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Assessing the economic viability of an ARC-like magnetic fusion power plant: Cost Estimation, LCOE, and Sensitivity Analyses

TESI DI LAUREA MAGISTRALE IN
MANAGEMENT ENGINEERING
INGEGNERIA GESTIONALE

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Abstract

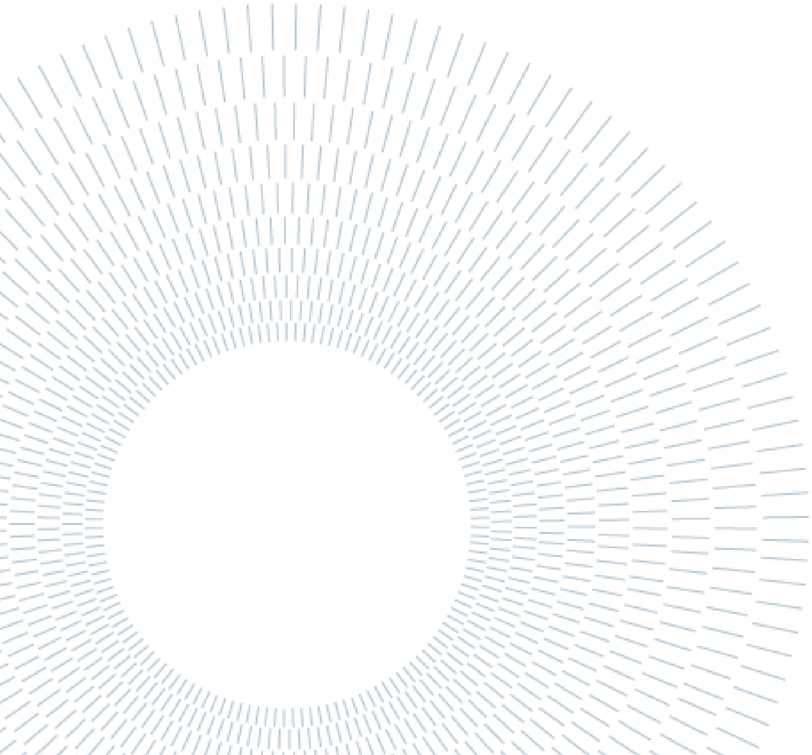
In the context of the ongoing energy transition, there arises a critical requirement of differentiating the energy sources and emerges the need for a green dependable "baseload" energy source to ensure grid stability and meet uninterrupted power demands. Fusion energy emerges as a highly promising technology for facilitating the transition and lowering the dependence from fossil fuels. Within this framework, the principal objective of this research is to assess the economic viability of an ARC-like magnetic fusion power plant and strategize methods to render its electricity competitive on the market. ARC is considered the first and most promising magnetic fusion power plant in which the most efficient technology of magnetic confinement (i.e., HTS) will be utilized. Nevertheless, the state of art of the technology is still at its primary phases and several milestones must be achieved in order to create such a reliable, affordable and competitive source of energy. The research methodology entails a thorough review of existing literature pertaining to magnetic fusion energy and established cost estimation methodologies. Data sources have been collected and incorporated into an automated model. This integration involves a cross-sectional analysis of costs derived from various fusion plants. Once LCOE has been determined, sensitivity analyses are rigorously conducted to evaluate the impact of input parameters and uncertainties on the LCOE and optimize and canalize the scientific research's efforts to make magnetic fusion power plants competitive on the electricity market. The methodology used reveals that magnetic fusion projects are inherently capital-intensive. As of the present analysis, the LCOE for such projects may not be competitive with other energy sources, but it exhibits a notable range of variability due to potential advancements in scientific targets and performance uncertainties. Magnetic fusion power plants necessitate government grants and incentives, similar to those already existing for fission plants, in order to mitigate the inherent risk associated with their capital-intensive nature and render its electricity competitive in the market. This strategy would not be far from reality as in the past the same process has been applied to solar PV to increase the adoption rate and positively contributing in tackling energy transition.

Key-words: Magnetic fusion, Cost estimation, LCOE, ARC.

Abstract in italiano

Nel' attuale contesto della transizione energetica, emerge un requisito critico di differenziare le fonti energetiche e sorge la necessità di una fonte energetica "a carico di base" verde e affidabile, per garantire la stabilità della rete e soddisfare le richieste di energia. L'energia da fusione emerge come una tecnologia estremamente promettente per agevolare la transizione e ridurre la dipendenza dai combustibili fossili. In questo contesto, l'obiettivo principale di questa ricerca è valutare la sostenibilità economica di una centrale elettrica a fusione magnetica simile ad ARC ed elaborare strategie per rendere competitiva la sua energia elettrica sul mercato. ARC è considerata la prima e più promettente centrale elettrica a fusione magnetica in cui verrà utilizzata la tecnologia più efficiente di confinamento magnetico (HTS). Tuttavia, la tecnologia è ancora nelle fasi iniziali e devono essere raggiunti diversi obiettivi per creare una fonte di energia così affidabile, conveniente e competitiva. La metodologia di ricerca prevede una revisione della letteratura esistente riguardante la fusione magnetica e le metodologie utilizzate per la stima dei costi. I dati raccolti sono stati poi incorporati in un modello automatizzato. Questa integrazione implica un'analisi trasversale dei costi derivati da diverse centrali a fusione. Una volta determinato il LCOE (Levelized Cost Of Electricity), sono state condotte analisi di sensitività per valutare l'impatto dei parametri di input e delle incertezze sul LCOE, al fine di ottimizzare e indirizzare gli sforzi della ricerca scientifica per rendere competitive sul mercato le centrali elettriche a fusione magnetica. La metodologia utilizzata rivela che i progetti di fusione magnetica sono intrinsecamente intensivi in termini di capitale. Al momento dell'analisi attuale, il LCOE per tali progetti potrebbe non essere competitivo con altre fonti energetiche, ma mostra un notevole margine di miglioramento dovuto ai potenziali progressi scientifici. Le centrali elettriche a fusione magnetica necessitano di sovvenzioni governative e incentivi, simili a quelli già esistenti per le centrali a fissione, al fine di mitigare il rischio intrinseco associato alla loro natura intensiva in termini di capitale e renderle competitive sul mercato. Questa strategia non sarebbe lontana dalla realtà, poiché in passato lo stesso processo è stato applicato a impianti fotovoltaici per aumentare il tasso di adozione e contribuire positivamente ad affrontare la transizione energetica.

Parole chiave: Fusione magnetica, Stima di costo, LCOE, ARC.



Contents

1.Introduction

The need for global decarbonization has never been so urgent, nevertheless, there are two conflicting factors that characterize the energy transition. Firstly, desirability refers to the countries' willingness to lower their dependence on fossil fuels in order to subsequently lower GHG emissions. A lot of policies and packages fostering the energy transition emerged over the years, either at the international and European levels so that each country knows exactly what is needed to be done to effectively tackle the energy transition. Secondly, feasibility, which refers to what countries are actually doing to lower their emissions. The data speak for themselves. From Figure 1.1 it can be seen that in 2021 global CO2 emissions reach their peak (37.12 billion tons, of which 73.2% comes from the energy industry [1]) and they are continuing to grow, revealing that the Nationally Determined Contributions (NDCs) are not aligned among countries.

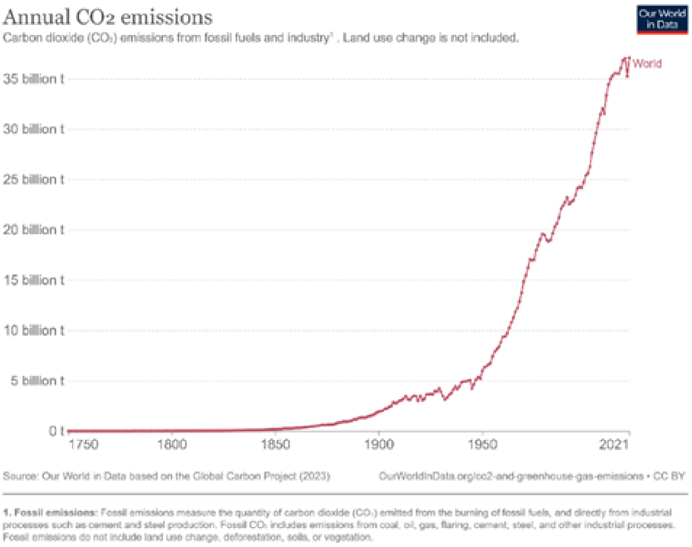


Figure 1.1: Annual CO2 emissions [1]

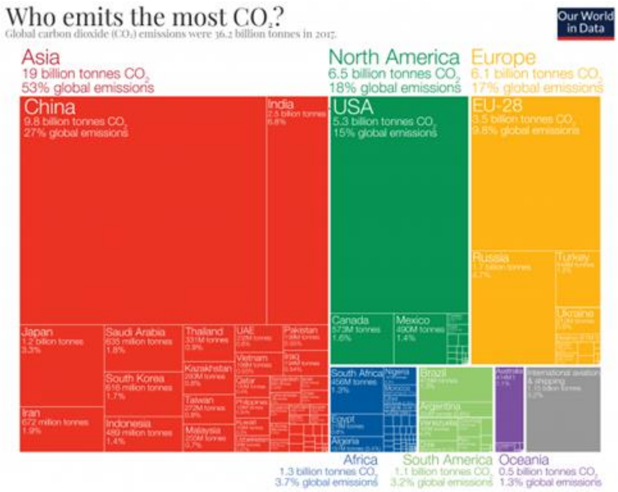


Figure 1.2: CO2 emissions per countries [1]

As Figure 1.3 shows [2], the growth in energy consumption in OECD countries is slower because of relatively slower population and economic growth, improvements in energy efficiency, and less growth in energy-intensive industries. Moreover, as the GDP growth is still correlated to an increase in energy consumption (see Figure 1.4) [3] and NON-OECD countries projections are characterized both by a relevant increase in population (Africa will pass from a population of 1.4 billion in 2022 to 4 billion in 2100 [4]) and an increase of their GDP, it can be estimated that in the near future, the energy demand will increase sharply and consequently global emissions will hardly decrease, unless effective policies and countries contributions are put in place.

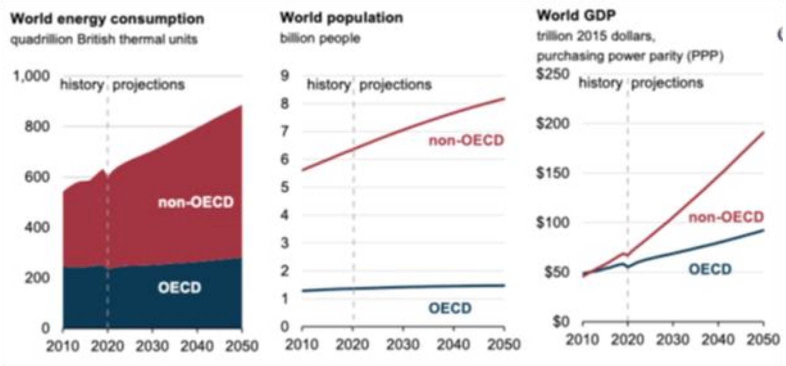


Figure 1.3: Projections of world energy consumption, population, and GDP [2]

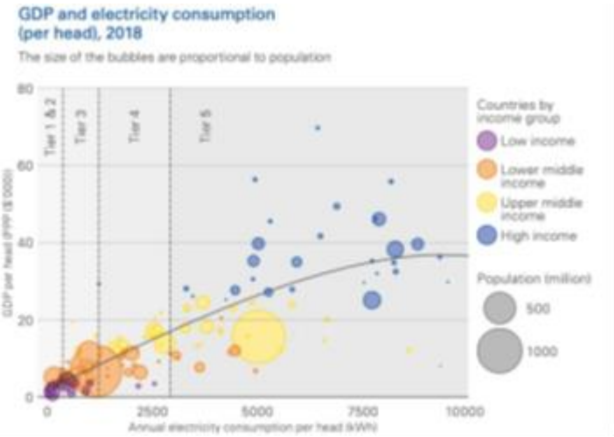


Figure 1.4: Correlation between GDP and electricity consumption [3]

1.1 Tackling Energy Transition

1.1.1 Policies

1.1.1.1 International commitment

The international community has demonstrated a strong commitment to address the energy transition through Conferences of Parties, of which the most important are COP21, COP26 and COP27. These conferences are important panels for nations to collaborate and develop strategies to tackle climate change and achieve a sustainable energy future.

COP 21, also known as Paris Agreement, took place in 2015 and marked a significant milestone. In this significant agreement, 195 nations collectively sought to enhance the worldwide approach to addressing the challenge of climate change. Their objective was to constrain the rise in the global average temperature to a level significantly below 2°C above pre-industrial levels, with dedicated endeavors aimed at capping the temperature increase at 1.5°C above pre-industrial level [5]. Moreover, participating nations committed to developing and regularly updating their Nationally Determined Contributions (NDCs), outlining their efforts to reduce greenhouse gas emissions. The Paris Agreement stressed the importance of transitioning to low-carbon economies, fostering sustainable development, and providing financial and technological assistance to developing countries in their climate actions.

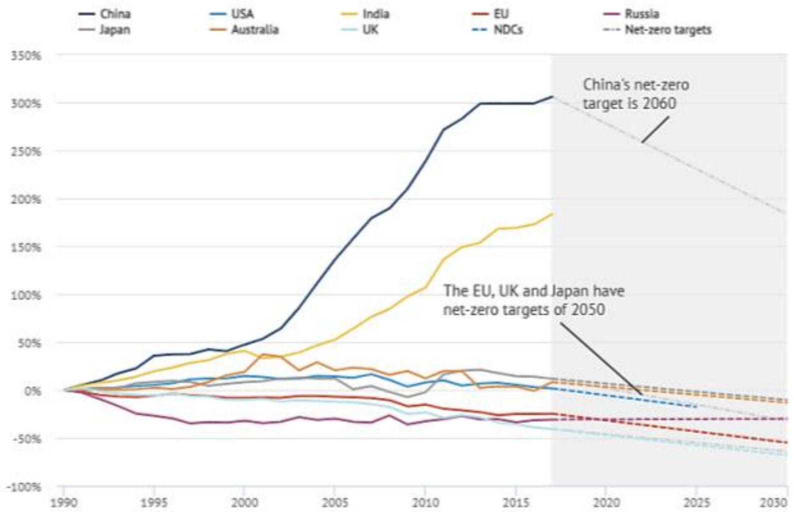


Figure 1.5: Changes in emissions in major economies since 1990 [6]

Building upon the Paris Agreement, COP26 took place in Glasgow in 2021. This conference placed particular emphasis on accelerating actions to address climate change, requiring global emissions almost to halve by 2030 and reach net zero by 2050. Numerous countries, including major emitters (China and India enter the COP in 2021), made significant commitments to achieve net-zero greenhouse gas emissions by mid-century or soon after, nevertheless, their NDCs are not in line with the Paris Agreement goal [6] (see Figure 1.5). This misalignment was confirmed also during COP27, in which 1.5 °C goal was perceived as impossible, moving expectations to 2 °C at the best [7].

1.1.1.2 European commitment

Europe is a front-runner in tackling the energy transition. A key policy milestone is the European Green Deal of 2019, which aims at making Europe a climate-neutral continent by 2050. An important objective of the Deal is decoupling economic growth from resource use and environmental impact through a just transition that leaves no one behind. Built upon the Green Deal, the European Commission published the Fit For 55 package in 2021, with the goal of reducing GHG emissions by at least 55% by 2030, compared to 1990 levels. Moreover, an important proposal is the introduction of the Carbon Border Adjustment Mechanism, which put a carbon price on imports of a targeted selection of products to ensure that ambitious climate action in Europe does not lead to “carbon leakage”.

