.g. beryllium) or high future concurrent usage (e.g. lithium for batteries).

The SES program also encompasses research on nuclear fusion costing. Specifically, the appraisal of commercial viability of fusion via a stochastic analysis of discounted cash flow and the exploration of alternative financing scheme for fusion, such as the Regulated Asset Base model is underway.

Finally, alternative applications of nuclear energy, such as heat production, for improving synergies within the energy system are also under examination. A range of industrial processes are under consideration, to which fusion may supply heat at a higher value than grid electricity. Doing so is a simple way to improve the economics and business case for all neutronic fusion reactors. However, key questions remain unanswered around the practicalities of such a use case.

4. SOCIO-ECONOMIC STUDIES WITHIN EUROFUSION PROSPECTIVE RESEARCH AND DEVELOPMENT

Under the umbrella of the EUROfusion consortium, a Prospective Research and Development (PRD) programme is being conducted [22]. The main scope of PRD is to bridge the gap in between DEMO and the future Fusion Power Plants (FPPs), providing alternative and risk-mitigating long term design options for DEMO and FPPs in order to accomplish Mission 7 of the EUROfusion Roadmap: Competitive Price of Electricity. Hence, the scope of PRD is to increase the attractiveness of fusion from public and investors. In this context, SES and PRD are strictly connected as the spread of economically competitive and socially accepted FPPs is also driven by the development and application of innovative design solutions. For example, the selection for DEMO of technologies easily applicable to FPPs, would imply a standardization of the manufacturing processes necessary to produce them with a direct reduction of costs and construction times. Moreover, a significant reduction of risks in the fusion reactor building and operations could allow increasing the positive perception of fusion in the public. A correct communication aimed at informing the public that, beside the DEMO programme, PRD and SES are working to create long term design solutions and address the public needs, can surely contribute in establishing a primary role of nuclear fusion in future energy systems.

5. CONCLUSIONS

The world is experiencing an era of significant changes driven by the need to maintain or even improve current living standards for a growing population while drastically reducing the carbon footprint of all human activities. Due to the consequent progressive electrification of the economy to move away from the direct use of fossil fuels, the power sector is covering a pivotal role in the decarbonization process. In this context, nuclear fusion power has a crucial role in ensuring the sustainability, reliability, affordability and social acceptability of the energy system by contributing to the generation of firm carbon-free electricity. However, many factors, aside from the technical aspects, might slow down fusion deployment or even prevent its success. In the pathway toward achieving fusion electricity, socio-economic studies can provide many insights for early planning of the optimal strategy to support fusion deployment.

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