1.1.2 The shift in energy production

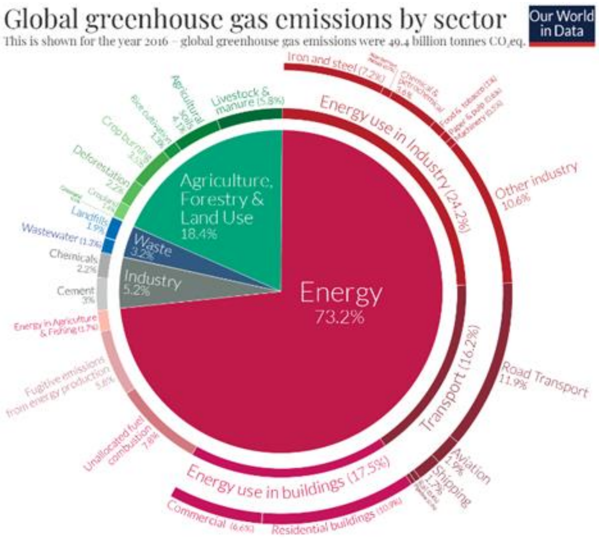


Figure 1.6: Global GHG emissions by sector [8]

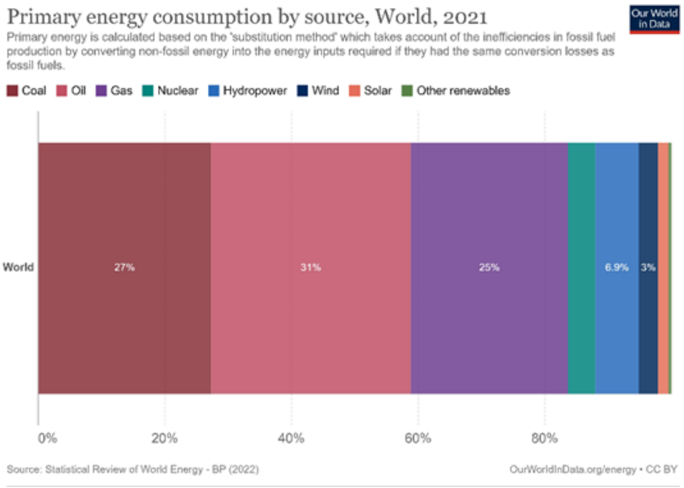


Figure 1.7: Primary energy consumption by source [9]

Effectively addressing the energy transition requires a dedicated emphasis on the energy sector. As shown in Figure 1.6, this sector is the higher source of greenhouse gas (GHG) emissions, comprising a substantial 73.2% of the total global emissions [8]. Nevertheless, the share of global primary energy production is currently satisfied by 84.2% of oil, coal, and natural gas (see Figure 1.7) [9].

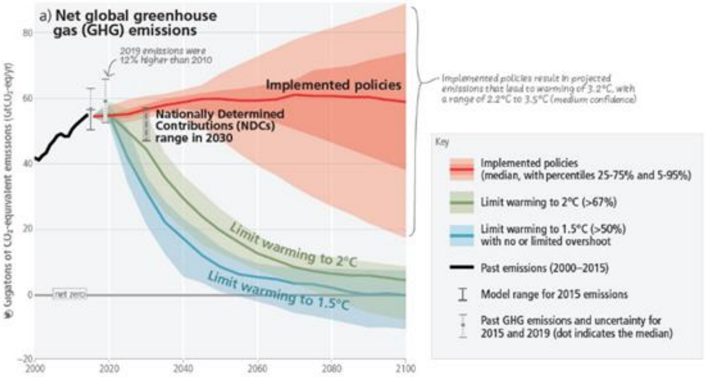


Figure 1.8: Actions to limit global warming to 1.5/2 °C are not aligned with implemented policy [90]

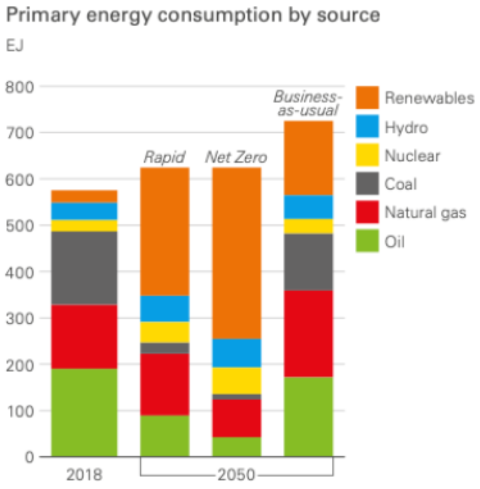


Figure 1.9: Primary energy consumption by source in 2050 scenarios [3]

The global energy system is facing a dual challenge: the need for an increase in energy production while reducing GHG emissions [10]. A cornerstone of achieving net-zero emissions lies in the widespread adoption and expansion of renewable energy sources. As shown in Figure 1.9 [3], solar and wind energy sources will face an important increase in the net-zero scenario in order to replace fossil fuel-dependent systems. The main drawbacks of RES lie in their intermittency. The notable prevalence of variable renewable energy sources leads to considerable fluctuations in electricity supply due to weather-related factors. When these fluctuations coincide with the inherent variations in power demand, it can lead to substantial oscillations in both electricity supply levels and the associated pricing.

This situation presents significant hurdles to ensuring a consistent and uninterrupted supply of electrical power. Consequently, it underscores the importance of backup and storage solutions, which constitute central components of overall system costs [11]. System expenses associated with variable renewable energy sources will be accrued as a result of the subsequent determinants:

- The generation may be situated at a considerable distance from the point of consumption, thereby introducing considerations pertaining to connection and transmission expenses;
- The variability in the generation profile may necessitate the removal of other suppliers from the system. Weather patterns exhibit fluctuations, and solar power, in particular, follows a cyclical pattern based on seasons and time of day;
- There is a need for backup generation or the maintenance of excess capacity to offset the intermittent nature of large-scale, extended-duration energy storage;
- Ensuring power grid stability becomes a significant challenge in the absence of traditional thermal power plants.

Such costs are often not included in the costs of renewable generation, leading to offset some low-cost advantages of RES [11]. Moreover, by investigating the feasibility of achieving 100% renewables in different markets, different studies reach the same conclusion that costs can become very significant, as curtailment can exceed 40% and highly interconnected power systems are required [11].

1.1.3 The need for a dispatchable power supply

In the backdrop of escalating energy requirements and the imperative to dramatically curtail global greenhouse gas (GHG) emissions, magnetic fusion emerges as a viable means to make a substantial contribution toward achieving these pivotal objectives. It stands out among energy sources capable of ensuring global energy sustainability while eliminating GHG emissions [12].

As stated by ENEA [12] , controlled nuclear fusion will provide a source of energy:

1. *Environment-friendly*: helium and neutrons are the only product of the most promising fusion reaction (Deuterium-Tritium, D-T). This reaction yields no persistent radioactive waste, and when appropriate materials are selected for the reaction chamber, the radioactivity induced in structural components exhibits a comparatively rapid decay rate when contrasted with values observed in carbon-fired plants. Indeed, in the design of a

magnetic fusion power plant, a particular care is given in designing fusion reactors on minimizing the inventory of tritium and other radioactive materials and researching on low activation materials [13];

2. *Intrinsically safe*: during the operations, no chain reaction is possible, as a little percentage of fuel is needed in the vacuum vessel, hence, in case of damage, accident, or loss of control, fusion reactions and heat generation will very rapidly and automatically switch off;
3. *Sustainable*: Deuterium is abundant in seawater and lithium is found in both rocks and ocean water. Moreover, through the tritium breeding, the latter is produced from lithium inside the reactor. These make the fuel widely available in nature and virtually limitless;
4. *GHG-free*: there is no production of greenhouse gases.

Moreover, magnetic fusion does not inherit the intermittency typical of renewable energy, with the possibility of playing a fundamental role as a base-load energy source.

2 The role of fusion in the energy transition

Nuclear fusion is not yet considered under the frame of either the Net Zero Road Map published by the IEA in 2021 [10], nor in the updated version published in 2023 [14]. This is justified primarily because this technology has not yet attained commercial viability and is not anticipated to make a substantial contribution to the global energy portfolio until the year 2050. Nevertheless, there is a significant difference between the role of nuclear power in the two Net Zero Roadmaps; in the NZE Scenario updated version, the share of nuclear power in 2050 is 15% higher than in the 2021 NZE Scenario, given the substantial policy support in leading markets and the promising future of small modular reactors. Consequently, given the higher importance that is attributed nowadays to nuclear power, it is imperative to acknowledge that, beyond nuclear fission, the successful development of nuclear fusion has the potential to address critical global challenges related to energy security, climate change mitigation, environmental impact mitigation, and the conservation of finite resources [13].

2.1 The global competitiveness of fusion in long-term scenarios

Several studies have been conducted in the literature with the purpose of investigating the potential role of fusion energy technologies in electricity generation by 2050.

As stated by Massachusetts Institute of Technology and Plasma Science and Fusion Center [15], fusion based on high-field superconducting magnets (i.e., an ARC-like power plant), can play an important role in electricity generation from 2030 (Figure 2.1) and its capacity for expansion aligns with the objective of mitigating the most severe consequences of climate change and making meaningful contributions to mid-century carbon dioxide (CO2) reduction targets. For sake of completeness, ARC is a magnetic fusion power plant that uses high temperature superconductive magnets (HTS). This technology allows to have a smaller size of the plant, thanks to the higher magnetic field generated, with respect to technology using low temperature superconductive magnets.

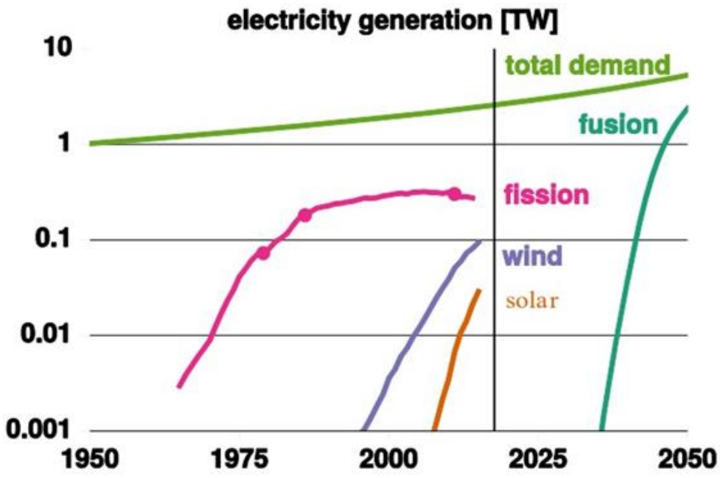


Figure 2.1: The role of an ARC-like fusion power plant in the electricity generation [15]

The paper of Cabal, et al. [16] (2017), express powerful insight in the exploration of the competitiveness of fusion in a future global energy market under different scenarios. The paper utilized the ETM global energy model, an economic model of the worldwide energy system. This model encompasses the majority of electricity generation technologies and spans a time frame from 2005 to 2100. For the purpose of setting carbon dioxide (CO2) emissions targets, the paper adopted two Representative Concentration Pathways (RCPs): RCP6 and RCP4.5. These pathways translate into specific CO2 emissions limits, with RCP6 corresponding to 48.2

Table 2.1: Data for fusion technologies in analysis [16]

Plant type	Date	Specific capital [$/kW]	Efficiency [%]	FIXOM [M$/Gwa]	VAROM [M$/PJ]
Basic plant	2050	5910	42	65.8	2.16
Basic plant	2060	4425	42	65.8	1.64
Advanced plant	2070	4420	60	65.3	2.14
Advanced plant	2080	3255	60	65.3	1.64

GtCO2 in 2050 and 50.4 GtCO2 in 2100, while RCP4.5 equates to 36 GtCO2 in 2050 and 14.4 GtCO2 in 2100 [16]. Moreover, the capital costs, fixed and variable operation and maintenance costs (i.e. FIXOM, VAROM), the efficiency and the date of construction of a basic and advanced magnetic fusion power plants are described in Table 2.1. The model results in the inclusion of fusion by 2070, even if it is made available from 2050, as the high investment cost of the first years (i.e. 4425-5910 $/kW, capital costs of the basic plants) has limited the competitiveness of this technology [16]. From Figure 2.2 it can be seen that the greatest degree of adoption occurs in the Harmony scenario, with fusion power plants accounting for 14% of the electricity generated in 2100, renewable energy sources (RES) contributing to 74%, and fossil fuel technologies representing a mere 2% [16]. Moreover, the average growth rate for fusion technologies is 12 %/year [16]. In this scenario, there is a notable emphasis on environmental responsibility, featuring cooperative operators with long-term perspectives and adhering to stringent global CO2 emissions targets (using RCP4.5 as a reference). Conversely, the Fragmentation scenario is marked by a diminished environmental commitment, leading to less demanding CO2 emissions targets (specifically, RCP6.5) and the involvement of non-cooperative operators with short-term orientations. In this latter scenario, electricity production is elevated, and there is a significant reliance on coal and gas technologies, accounting for 23% with CCS (Carbon Capture and Storage) and 17% without CCS [16]. Renewable technologies are responsible for 48% of the total production in 2100, the lowest share in the three scenarios, as nuclear technologies where fusion ones produce 10% of the total and fission ones 3% [16]. The average growth rate for fusion technologies in this scenario is also the lowest with 0.9%/year [16].

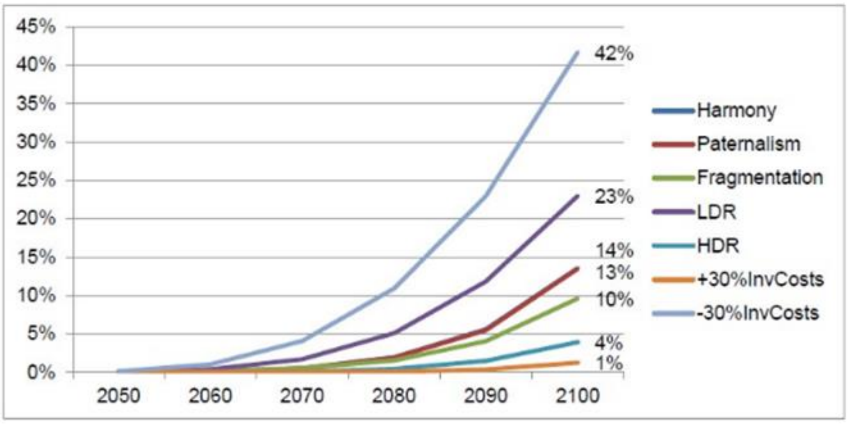


Figure 2.2: Fusion share in the global electricity system [16]

It is worth noticing that technology costs have a huge impact on the fusion market's chances. Indeed, when fusion costs are 30% higher than the ones proposed in Table 2.1, fusion penetration in the global system decreases dramatically until it reaches 1% in 2100 [16], and on the contrary, when costs are 30% lower, the share of fusion technologies reaches 42% in 2100 [16].

The primary conclusion that emerges from the paper is that fusion technologies play a predominant role within the global electricity landscape, contributing significantly to the realization of a nearly fully decarbonized global electricity system. This achievement is accomplished in conjunction with renewable technologies and, to a lesser extent, carbon capture and storage (CCS) technology. This transformation occurs within a world characterized by a robust commitment to environmental responsibility and the enforcement of stringent global carbon emissions targets. Ensuring the cost competitiveness of fusion technologies emerges as the central strategy for their integration into the global electricity system in the foreseeable future [16].

Analyzing another point of view, the study conducted by Entler, et al. [17] (2018) analyses DEMO2 magnetic fusion power plant and shows the impact that external costs have on the Levelized Cost of Electricity (LCOE). DEMO2 is a magnetic fusion power plant facility designed to demonstrate the practical feasibility of generating electricity from controlled fusion reactions, using low temperature superconductors (LTS). As stated by Entler, et al. [17] (2018), "external costs are defined as the impact of the production or consuming behavior of the economic entities on the welfare of a third party, whilst it is not reflected in the market transactions". To estimate the external cost the European methodology ExternE[1] has been utilized.

This methodology conducts an evaluation of three principal categories concerning the energetic impact [17], which encompass:

- Detrimental effects on human health, involving heightened risks of mortality and morbidity;
- Consequences on ecosystems and biodiversity, encompassing alterations in the environment and the loss of biodiversity;
- The influence on resources and depletion, primarily pertaining to water, metals, and fuels, while also extending to crops, infrastructure, and similar aspects.

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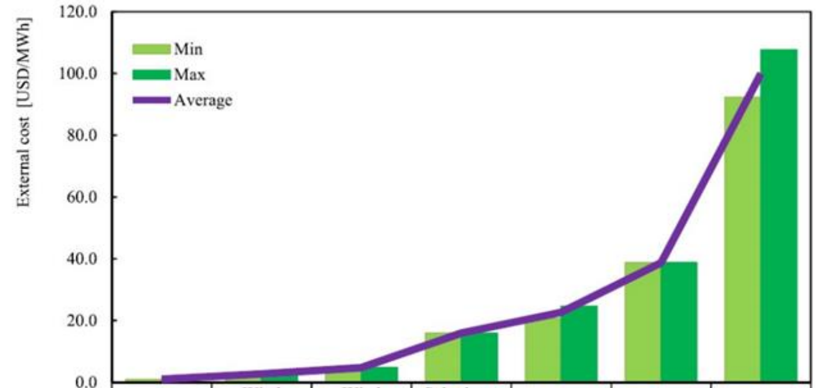
[1] ExternE is a report that delineate the analysis of nuclear, fossil, and renewable fuel cycles to assess the externalities linked to electricity generation. [88]



	Fusion	Wind offshore	Wind onshore	Solar large PV	Nuclear	Natural gas	Coal
Min	0.9	2.7	4.7	16	21	39	92
Max	1.1	2.7	4.7	16	25	39	108
Average	1.0	2.7	4.7	16	23	39	100

Figure 2.3: External costs of selected energy sources according to the ExternE methodology [17]

Although fusion has the highest capitalized investment (between 3472 $/kWe and 8525 $/kWe [17]) among other energy sources, Figure 2.3 shows that nuclear fusion will create the lowest external costs of all the benchmarked sources [17]. Consequently, if external costs are included in the LCOE computation (i.e. TCOE), they would decrease it, making fusion energy more competitive in the market. According to [17], from the perspective of the current perception of the need for sustainable energy, TCOE should be the decisive criterion for assessing the profitability of individual energy sources. As stated by Entler, et al. [17] (2018), "When accounting the environmental impact in the case of internalization of external costs, fusion power plants will be economically the second most favorable source of energy" [17].

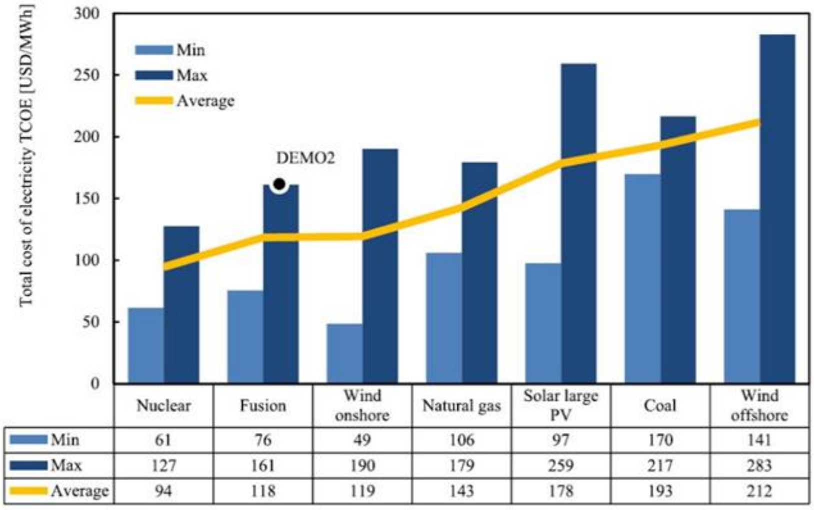


Figure 2.4: Total Levelized Cost Of Electricity including external costs (TCOE) [17]

For sake of completeness, the study conducted by Banacloche, et al. [13] (2020), evaluate the sustainability impact in terms of total good and services production, value added creation, employment generation and CO2 emissions, using an extended multiregional input-output approach.

The analysis of potential impacts related to the investment required for the construction and operation of a fusion power plant relies upon Input-Output Analysis (IOA) [13]. This methodology holds significant effectiveness, since it enables the estimation of the comprehensive economic stimulus generated across diverse economic sectors due to an upsurge in the demand for goods and services driven by an investment. When examining different regions or nations globally, the alteration in demand for goods and services originating in one country due to an investment made in another country can be assessed through the utilization of Multiregional Input-Output Tables (MRIOTs) [13]. A multi-regional input-output (MRIO) analysis has been conducted. This analysis empowers the quantification of economic exchanges among sectors and nations globally, encompassing trade categorized by both sector and the countries of origin and destination.

The indicators selected for the analysis are:

- Global warming emissions as environmental indicator: The environmental effects of fusion technology can be linked to a range of factors encompassing emissions of both conventional and radioactive pollutants, utilization of land, water, and mineral resources, as well as energy consumption [13];

- Value generation added and generation of employment as economic and social indicator.

The model results in the involvement of Europe, for the 47% of total production and the United States, for the 20% of total production in the value chain [13].

However, it is noteworthy that countries such as China, Japan, and Russia play a significant role in the supply of components for O&M purposes [13]. Moreover, to understand the role of the countries in the fusion value chain, the paper analyses the value added. The United States and the European Union are the only regions where their participation, quantified by value added, surpasses their input in terms of production. This insight suggests a relatively higher reliance on domestically sourced components within their contributions to the project [13].

In the context of employment, the initial establishment of this fusion power plant would have a substantial effect on job generation, amounting to approximately 183.2 thousand full-time equivalent jobs (FTE) [13]. The European Union, as a host region of the fusion power plant, is expected to boost domestic direct employment in this phase more than the rest of the regions that would be more benefited in terms of indirect job creation [13].

Regarding the carbon footprint associated with the deployment of this technology, it amounts to 11.4 grams of CO2 per kilowatt-hour (gCO2/kWh). Unlike value added and employment, where the European Union has larger impacts, when measuring CO2 emissions this region is close to others such as the United States and Japan [13]. Indeed, the participation of the European Union in the CO2 emissions accounts for approximately the 22% of total CO2 emissions. However, the expected improvements towards energy transition and energy efficiency will impact the production processes, reducing the CO2 emissions in fusion energy deployment. From Figure 2.5, it can be easily understood what are the countries most responsible for a) value-added, b) employment, and c) CO2 emissions.

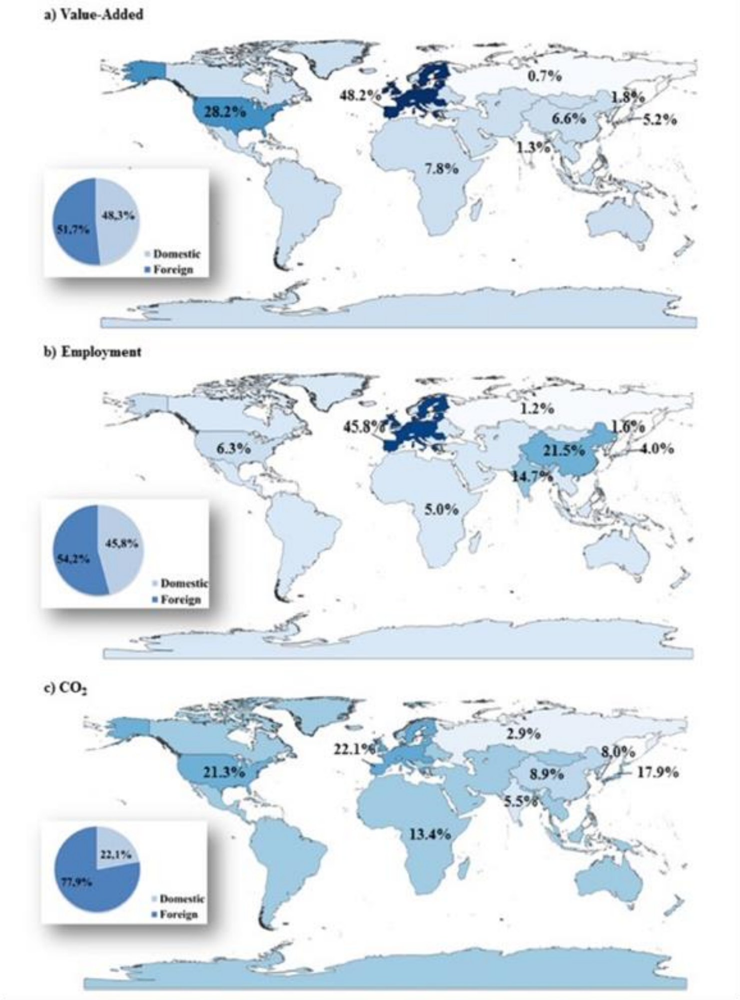


Figure 2.5: Regional participation in terms of value-added, FTE employment creation and CO2 emissions [13]

2.2 The European Role of Fusion in the energy mix

Fusion energy will constitute an important share of the energy mix after 2050, when the probability that the European energy mix will be fully decarbonized is very high. The study of Bustreo, et al. [18] (2019) provides a range of scenarios aimed at estimating to what extent fusion power will be able to enter the scene in Europe together with renewable energy sources (RES) by the last two decades of this century. In order to do that, the electricity demand is assumed to grow 600 TWh/year, due to the electrification of the energy sector [18] and two cases are proposed: “South Europe”, in which Italy is chosen as reference Country with a predominant solar generation and “North Europe”, largely based on wind power and with UK as reference Country. Regarding South Europe, three energy scenarios are simulated [18]:

1. 100% RES, without any fusion contribution [18];
2. Fusion base-load, where fusion power plants generate 260 terawatt-hours (TWh) at 30 gigawatts (GW) constant power (i.e., 37 GW installed capacity with 80% availability) [18];
3. Fusion-two-seasons, where fusion still generates 260 TWh, but at 25GW power in the six months when solar radiation is higher (i.e., from April to September) and at 35GW power during the rest of the year [18].

In all the scenarios, 50 TW are supplied by base-load generation and wind farms generate 50 TWh [18].

In the 100%-RES scenario, 450 GW PV capacity must be installed, generating 590 TWh [18]. Nonetheless, owing to the intermittent nature of renewable energy sources (RES), a total of 690 TWh, comprised of 590 TWh from photovoltaics (PV), 50 TWh from base-load sources, and another 50 TWh from wind power, falls short of meeting the demand of 600 TWh. This shortfall results from instances of over-generation exceeding 3000 hours and under-generation lasting for 5700 hours [18]. Consequently, to address this issue, dispatchable generators totaling 41 GW need to be incorporated into the system, alongside the integration of pumped-hydro facilities amounting to 9 GW and battery storage systems with a cumulative capacity of 150 GW.

In contrast, within the fusion-baseload scenario, the installed photovoltaic (PV) capacity is significantly lower, amounting to less than one-third of that in the 100% renewable energy scenario, specifically 123 GW, capable of generating 162 TWh of electricity [18]. In contrast to the 100% renewable energy scenario, there is a 17% increase in the demand for dispatchable energy. However, the required capacity is reduced by 15%. In terms of storage systems, the maximum potential of pumped-hydro in Italy is fully utilized, mirroring the 100% renewable energy scenario. Nevertheless, the size of the battery storage system is scaled down by 67% [18]. This adjustment results in a 95% reduction in curtailed energy and an 82% decrease in energy losses due to the improved efficiency of the battery system [18].

In the fusion-two-seasons scenario, it is noteworthy that despite having a higher photovoltaic (PV) installed capacity, which stands at 153 GW, compared to the fusion-baseload scenario, the configuration for dispatchable energy and storage is advantageous. There is a 21% reduction in dispatchable energy and capacity compared to the 100% renewable energy scenario. The setup includes 9 GW of pumped-hydro and 62 GW of battery storage, resulting in 11 TWh of curtailed energy and 11 TWh of losses due to battery efficiency [18].

In the context of the North-Europe scenario, the analysis concentrated exclusively on two scenarios: the 100% renewable energy (RES) scenario and the fusion-baseload scenario. The findings closely mirror those observed in the South-Europe scenario. However, a significant distinction lies in the North-Europe scenario, where solar PV are substituted with offshore wind farms, amounting to 170 GW, in conjunction with 40 GW of dispatchable energy and 3 GW of storage systems. In contrast, the fusion-baseload scenario for North-Europe sees a reduction in the installed offshore wind capacity, to less than half of that in the 100% RES scenario, specifically 75 GW. While the capacity for dispatchable energy remains consistent, the size of the battery storage system is reduced by 60%. This adaptation leads to a notable 69% reduction in curtailed energy and a corresponding 67% decrease in energy losses due to battery efficiency [18].

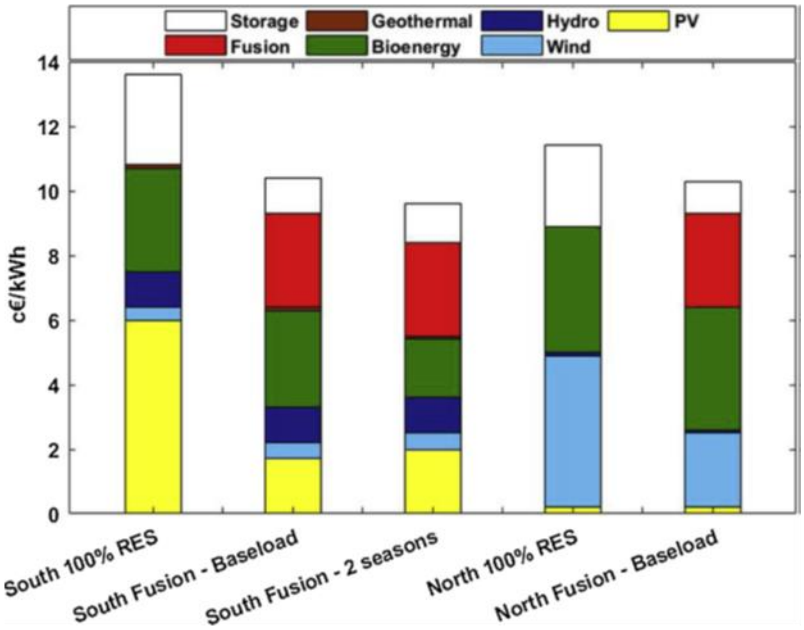


Figure 2.6: Breakdown of the LCOTE when all cost parameters are set at their middle value [18]

Figure 2.6 shows the impact that the different technologies have on the LCOTE in the different scenarios. As for fusion, a steady-state fusion power plant is considered, with 6000 €/kW investment cost, 110 €/kWy O&M costs, 60 years lifetime and 80% availability, which are in line with the ranges proposed by EUROfusion for “basic” commercial power plant . By looking at the 100% RES scenarios almost one-half of the LCOTE is occupied by dispatchable energy and storage, which must face the intermittency of RES.

The paper arrives at the conclusion that the inclusion of fusion energy within the power generation mix results in a substantial reduction in the Levelized Cost of Total Electricity (LCOTE) due to a significant decrease in the utilization of storage systems and the amount of curtailed energy.

2.3 The global fusion Industry

The benefits highlighted earlier, which fusion can potentially offer to the energy sector, are gradually becoming more apparent in the marketplace. Furthermore, numerous technological milestones have been reached since 2021. These include the successful demonstration of controlled burning plasma at the National Ignition Facility in California, the achievement of record energy production levels at the Joint European Torus (JET) in Oxford, and the establishment of record-setting durations of high-temperature plasma confinement at both KSTAR in South Korea and EAST in China [19]. Similarly, privately financed fusion enterprises within the FIA (Fusion Industry Association) accomplished significant milestones of their own. For instance, Commonwealth Fusion Systems in Massachusetts showcased the world's most powerful magnet. Meanwhile, Helion in Washington and Tokamak Energy in the UK achieved significant breakthroughs by attaining plasma temperatures exceeding 100 million degrees, and General Fusion in Canada demonstrated their capability to accurately compress a plasma [19]. For all these reasons, private investment is coming in, allowing the fusion industry to build the proof-of-concept devices that will show fusion energy can work [19]. Indeed, private industry has secured over $2.8 billion in new private investment from 2021 to 2022, bringing total private investment to over $4.7 billion and more than doubling the industries entire historic investment in a single year [19].Jude

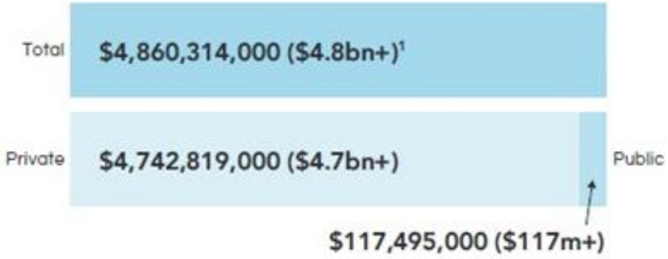


Figure 2.7: Private & public funding for fusion companies [19]

These notable investments included a massive $1.8 billion investment into Commonwealth Fusion Systems, $500 million into Helion Energy and several important ones over $100 million [19].

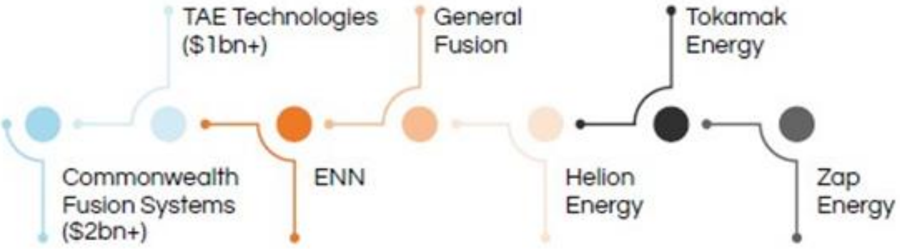


Figure 2.8: Companies with $200M investment or more [19]

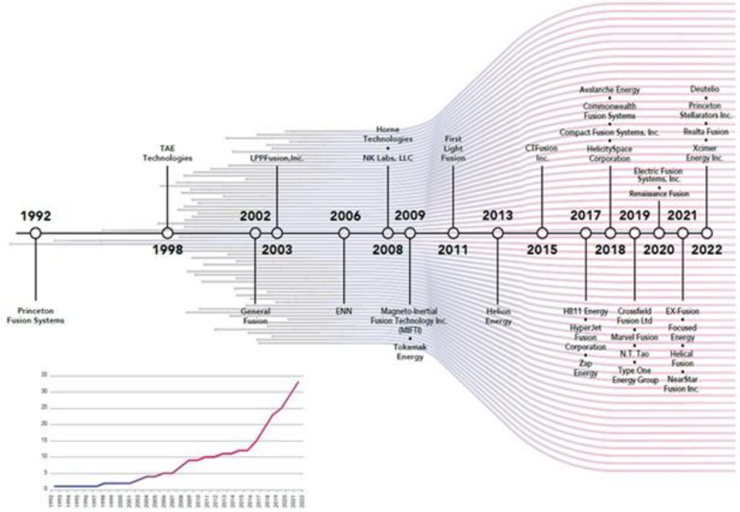


Figure 2.9: Total number of private fusion companies by year [19]

Analyzing the companies' answers to the survey conducted by the Fusion Industry Association in 2022, shown in Figure 2.10 [19], the majority of the companies stated that their fusion power plant will deliver electricity to the grid and will demonstrate a low enough cost / high enough efficiency (Q) to be considered commercially viable between 2031 and 2035, revealing that the fusion's benefits could be exploited by the market in the near future.

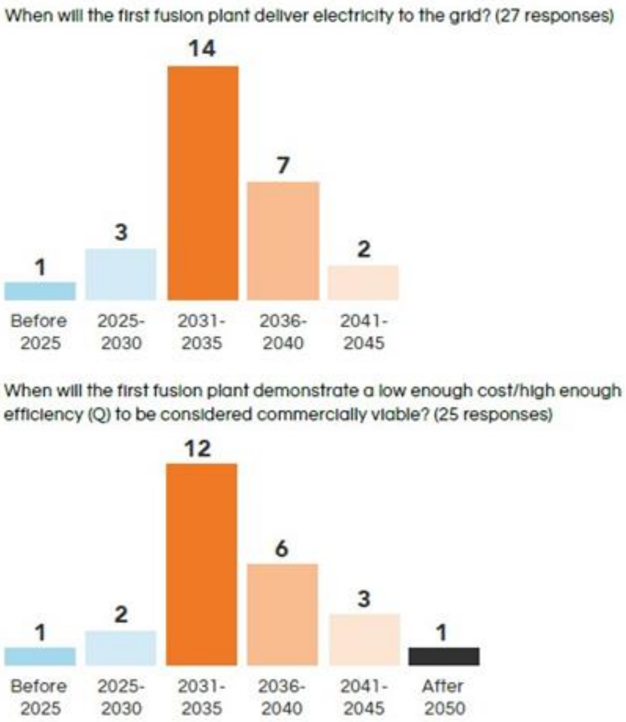


Figure 2.10: FIA survey [19]

3 Technology overview

3.1 Introduction

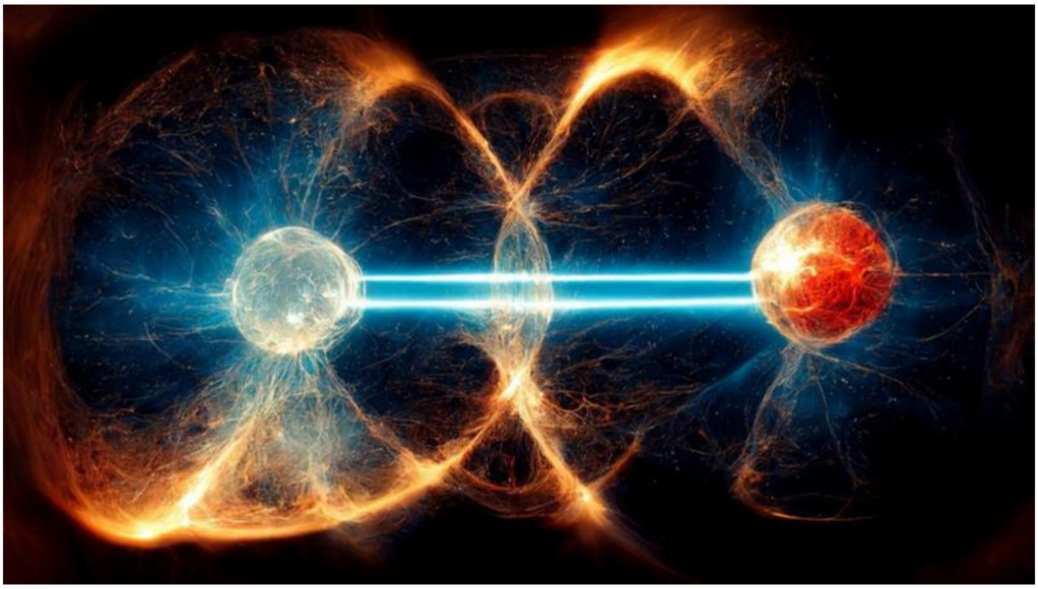


Figure 3.1: Nuclear fusion [91]

This Chapter provides an overview of the physics and technologies behind nuclear fusion. Nuclear fusion involves the fusion of atomic nuclei to release abundant and clean energy. To achieve controlled fusion reactions, scientists and engineers have developed advanced technologies, such as tokamaks, which use magnetic confinement to control a superheated plasma. These devices require powerful magnets and sophisticated heating systems. Additionally, materials capable of withstanding extreme conditions are crucial. International collaborations, like the ITER project, are pushing the boundaries of fusion research. This technology overview explores the principles of fusion physics and the innovative technologies driving us closer to realizing the incredible potential of fusion energy.

3.1.1 Nuclear fusion

Nuclear fusion is a process in which two atomic nuclei combine to form a heavier nucleus, releasing an enormous amount of energy in the process. It is the fundamental process that powers the sun and other stars, as well as the potential future source of clean, abundant energy here on Earth.

At the heart of nuclear fusion are atoms, which consist of a central nucleus composed of protons and neutrons, surrounded by orbiting electrons. The nucleus carries a positive charge due to the protons, while the electrons carry a negative charge. The number of protons determines the element's identity.

Since protons in the atomic nucleus carry positive charges, they naturally repel each other due to electromagnetic forces [20]. For fusion to occur, the repulsion between protons must be overcome to bring them close enough together. The electromagnetic force is one of the four fundamental forces of nature, also known as fundamental interactions, are the basic interactions that govern the behavior of particles and the interactions between them. These forces are responsible for all physical phenomena we observe in the universe. These forces are the gravitational force, the weak nuclear force, the strong nuclear force, and the electromagnetic force. The gravitational force is the weakest of the four fundamental forces but operates on a large scale, governing the interactions between massive objects. It is responsible for the attraction between objects with mass. Every object with mass exerts a gravitational force on other objects, pulling them toward each other. It is described by the formula: $F = G \times \frac{m_1 \times m_2}{r^2}$. The weak nuclear force is responsible for certain types of radioactive decay and plays a crucial role in nuclear reactions. It is much stronger than gravity but weaker than the electromagnetic force. The weak force is responsible for processes such as beta decay, where a neutron in an atomic nucleus transforms into a proton, releasing an electron and an antineutrino. The strong nuclear force is the strongest of the four fundamental forces. It binds protons and neutrons together within atomic nuclei and holds the nucleus together despite the electromagnetic repulsion between protons. The strong force is responsible for the stability of atomic nuclei. It acts over very short distances, within the size of an atomic nucleus. Outside of the nucleus, the strong force is negligible. The electromagnetic force is responsible for the interactions between electrically charged particles. It is much stronger than the gravitational force but still acts over relatively short distances. The electromagnetic force has two aspects: electric forces, which attract or repel charged particles, and magnetic forces, which act on moving charges. This force holds electrons in orbit around atomic nuclei, binds atoms together to form molecules, and governs the behavior of electric and magnetic fields.

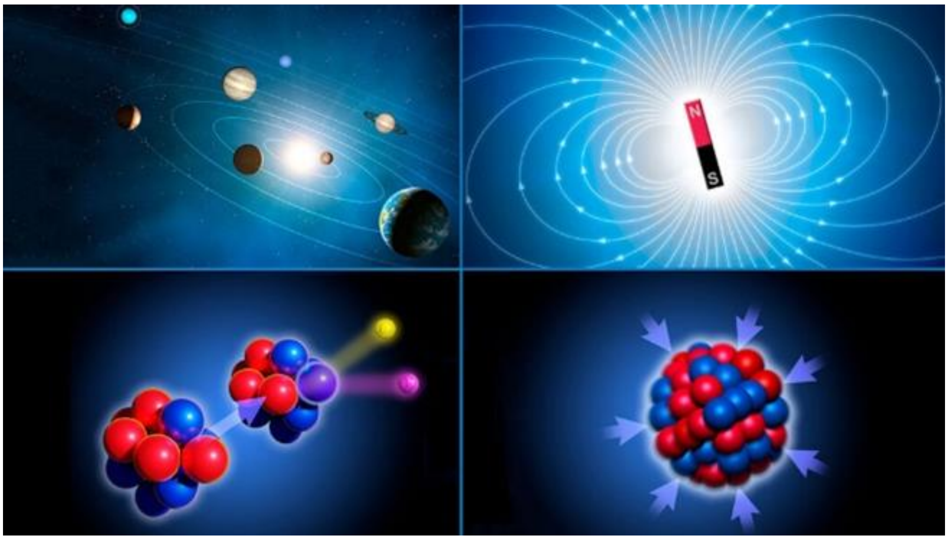


Figure 3.2: Four fundamentals forces of nature [38]

To overcome the repulsion, fusion requires extremely high temperatures and pressures. At high temperatures, the atoms gain enough kinetic energy to overcome the electromagnetic repulsion, and at high pressures, they are squeezed together, reducing the distance between them. Indeed, fusion reaction take places in the sun with very high temperatures and pressure. There are several fusion reactions that can occur, but the most promising one for practical energy production involves isotopes of hydrogen: deuterium (D) and tritium (T).

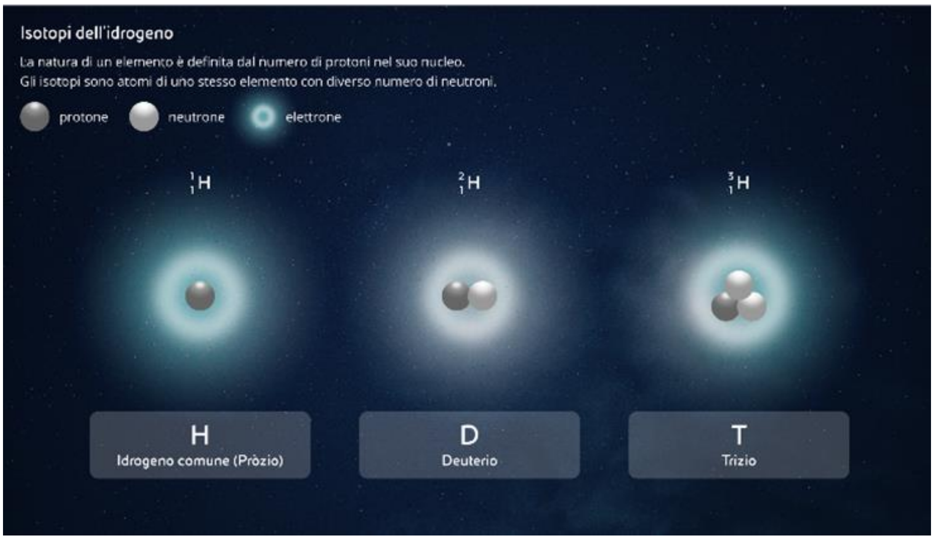


Figure 3.3: Hydrogen isotopes [20]

Deuterium is an isotope of hydrogen, meaning it is a variant of the hydrogen atom with a different number of neutrons in its nucleus. While the most common form of hydrogen, known as protium, has only one proton and no neutrons, deuterium has one proton and one neutron in its nucleus. It is symbolized as "D" or "^{2}H" (denoting its mass number) [21]. Deuterium is relatively rare compared to protium. It is estimated that deuterium makes up about 0.0156% [22] of all naturally occurring hydrogen atoms on Earth. It occurs naturally in small amounts in water molecules, where it is known as "heavy water" due to its higher mass compared to regular water.

Tritium is even rarer and heavier than deuterium. It has one proton and two neutrons. It is symbolized as "T" or "^{3}H". It is β-unstable and is consequently not present in large quantities on Earth. The radioactivity of tritium obviously creates practical problems for its manipulation. It is not found naturally in significant quantities on Earth but is produced through various artificial processes. Tritium can be generated in nuclear reactors, as a by-product of certain nuclear reactions, or through the bombardment of lithium-6 with neutrons. It is also produced in small amounts by cosmic rays in the upper atmosphere.

In the D-T fusion process, a deuterium and a tritium nucleus combine to form a helium nucleus (two protons and two neutrons) and release a high-energy neutron. This reaction releases an enormous amount of energy in the form of kinetic energy of the products and radiation. The energy release in nuclear fusion arises from the mass difference between the reactants and the products (helium nucleus and neutron). This difference in mass, according to Einstein's famous equation $E=mc^2$, is converted into energy. The released energy is several million times greater than that obtained from traditional chemical reactions, such as burning fossil fuels.

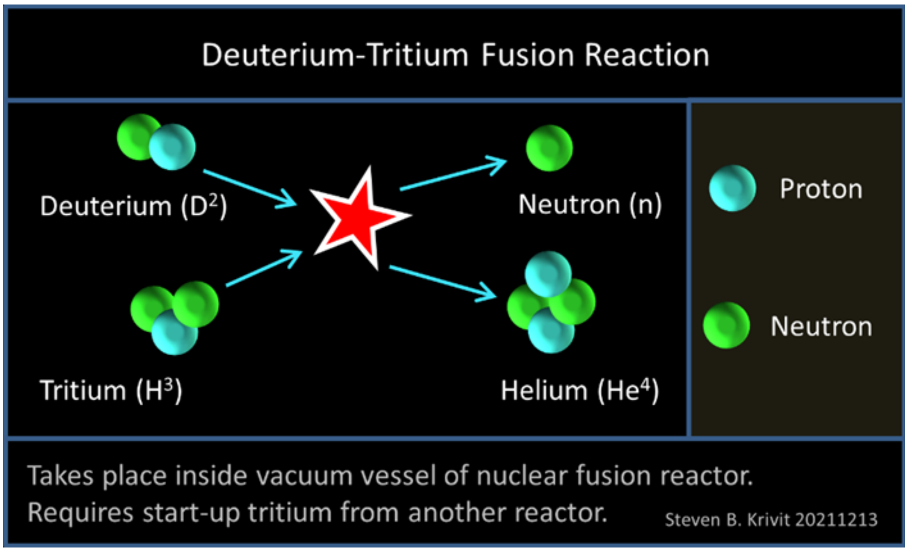


Figure 3.5: D-T fusion reaction [93]

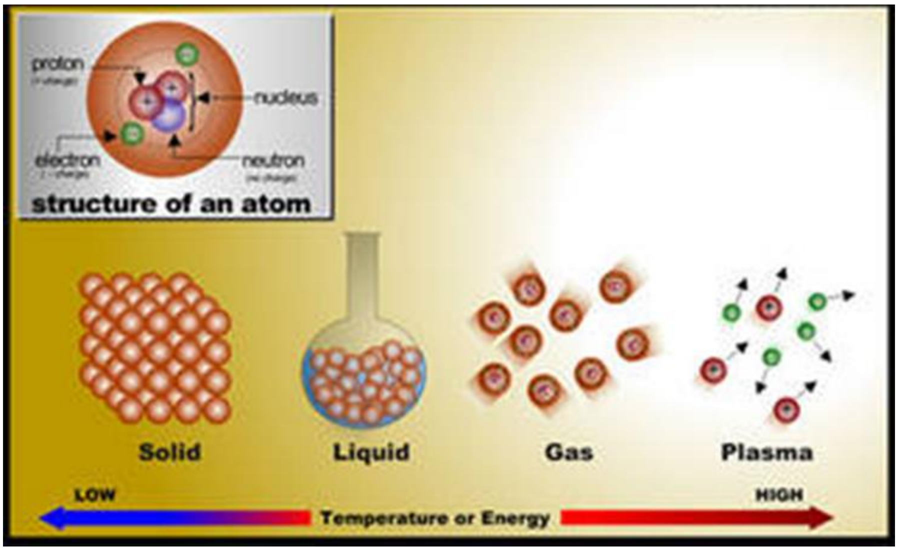


Figure 3.4: Phases of matter [92]

Achieving the necessary high temperatures and pressures for fusion requires the fuel to be in a high-energy state called plasma. Plasma is the fourth state of matter, distinct from solid, liquid, and gas. It is a highly ionized gas that consists of charged particles, such as ions and electrons. Plasma is often referred to as the “ionized gas” or the “fourth state of matter” because of its unique properties. Plasma is formed when enough energy is supplied to a gas to strip electrons from its atoms or molecules, resulting in the formation of positively charged ions and free electrons. The ionization process can occur through various means, such as heating, exposure to strong electromagnetic fields, or exposure to high-energy radiation.

3.2 Fusion technology

To achieve fusion on Earth, the challenge is to confine the hot plasma long enough and provide sufficient heating to maintain the high temperatures needed for sustained fusion reactions. There are different approaches to achieving this, such as magnetic confinement in devices like tokamaks (e.g., ARC, ITER and DEMO2) and stellarators, or inertial confinement using powerful lasers or particle beams. The area of interest of the thesis regards the magnetic confinement of the plasma. Magnetic confinement is a method used to control and confine plasma. It involves the use of strong magnetic fields to contain and stabilize the high-temperature plasma, preventing it from coming into contact with the walls of the containment vessel that would decrease the temperature of the plasma. The goal of magnetic confinement is to maintain the plasma at sufficiently high temperatures and densities for nuclear fusion reactions to occur [23].

3.2.1 Tokamak

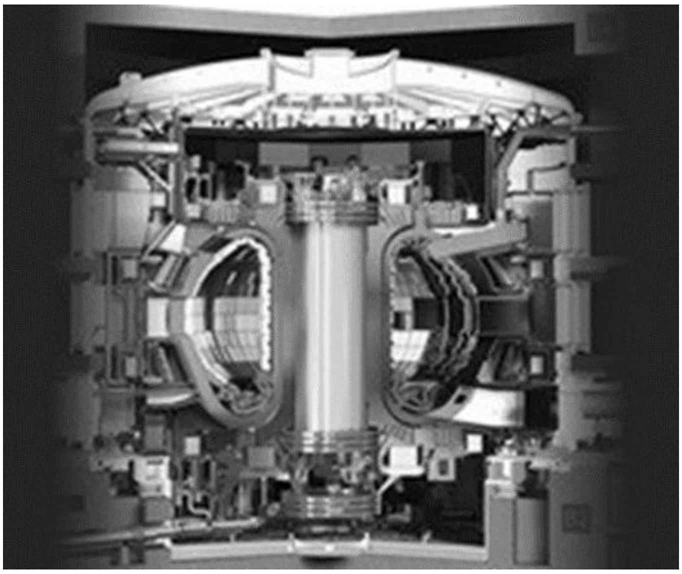


Figure 3.6: Tokamak configuration [23]

The magnetic confinement technology taken as reference in this dissertation is the Tokamak. As stated by the ITER website [23], (2023) "The tokamak is an experimental machine designed to harness the energy of fusion. Inside a tokamak, the energy produced through the fusion of atoms is absorbed as heat in the walls of the vessel. Just like a conventional power plant, a fusion power plant will use this heat to produce steam and then electricity by way of turbines and generators”.

It consists of a toroidal (doughnut-shaped) vacuum chamber surrounded by powerful magnetic coils. The magnetic field is primarily generated by a set of toroidal and poloidal coils, producing a magnetic configuration known as a toroidal field and a poloidal field, respectively. The toroidal field is created by passing a strong current through the coils, which generates a magnetic field that encircles the torus. This field provides a confining force, preventing the plasma from expanding radially outwards. The poloidal field is created by a combination of external coils and the plasma current itself. This field creates a series of nested magnetic surfaces called magnetic flux surfaces or magnetic field lines, along which the plasma particles follow helical paths. The combination of the toroidal and poloidal fields creates a helical magnetic field that confines the plasma within the torus. The plasma particles move freely along the magnetic field lines, circulating around the torus without touching the walls of the chamber.

3.2.2 Magnets

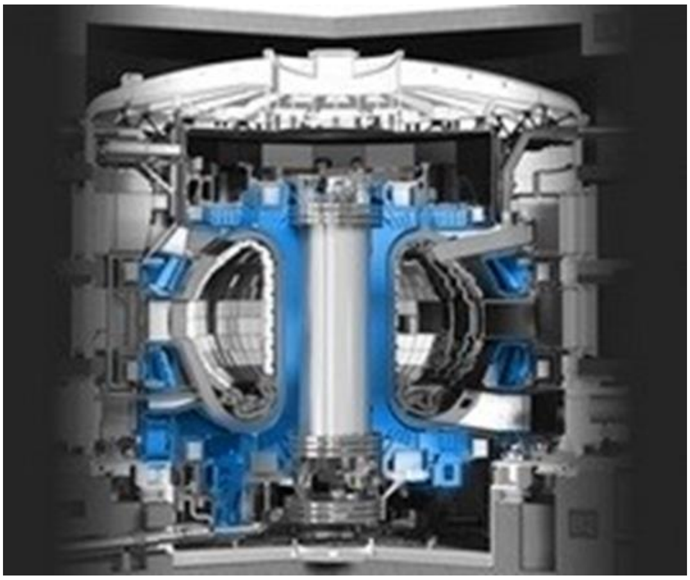


Figure 3.7: Magnets configuration [23]

It is understandable that the most important components are the magnets. There are two principal types of magnets: REBCO (i.e., high temperature superconductor (HTS)) and Nb3Sn (i.e., low temperature superconductor (LTS)). The main difference of these two superconductors is in the temperature needed by them in order to maintain the magnetic field strong enough to have not electromagnetic losses during their operations. Indeed, the Nb3Sn superconductor need a temperature of about 4K (-269 degree Celsius), instead the REBCO need a temperature of about 93K (-180 degree Celsius) [24].

3.2.3 Vacuum vessel

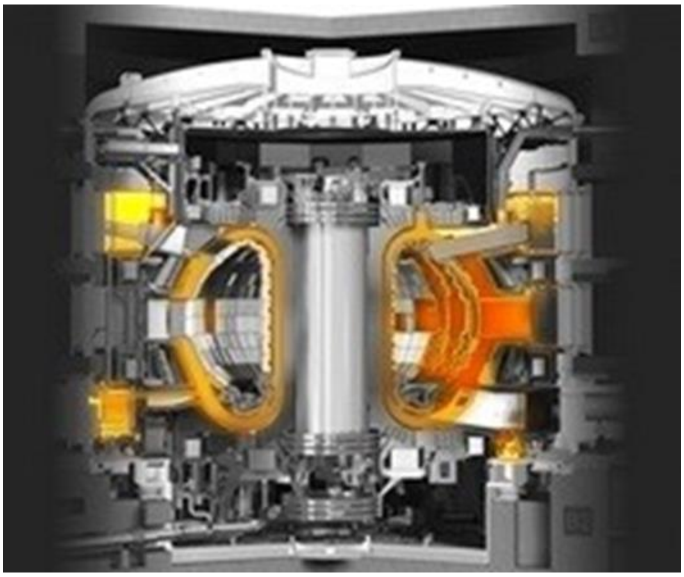


Figure 3.8: Vacuum vessel configuration [23]

The vacuum vessel is a crucial component of a tokamak, serving as the primary containment structure for the plasma and surrounding the fusion reaction. It provides a high vacuum environment necessary for the successful operation of the tokamak. The vacuum vessel's main purpose is to create a low-pressure environment by removing air and other gases from the containment area. This vacuum is essential to prevent the plasma from coming into contact with particles or impurities that could disrupt the fusion reactions or damage the plasma-facing components. It is designed to withstand the mechanical forces and thermal loads imposed by the plasma and associated equipment. It must maintain its structural integrity under the high-pressure differentials, electromagnetic forces, and intense heat generated during plasma operation. The VV is typically constructed using materials that can withstand the extreme conditions inside the tokamak. These materials should have excellent resistance to heat, high vacuum, and potential exposure to radiation. It incorporates various ports and access points for diagnostic tools, heating systems, fueling mechanisms, and other devices. These ports allow researchers to monitor the plasma, introduce auxiliary heating methods, inject fuel, and perform maintenance tasks without compromising the vacuum environment. The inner surfaces of the vacuum vessel, known as the plasma-facing components, are subject to intense heat, high-energy particle bombardment, and radiation. To protect the vacuum vessel and ensure long-term operation, these surfaces often employ additional layers or specialized materials that can withstand the harsh plasma environment. Tungsten, Inconel 718 or other refractory metals are commonly used for the plasma-facing components due to their high melting points and resistance to erosion.

3.2.4 Blanket

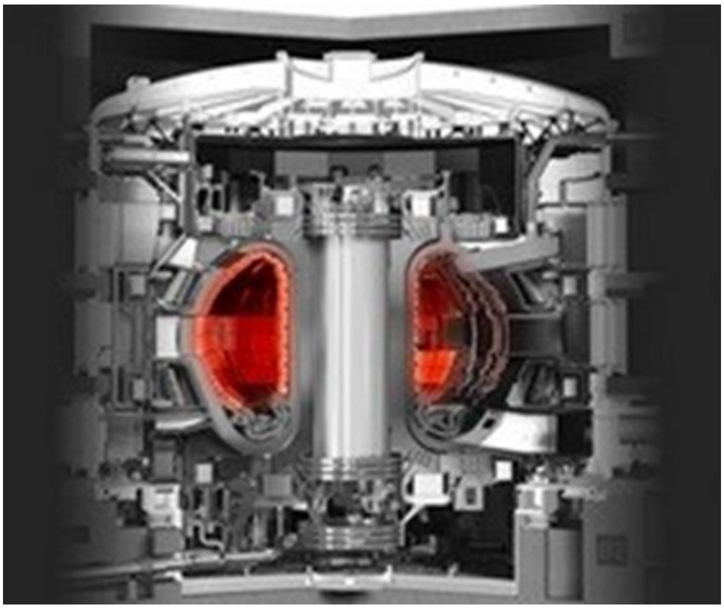


Figure 3.9: Blanket configuration [23]

In a tokamak, the blanket refers to a region surrounding the plasma where a specialized material structure is placed. The primary purpose of the blanket is to extract heat from the plasma and convert it into usable thermal energy. The blanket is responsible for extracting the immense heat generated by the fusion reactions occurring within the plasma. The energy released during fusion is carried by high-energy neutrons produced in the plasma. These neutrons transfer their energy to the blanket material as they collide with its atoms. The blanket material must have several essential properties to effectively handle the high heat and neutron fluxes. Some of the desirable characteristics include high melting point, good thermal conductivity, high resistance to radiation damage, low neutron absorption, and efficient heat transfer capabilities. The material utilized in the reference design of the thesis is the FLiBe. It is a molten salt made from a mixture of lithium fluoride and beryllium fluoride. This material is fundamental for cooling and for production of tritium. Indeed, as said before, tritium is extremely rare on heart, and it means that must be recovered after using it. This process is called tritium breeding, and it happens thanks to the FLiBe. The high energy neutrons can interact whit the lithium and produce tritium through a process called neutron breeding, the tritium is then captured and recycled to fuel future fusion reactions. If the neutrons hit the Beryllium, this reaction generates two further neutrons with lower energy that can hit the lithium in turn. The FLiBe acts as a shield for the other components, indeed, if neutrons do not hit the Blanket but the Vacuum Vessel, they will damage the crystal lattice of the metal, causing radioactivity. Anything that is not protected by FLiBe must be replaced.

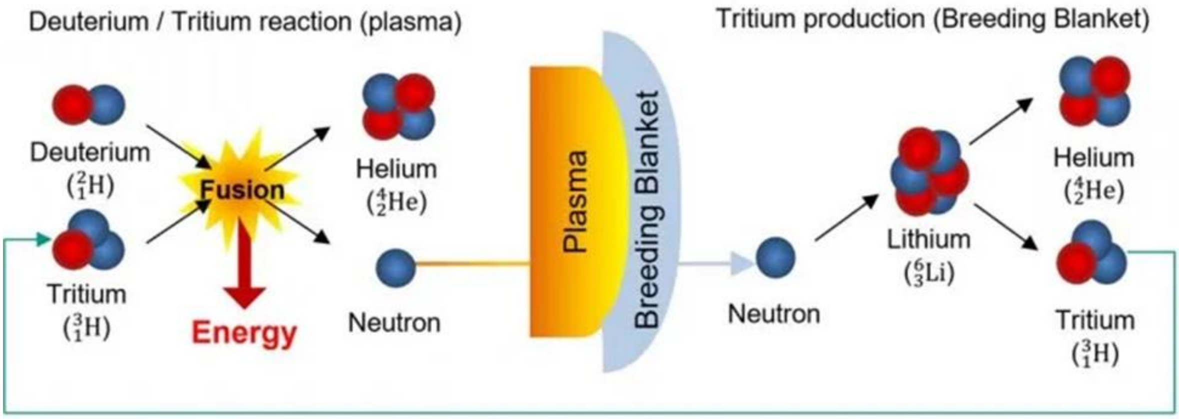


Figure 3.10: Tritium breeding process [93]

3.2.5 Divertor

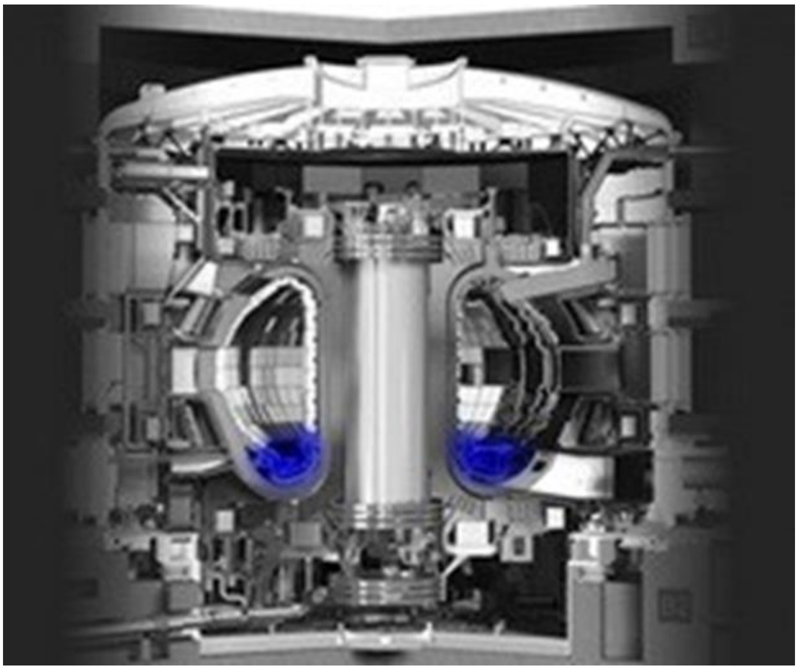


Figure 3.11: Divertor configuration [23]

The divertor is an essential component that helps manage and control the plasma during operation. It is designed to handle the high heat and particle fluxes generated by the fusion reactions and to protect the vessel walls from damage. The primary function of the divertor is to extract and remove the impurities and exhaust the heated particles from the plasma. It accomplishes this by providing a specialized region where the plasma particles, including the fusion reaction by-products and impurities, can be safely directed and processed. The divertor is typically situated at the bottom of the tokamak. The divertor region is strategically positioned to capture particles and heat that would otherwise impact the vessel walls. The divertor features a specific geometry that allows for efficient particle and heat extraction. It consists of a series of specially shaped plates or components, often made of a high-temperature-resistant material like tungsten, that form a structure known as the divertor target. These plates are designed to withstand the intense heat and particle fluxes experienced in the divertor region. The divertor targets are typically cooled by a flow of coolant, such as water, to absorb the heat energy carried by the plasma particles. This cooling helps protect the divertor plates from damage due to excessive temperatures. The extracted particles, including helium ash and impurities, are removed from the divertor region using pumps or other exhaust systems to maintain the desired plasma conditions.

3.2.6 Cryostat

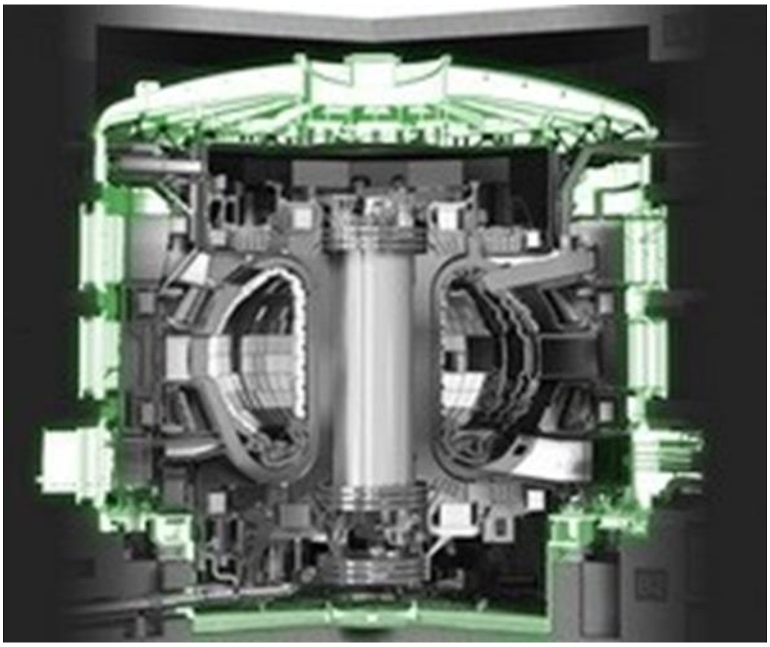


Figure 3.12: Cryostat configuration [23]

The cryostat serves as a specialized enclosure that houses and maintains the low-temperature environment required for the operation of superconducting magnets. It surrounds the vacuum vessel and provides insulation and cooling to keep the magnets at cryogenic temperatures. The primary purpose of the cryostat is to create a low-temperature environment to support the operation of the superconducting magnets used in a tokamak. As said before, superconducting magnets require extremely low temperatures to achieve and maintain the superconducting state, where they can carry large electrical currents without resistance or energy loss. The cryostat is designed with high-quality thermal insulation to minimize heat transfer from the external environment into the superconducting magnets. This insulation helps maintain the low temperature necessary for the magnets' superconducting properties. The cryostat is often made of multiple layers, including materials like vacuum panels, multilayer insulation, or other low-heat-conducting materials. It incorporates a cooling system to remove heat and maintain the low temperatures. This cooling system typically utilizes cryogenic fluids, such as liquid helium or liquid nitrogen, which have low boiling points and excellent heat transfer properties. The cryogenic fluids circulate through channels or pipes within the cryostat to cool the magnets and maintain their temperature. Furthermore, it provides structural support and rigidity to the tokamak system. It houses the vacuum vessel, superconducting magnets, and associated components, ensuring their proper alignment and stability during operation. The cryostat's design considers the mechanical forces and thermal expansions that occur during operation to maintain the structural integrity of the tokamak. It incorporates safety measures to handle and contain cryogenic fluids safely. These measures include appropriate sealing systems, pressure relief devices, and emergency systems to prevent the release of cryogens into the environment and ensure the protection of personnel and equipment. Finally, the cryostat is designed to provide access to the internal components, such as the superconducting magnets, for maintenance, inspection, and repairs. It includes access ports and interfaces to allow for the installation and removal of magnets and other equipment.

3.2.7 Auxiliaries

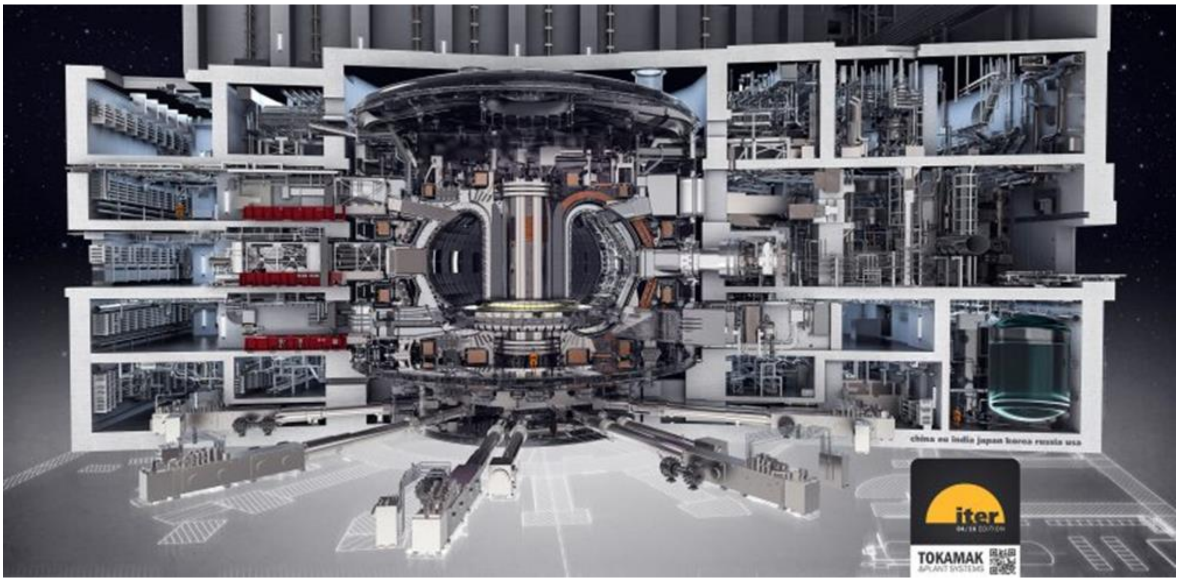


Figure 3.13: Auxiliary system [23]

A tokamak, as a complex fusion device, requires several supporting auxiliary systems to ensure its proper operation, safety, and control. These auxiliary systems provide various functions necessary for plasma production, heating, diagnostics, fueling, and overall operation.

Tokamaks require different *power supply systems* to operate various components. These power supplies deliver the required currents to generate the magnetic fields for plasma confinement and for the cooling water system and cryogenic systems. The plant needs an electrical substation to provide the needed electricity.

Additional *heating systems* are employed to increase the plasma temperature and initiate fusion reactions. Common heating methods include neutral beam injection

(NBI), radio frequency (RF) heating, and electron cyclotron resonance heating (ECRH). These systems provide the energy required to raise the plasma temperature at 150 million degrees Celsius and sustain the fusion reactions.

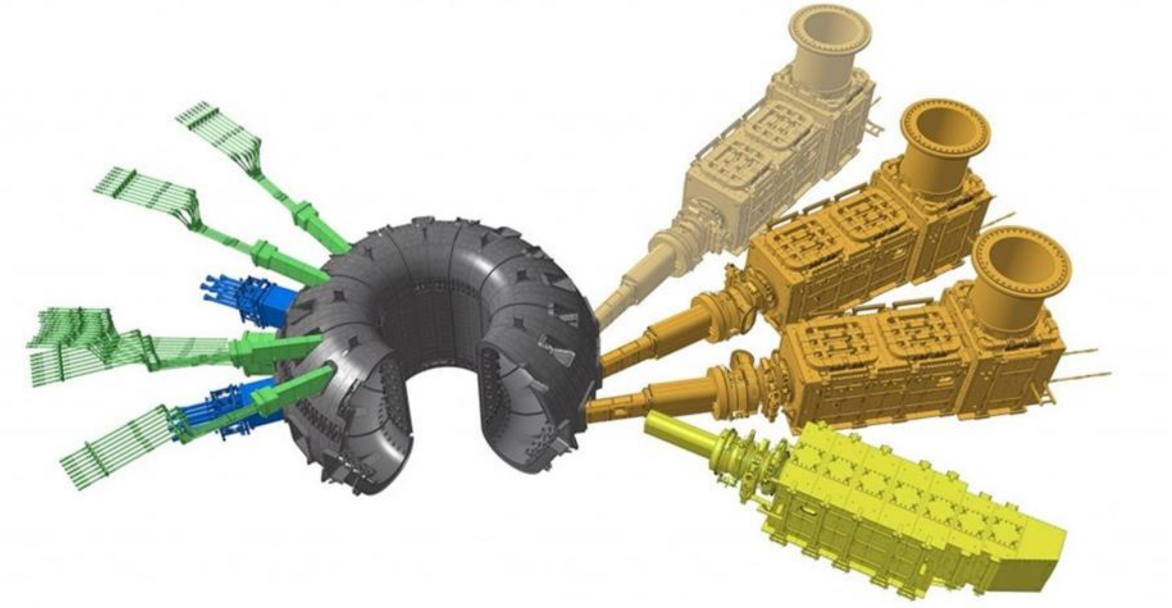


Figure 3.14: Heating systems [23]

Specifically, Neutral beam injection (NBI) involves the injection of high-energy neutral particles into the plasma to increase its temperature and modify its behavior. The neutral beam injection system begins with the acceleration of particles, typically deuterium or hydrogen, to high energies. This is achieved using a particle accelerator, it imparts high kinetic energy to the ions, giving them high velocities. Once the ions are accelerated, they enter a region known as the ionization chamber. In the ionization chamber, the high-energy ions pass through a gas where they collide with the gas atoms. These collisions strip electrons from the gas atoms, converting the accelerated ions into high-energy neutral particles. The high-energy neutral particles are then extracted from the ionization chamber using a series of electrodes or grids. These grids selectively extract the neutral particles while preventing the charged particles from passing through. The extracted particles are now in a neutral state, carrying no electric charge. The extracted neutral particles are focused into a beam using magnetic fields. Magnetic lenses or grids guide and shape the neutral particle beam, ensuring its proper direction and control. The beam is then directed towards the tokamak plasma for injection. The neutral particle beam penetrates the edge of the plasma, where collisions occur between the high-energy neutral particles and the plasma particles. These collisions transfer energy from the neutral particles to the plasma particles, increasing their temperature. This heating mechanism helps raise the plasma temperature, enabling the fusion reactions to occur and sustaining the plasma confinement.

Radio frequency (RF) heating is a technique used to heat the plasma by transferring energy through electromagnetic waves at radio frequencies, much in the same way that a microwave oven transfers heat to food through microwaves. RF heating can provide controlled and localized heating to raise the plasma temperature and enable efficient fusion reactions. RF heating systems typically involve the generation of high-power radio frequency waves. The RF power is generated by specialized RF. The generated RF power is transmitted to the tokamak plasma through antennas strategically positioned in the vacuum vessel. These antennas create an electromagnetic field that propagates through the plasma. Once inside the plasma, the RF waves interact with the plasma particles, primarily electrons. As the RF waves interact with the plasma particles, their energy is absorbed by the particles through resonant absorption or other mechanisms. The absorbed energy increases the kinetic energy and temperature of the particles, thereby heating the plasma.

Eventually, Electron cyclotron resonance heating (ECRH) utilizes the interaction between high-frequency electromagnetic waves and the plasma electrons. By applying electromagnetic waves at the electron cyclotron frequency, ECRH can efficiently transfer energy to the plasma electrons, thereby increasing the plasma temperature. Electron cyclotron resonance refers to the phenomenon where electrons in a magnetic field absorb energy from electromagnetic waves whose frequency matches the electron cyclotron frequency. The electron cyclotron frequency is determined by the strength of the magnetic field and the mass of the electron. ECRH involves generating high-power electromagnetic waves at the frequency corresponding to the electron cyclotron resonance. Then the transmission and propagation mechanisms are the same as the Radio Frequency heating technique mentioned above.

A tokamak operates in a high-vacuum environment to prevent plasma contamination and maintain the desired conditions for fusion reactions. *Vacuum systems* include pumps and pressure control devices to establish and maintain the necessary low-pressure environment inside the vacuum vessel and cryostat.

Diagnostic systems are essential for measuring and monitoring various plasma parameters and properties. These systems provide real-time data on plasma temperature, density, magnetic field, particle flux, impurities, and other crucial information. Diagnostics help researchers understand the plasma behavior, optimize fusion conditions, and assess the overall performance of the tokamak.

Tritium handling systems include processes for tritium fuel production, storage, extraction, purification, and recycling. These systems ensure the safe and efficient handling of tritium, preventing its release into the environment.

Tokamaks require mechanisms to introduce fuel into the plasma. *Fueling systems* include fuel injection methods such as gas puffing, pellet injection, or molecular beam injection. These systems control the density and composition of the plasma by introducing appropriate isotopes, such as deuterium and tritium, into the plasma chamber.

Cryogenic systems provide cooling through the circulation of cryogenic fluids, such as liquid helium or liquid nitrogen, to maintain the superconducting state of the magnets and ensure their proper functioning.

The remote handling system in a tokamak is an integral part of the facility that is designed to handle and manipulate components and equipment in areas where direct human access is limited or impossible due to hazardous conditions, such as intense radiation, high temperatures, or the presence of toxic materials. It enables maintenance, inspection, repair, and replacement of components within the tokamak without exposing personnel to these hazardous environments.

Safety and control systems are crucial for maintaining the safe operation of the tokamak. These systems include interlocks, alarms, and safety protocols to protect personnel, equipment, and the environment. They ensure the control and monitoring of various parameters, including temperature, pressure, magnetic fields, and radiation levels, to prevent any hazardous situations.

3.3 Functioning

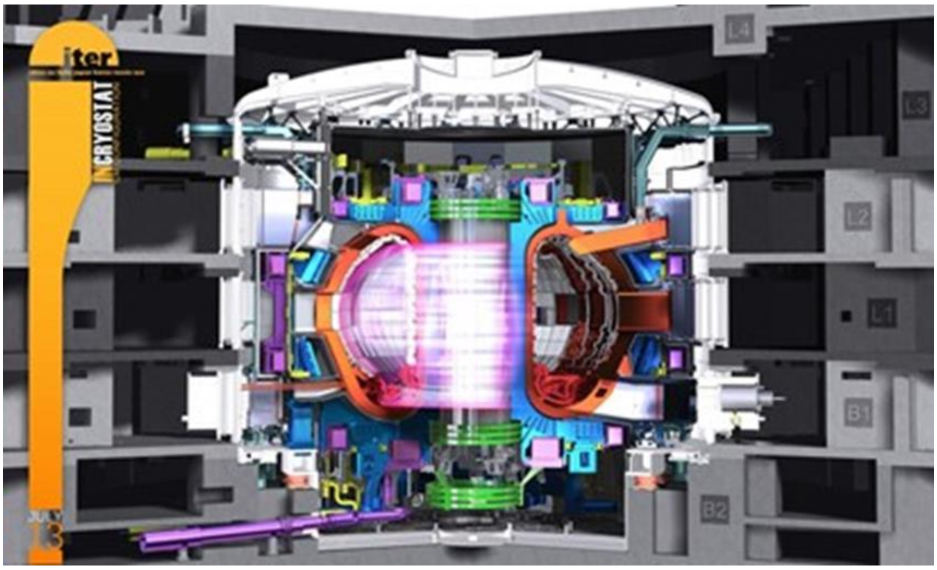


Figure 3.15: Working tokamak [23]

The functioning of a tokamak, from switch-on to the generation of electricity, involves a series of carefully orchestrated steps:

- The tokamak is prepared by ensuring that all necessary components and systems are operational and in a safe state;
- The vacuum vessel is evacuated to create a low-pressure environment, removing any impurities or gases that could interfere with the plasma;
- The magnetic field coils are cooled down to very low temperatures (e.g. in ARC 93K), it requires a lot of time (from one week to one month) but not a great amount of energy. Then they are energized to create a strong magnetic field within the tokamak;
- The molten salts of the blanket are warmed up to melt them so that they can be useful for heat exchangers;
- Deuterium and tritium gases are introduced into the vacuum vessel;
- Heating systems are employed to raise the temperature of the gases and form a plasma. The heating systems gradually increase the plasma temperature to several million degrees Celsius, initiating fusion reactions;
- The magnetic field generated by the tokamak's coils confine the plasma, preventing it from contacting the vessel walls;

- Control systems monitor and adjust the magnetic field and heating systems to maintain stable plasma conditions;
- Diagnostic instruments measure various plasma parameters, such as temperature, density, and plasma shape, providing real-time feedback for control and optimization;
- Within the hot plasma, deuterium and tritium nuclei collide and undergo fusion reactions, producing helium nuclei and releasing a large amount of energy;
- The energy released from fusion reactions primarily appears as high-energy neutrons, which carry the majority of the energy and interact with the surrounding materials;
- To extract energy from the fusion reactions, the high-energy neutrons transfer their energy to the surrounding structures, including the blanket and coolant. The blanket consists of materials that capture the energy from the neutrons but also of lithium to allow the tritium breeding. The high energy neutrons pass through the magnetic field as they are particles without any charge and pass through the metal structure of the vessel even because they are not attracted by the crystal reticulum, so they hit the metal only with a certain probability activating the structure that should be then change when the level of radioactivity exceeds the safety one;
- The helium remains within the plasma and it does not cooperate in the fusion reaction so if it exceed certain amounts it tends to switch off the reaction. For this reason, a percentage of helium is extracted through the divertor;
- The burning efficiency of the reaction is not very high (around 5-10%), it means that not every nuclei of Deuterium and Tritium reacts so also these particles flows to the divertor;
- The flux that flows to the divertor must be processed in order to separate the hydrogen from helium to allow the recycling of the hydrogen isotopes;
- The coolant carries the captured heat to a heat exchanger, where it is used to generate steam or drive a turbine;
- The heat extracted from the fusion reactions is used to generate steam, which drives a turbine connected to an electric generator;
- The spinning turbine generates electricity through electromagnetic induction, converting the thermal energy into electrical energy;
- The generated electricity can be integrated into the power grid, providing clean and sustainable energy to meet various energy demands.

3.4 Comparison between DEMO2, ARC and DTT

Figure 3.16: ARC configuration [94]

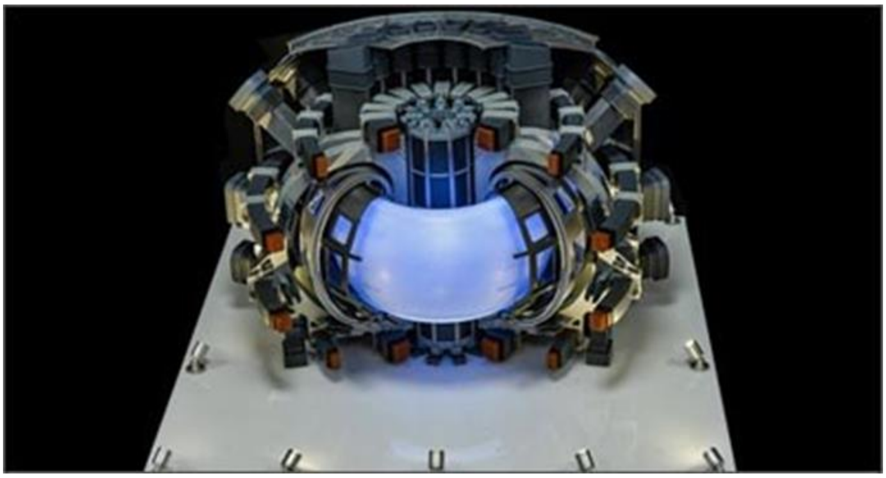


Figure 3.17: DTT configuration [95]

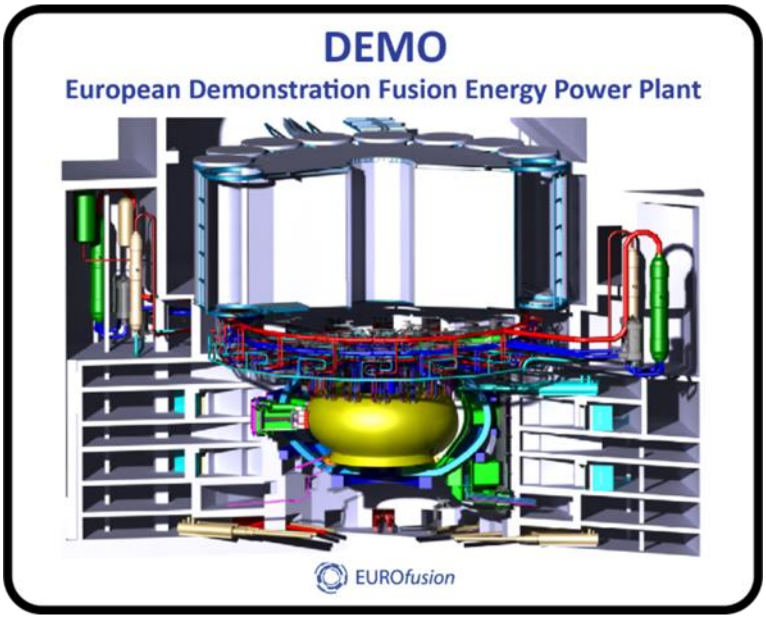


Figure 3.18: DEMO2 configuration [96]

DEMO2, ARC, and DTT are the three reference designs for this dissertation. Although they share the common goal of achieving practical fusion power generation, they differ in their specific approaches and technologies. Starting from the design, DEMO2 is a conceptual design for a fusion reactor that follows the tokamak configuration, similar to existing experimental devices like ITER. It aims to demonstrate the viability of fusion power on a larger scale and is expected to be a steppingstone towards a commercial fusion power plant. ARC (Affordable Robust Compact) is a compact and simplified fusion reactor design that focuses engineering practicality. It employs high-temperature superconducting magnets and leverages advances in materials and manufacturing techniques to reduce the size and complexity of the reactor. Eventually, DTT (Divertor Tokamak Test facility) is a proposed experimental facility that specifically focuses on testing advanced divertor technologies. DTT aims to explore innovative divertor concepts to improve the efficiency and reliability of future fusion reactors. Furthermore, DEMO2 is designed to be a larger-scale fusion reactor, it is envisioned to generate a fusion power of about 3.2 Gigawatts. ARC is a compact fusion reactor concept that aims to have a smaller physical footprint compared to traditional tokamaks. It is designed to produce about 500 megawatts of fusion power. DTT, instead, is primarily an experimental facility and not intended for electricity production. Regarding the utilized magnets, DEMO2 is likely to utilize conventional superconducting magnets (i.e. LTS), such as Nb3Sn, to generate the required magnetic fields for plasma confinement. ARC incorporates high-temperature superconducting (HTS) magnets, which can operate at higher magnetic fields and temperatures compared to conventional magnets. HTS magnets offer increased performance and potentially reduce the size and cost of the reactor. The specific magnet design for DTT would depend on the divertor technologies being tested and may utilize a combination of conventional and HTS magnets. DEMO2 would incorporate advanced materials and plasma-facing components capable of withstanding the harsh fusion environment, including intense heat, radiation, and particle bombardment. Tungsten and other refractory materials may be used for the divertor and plasma-facing surfaces. ARC aims to simplify the reactor design by utilizing innovative materials and engineering techniques. It may explore alternative divertor designs and materials to improve efficiency and reduce the maintenance and operational costs associated with plasma-facing components. DTT's main focus is on divertor technologies. They differ also for the timeline perspective, indeed, DEMO2 is a future concept, with construction and operation anticipated after the completion of ITER. It is expected to bridge the gap between ITER and the first commercial fusion power plant, demonstrating the technological readiness and economic viability of fusion energy. ARC is a mid-term concept, aiming for a more rapid development path compared to DEMO2. It focuses on leveraging existing technologies and advancements to accelerate the timeline for practical fusion power generation. DTT is also a mid-term project that primarily focuses on divertor technologies. It aims to provide essential experimental data and insights to inform the design of future fusion reactors. The timeline perspective will be further analyzed in Chapter 5.

3.5 Lifecycle

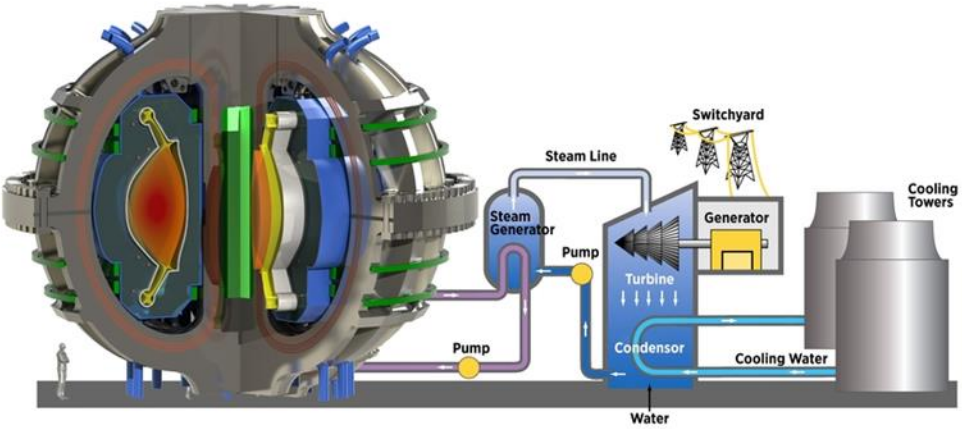


Figure 3.19: Commercial power plant [97]

The lifecycle of a tokamak power plant, exemplified by models such as ARC or DEMO2, represents a meticulously structured sequence of developmental stages encompassing conception, operational implementation, and eventual decommissioning of a fusion-based energy infrastructure. This progression, spanning from inception to culmination, is underpinned by a fusion of scientific acuity, engineering finesse, and unwavering dedication.

Initiating with the embryonic phase of conceptual design, the blueprint for the tokamak power plant is systematically delineated. Scientists and engineers collaboratively engage to ascertain critical parameters, encompassing geometric dimensions, power yield characteristics, plasma confinement configurations, and constituent components. This foundational design framework establishes the theoretical groundwork directing subsequent developmental endeavors.

Subsequent to this, the engineering design phase ensues, facilitating the translation of theoretical constructs into definitive engineering schematics. The intricate intricacies of the tokamak's architectural layout are exhaustively elucidated. Simultaneously, a judicious site selection process unfolds, encompassing multifaceted criteria spanning logistical accessibility, infrastructural prerequisites, environmental impact assessment, and meticulous adherence to rigorous safety standards.

Progressing from design to realization, the construction phase unfolds as a pivotal endeavor. The tokamak power plant materializes as an intricate symphony of engineered components. The vacuum vessel, a critical element housing the plasma, takes shape alongside a precisely orchestrated assembly of magnetic configurations, diagnostic instrumentation, cooling systems, and ancillary equipment. This meticulous assemblage culminates in the establishment of a fully functional fusion apparatus.

The ensuing commissioning phase heralds the operational integration of the constructed apparatus. Comprehensive testing, calibration procedures, and the seamless integration of intricate systems culminate in the attestation of operational readiness. Therein, the initiation of the first plasma eventuates, a definitive marker of achievement materializing within the core of the tokamak.

Advancing to the operational phase, the tokamak transitions into a dynamic fusion reactor. Controlled fusion reactions instigate the generation of thermal energy, a resource adroitly harnessed through conversion mechanisms involving turbines and generators. This energy integration is seamlessly channeled into the power grid, thereby contributing tangibly to societal energy requisites.

Maintenance imperatives and periodic enhancements underscore the maintenance phase to sustain optimal operational efficiency. Routine vigilance ensures operational safety and efficacy. The extended operational lifecycle may warrant strategic component replacements owing to radioactivity-induced degradation, thus ensuring the preservation of safety thresholds and operational benchmarks.

As the operational lifecycle concludes, the decommissioning stage is initiated. This intricate undertaking involves the systematic cessation of fusion activities, the judicious handling of radioactive waste, and comprehensive decontamination protocols aimed at eliminating residual radioactivity.

Culminating the lifecycle, site restoration protocols are executed, meticulously orchestrating the rehabilitation of the physical environment to its original state. Strategies encompassing environmental remediation, structural disassembly, and exhaustive cleanup processes converge to render the site optimally amenable for subsequent applications.

Within this structured expanse, it is imperative to acknowledge the inherent dynamism characterizing each lifecycle phase. This dynamism arises from a synthesis of evolving technologies, regulatory dynamics, and experiential assimilation from prior undertakings. Hence, the lifecycle of a tokamak power plant stands as a testament to the harmonious convergence of scientific exploration, engineering precision, and collaborative persistence, all converging toward the realization of the transformative potential of controlled nuclear fusion as a sustainable and enduring energy paradigm.

4 History of magnetic fusion

4.1 Introduction

The investigation of nuclear fusion, the process that fuels celestial bodies and holds the potential for revolutionary energy production, has unfolded across a captivating historical continuum. This chapter undertakes a meticulous retrospective analysis, elucidating the progression of fusion research from its embryonic inception to its present-day vanguard of scientific and technological exploration. As the intricacies of atomic and subatomic phenomena unfolded over time, so did the intricate ambition of controlled nuclear fusion. This chapter unfurls a chronicle marked by pivotal scientific revelations, innovative experimental apparatus, and paradigm-shifting theoretical constructs, propelling fusion research towards its current state of sophistication. From rudimentary conjectures about stellar energy sources to the erection of epochal international initiatives like the International Thermonuclear Experimental Reactor (ITER), this historical panorama unveils the vicissitudes, accomplishments, and enduring quest to harness the fundamental forces powering our cosmos. In the following pages, the fundamental contributions of luminaries such as Albert Einstein, Arthur Eddington, Hans Bethe, and Francis W. Aston will be shown, who laid the intellectual bedrock for comprehending nuclear fusion and its ramifications for energy generation [25].

4.2 Einstein theory: $E = mc^2$

The equation $E = mc^2$, also known as Einstein's mass-energy equivalence equation, is one of the most famous and fundamental equations in physics. It was formulated by Albert Einstein in 1905 as part of his Special Theory of Relativity. This equation revolutionized the understanding of the relationship between mass and energy and has had profound implications for various fields of science, including nuclear fusion. In 1905, Einstein published a paper titled “Does the Inertia of a Body Depend Upon Its Energy Content?” This paper introduced the concept that mass and energy are interconnected in a profound way. The equation $E = mc^2$ is a simple representation of this relationship, where: E represents energy, m represents mass, and c represents the speed of light in a vacuum. The development of $E = mc^2$ was a result of Einstein's deep insights into the nature of space, time, and energy. It challenged the traditional understanding of mass as an invariant quantity and introduced the concept that mass and energy are interchangeable. Einstein realized that energy and mass are two forms of the same physical quantity and that they are related by a constant (the speed of light) raised to the power of two. The equation was not immediately recognized for its profound implications. $E = mc^2$ plays a critical role in nuclear fusion, particularly in understanding the energy source of stars and the immense power released during fusion reactions. When hydrogen nuclei (protons) fuse to form helium nuclei in the sun and other stars, a small fraction of the initial mass is converted into energy according to Einstein's equation. This energy is radiated as light and heat, powering the star and sustaining life on Earth.

In nuclear fusion on Earth, such as in tokamaks, a similar process occurs. Deuterium and tritium nuclei fuse to form helium nuclei, releasing energy in the form of high-energy particles and radiation. The energy released is a direct result of the mass difference between the reactants and the products, in accordance with $E = mc^2$. In practical terms, $E = mc^2$ provides a way to quantify the amount of energy released during fusion reactions. The equation's application to nuclear fusion calculations helps scientists and engineers understand the energy generation potential of fusion reactions and design more efficient fusion devices.

In summary, $E = mc^2$ is a cornerstone of modern physics, revealing the deep interconnection between mass and energy. Its role in nuclear fusion helps explain the enormous energy release during fusion reactions, whether in the cores of stars or in controlled experiments on Earth [26].

4.3 Russell theory

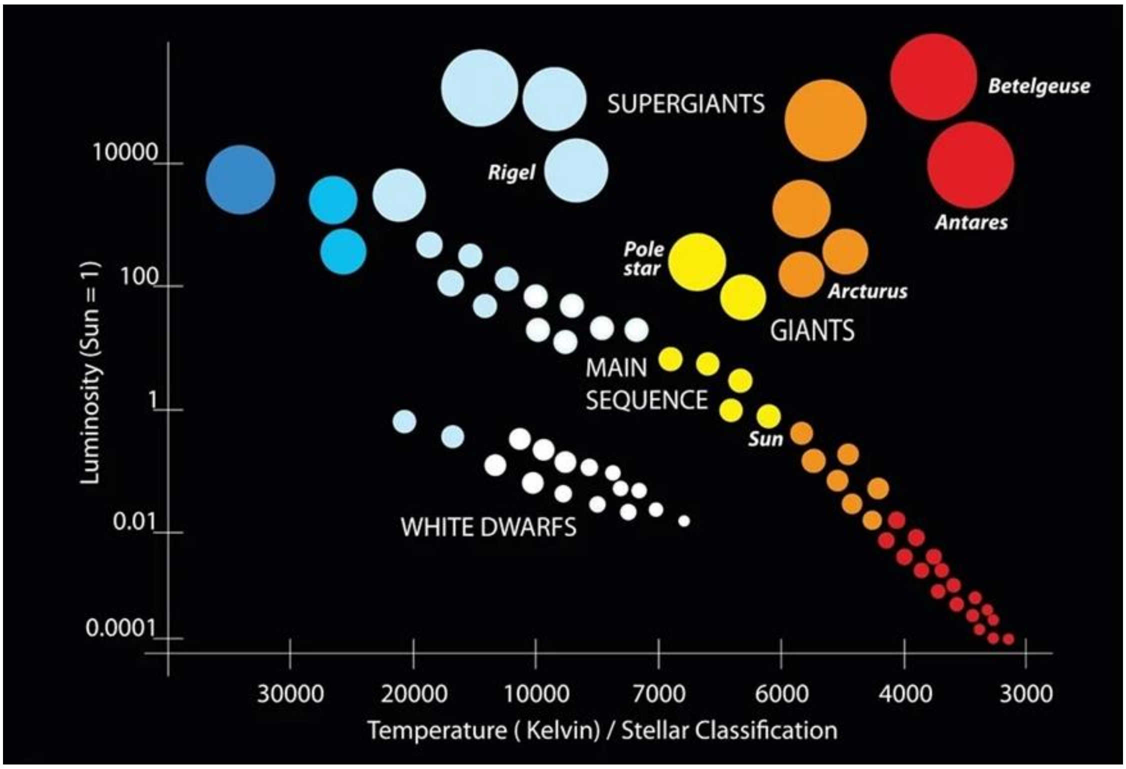


Figure 4.1: Hertzsprung-Russell Diagram [27]

Henry Norris Russell, an American astronomer, played a significant role in shaping the understanding of stellar evolution and the energy source that powers stars. His work laid the foundation for the theory of nuclear fusion as the mechanism behind stellar energy production.

In collaboration with Danish astronomer Ejnar Hertzsprung, Russell was instrumental in developing the Hertzsprung-Russell (H-R) diagram in 1910. This diagram plotted stars' luminosity (energy output) against their temperature or spectral type. The H-R diagram revealed patterns in stellar properties and was a key advancement in understanding stellar evolution. Russell's analysis of the H-R diagram led to the discovery of a relationship between a star's mass and its luminosity. He found that more massive stars were generally brighter than less massive ones. This insight suggested a link between a star's mass and its energy source.

Building on earlier work by Indian physicist Meghnad Saha, Russell proposed a novel hypothesis in 1920: stars derive their energy from nuclear reactions, specifically the fusion of hydrogen nuclei (protons) to form helium nuclei. He suggested that the intense heat and pressure in a star's core facilitate these nuclear reactions, releasing an enormous amount of energy. Russell's hydrogen fusion hypothesis was a groundbreaking idea that challenged the prevailing view of gravitational contraction as the sole energy source for stars. His proposal laid the groundwork for the understanding of nuclear fusion as the primary mechanism driving stellar energy production.

However, it's important to note that Russell's theory was not fully accepted at the time. The detailed mechanisms of nuclear fusion were not yet well understood, and it took several more decades of research and experimentation to confirm the validity of his hypothesis.

Russell's hydrogen fusion hypothesis foreshadowed the discoveries of nuclear fusion reactions within stars, including the sun, where hydrogen nuclei are indeed fused to form helium, releasing energy in the process. This understanding of stellar energy production has played a crucial role in the development of nuclear fusion research on Earth, as scientists seek to replicate the conditions that power stars for practical energy generation [27].

4.4 Aston theory

Francis William Aston, a British chemist and physicist, made significant contributions to the field of mass spectrometry, which played a crucial role in advancing the understanding of atomic and nuclear structure. His work was instrumental in measuring atom masses accurately and laid the foundation for the understanding of isotopes and nuclear reactions, including those involved in nuclear fusion. Isotopes are atoms of the same element with different numbers of neutrons, resulting in varying atomic masses.

Aston's breakthrough came with the development of the mass spectrograph, a device that allowed him to separate and analyze isotopes based on their mass-to-charge ratios. He built the first mass spectrograph in 1919, which allowed him to measure atomic masses more accurately than ever before. Aston's mass spectrograph enabled him to make precise measurements of atomic masses, revealing the existence of isotopes in various elements. He discovered that elements previously thought to have constant atomic masses consisted of mixtures of isotopes with slightly different masses. His measurements provided the first accurate atomic mass values and revealed the complexity of atomic structure.

Aston's mass spectrograph allowed scientists to identify isotopes and understand their contributions to various nuclear processes, such as fusion reactions. This was essential for deciphering the mechanics of nuclear reactions and energy release in stars and experimental fusion devices. Accurate knowledge of atomic masses was essential for calculating the energy released during nuclear fusion reactions. Aston's work contributed to understanding the energy balance in fusion reactions and the conditions required for sustained energy production. His measurements contributed to understanding the stability of atomic nuclei and the pathways by which elements could undergo fusion reactions. Aston's insights into isotopic abundances and atomic masses contributed to the understanding of element formation in stars through nucleosynthesis, shedding light on the processes that create heavier elements from lighter ones.

In summary, Francis W. Aston's work played a fundamental role in advancing nuclear physics and was instrumental in shaping the theoretical and experimental approaches to nuclear fusion [28].

4.5 Eddington theory

At the heart of Eddington's theory was the concept that the primary energy source of stars, including our sun, is nuclear fusion. In the early 20th century, there were competing theories about the energy generation mechanisms of stars, including gravitational contraction and chemical processes. Eddington's work supported the idea that nuclear reactions, particularly hydrogen fusion, were the driving force behind stellar luminosity and longevity.

Eddington's work on the pressure-temperature relationship within stars provided crucial insights into the conditions required for nuclear fusion to occur. He recognized that the high temperatures and pressures at the core of stars were conducive to nuclear reactions, specifically the fusion of hydrogen into helium. This theory also addressed how energy generated through nuclear fusion is transported from the stellar core to the surface, where it is radiated as light and heat. He proposed that energy is transported through a combination of radiation and convection, depending on the temperature and opacity of different layers within a star. Building on the work of Henry Norris Russell, Eddington contributed to the understanding of the mass-luminosity relationship – the connection between a star's mass and its energy output.

Eddington's theories and insights played a crucial role in shaping the development of nuclear fusion research and its history. Eddington's support for nuclear fusion as the energy source of stars helped solidify the understanding of fusion reactions as the primary mechanism driving stellar luminosity and longevity. Eddington's insights into nuclear fusion within stars inspired researchers to explore controlled fusion reactions on Earth. His theories highlighted the immense energy potential of nuclear fusion and its potential for practical energy generation [29].

4.6 Bethe theory

Hans Bethe, a German American physicist, is most renowned for his work on stellar nucleosynthesis, which refers to the processes by which elements are synthesized within stars. In 1938, Bethe proposed the carbon-nitrogen-oxygen (CNO) cycle, a set of nuclear reactions occurring in stars that burn hydrogen to produce helium through a catalytic process involving carbon, nitrogen, and oxygen nuclei. This cycle is an alternate pathway to the more common proton-proton chain reaction that powers stars like our sun. Bethe's work elucidated how nuclear reactions within stars, specifically fusion processes, release enormous amounts of energy. He calculated the energy produced by the CNO cycle and other fusion reactions, showing how this energy is radiated as light and heat, sustaining a star's luminosity and preventing gravitational collapse. These theories also predicted the emission of neutrinos as a byproduct of nuclear fusion in stars. In the 1960s, experiments were conducted to detect these solar neutrinos emitted by the sun.

Hans Bethe's theories and insights had a profound impact on the field of nuclear fusion research and its history, his calculations provided a theoretical basis for understanding the energy generation processes in different types of stars. The work on stellar nucleosynthesis and energy generation inspired researchers to explore controlled nuclear fusion on Earth. His insights into the fundamental processes of nuclear reactions motivated scientists to study fusion as a potential clean and abundant energy source.

In summary, Hans Bethe's theories on stellar nucleosynthesis, energy generation in stars, and neutrino physics played a pivotal role in advancing the understanding of nuclear fusion. His work provided the theoretical foundation for the fusion processes that power stars and opened new avenues of research into controlled fusion for practical energy generation on Earth. Bethe's legacy continues to influence both astrophysics and fusion research, highlighting the interconnectedness of nuclear processes at cosmic and laboratory scales [30].

4.7 Tokamak history

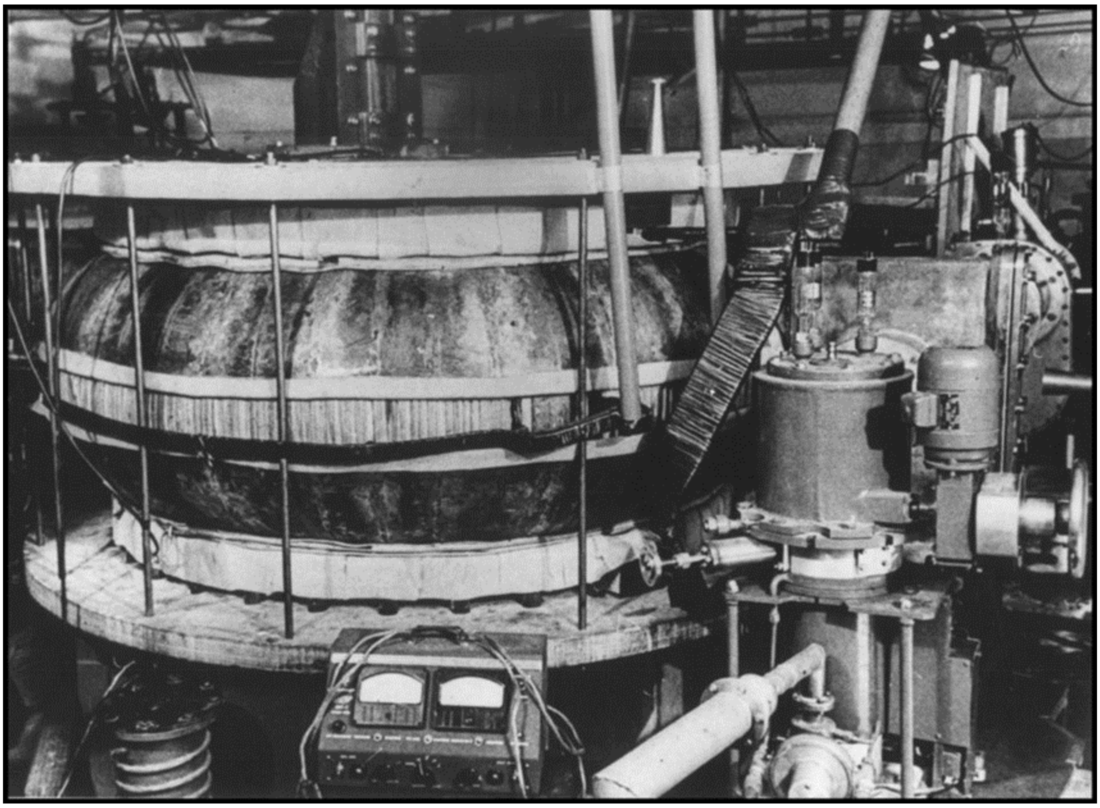


Figure 4.2: Tokamak T-1 [94]

The journey to create the first tokamak, a device that would become central to the quest for controlled nuclear fusion, was a story of innovative ideas, persistent experimentation, and significant scientific advancements. In the early 1950s, as nuclear fusion research gained momentum, physicists began contemplating how to create a stable, high-temperature plasma environment where nuclear reactions could take place. Among them were Soviet physicists Andrei Sakharov and Igor Tamm, who envisioned a revolutionary approach - the tokamak. This device would employ a toroidal, or doughnut-shaped, configuration, combined with a complex system of magnetic fields, to contain and stabilize a super-hot plasma.

The first practical realization of the tokamak concept was the T-1, constructed in 1958 at the Kurchatov Institute in Moscow. Despite its basic design, T-1 demonstrated the potential of the tokamak approach by producing and confining plasma. It was a crucial proof of concept that set the stage for the development of more sophisticated designs.

A pivotal moment arrived with the creation of the T-3 tokamak in 1968, also at the Kurchatov Institute. The T-3 featured improved magnetic field configurations, particularly strong toroidal magnetic fields generated by external coils. The result was a major leap forward, the T-3 achieved the first-ever plasma confinement time exceeding one second. It showcased enhanced plasma stability and energy confinement, which are key factors for achieving sustained fusion reactions.

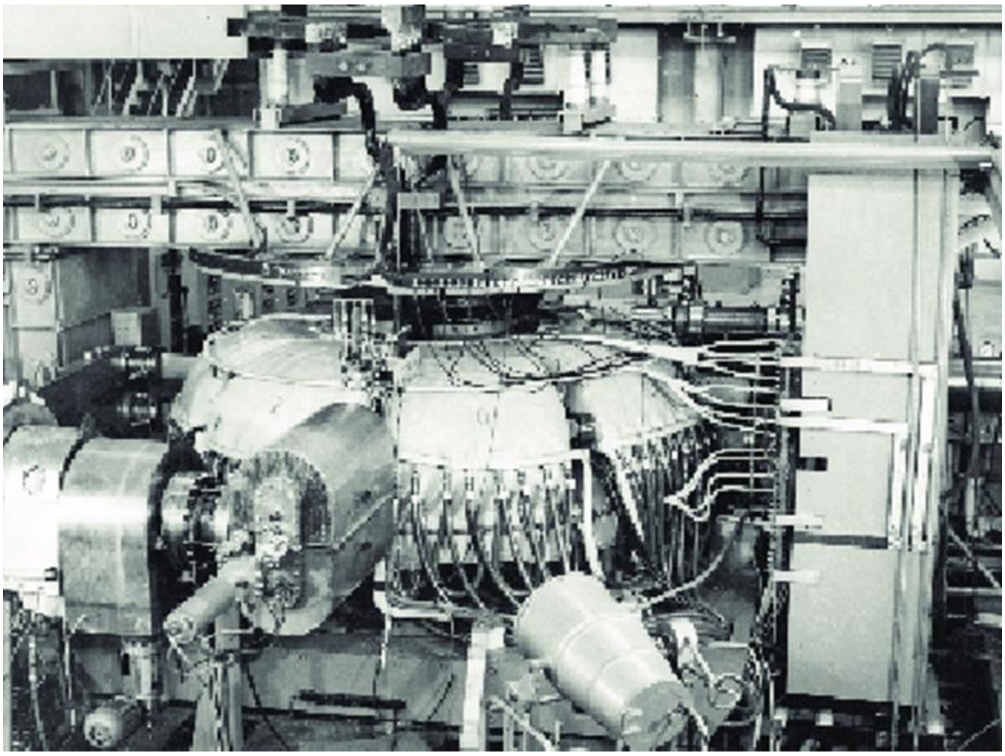


Figure 4.3: Tokamak T-3 [95]

As tokamak research progressed, it attracted international attention. The T-3 experiments, along with advancements in other fusion devices, bolstered the reputation of the tokamak as a leading contender for practical fusion energy production. The international scientific community recognized that the tokamak's unique combination of magnetic fields, plasma shaping, and confinement techniques held promise for achieving the necessary conditions for nuclear fusion. By the mid-1970s, the potential of tokamaks for practical fusion power plants led to discussions about larger and more ambitious devices. The INTOR Workshop (International Tokamak Reactor) in 1975 was a turning point. It was a gathering of global experts to explore the feasibility of tokamak-based fusion reactors for electricity generation. Its outcomes contributed to the design parameters for fusion reactors, emphasized safety, and played a significant role in the development of projects like ITER, which aims to demonstrate controlled nuclear fusion's potential for clean energy [31]. It became evident that a larger tokamak design was required to achieve the energy gain necessary for a sustained fusion reaction, and to truly assess fusion's potential as a reliable energy source.

Building upon these foundational achievements, tokamak research continued to advance. Devices like JET (Joint European Torus) and TFTR (Tokamak Fusion Test Reactor) [32] pushed the boundaries further. They achieved higher plasma temperatures, longer confinement times, and even significant fusion power outputs, laying the groundwork for the construction of ITER. JET is a large tokamak, located in the United Kingdom. In 1997, JET achieved a major milestone by achieving a Q-value of 0.67. This means that, for a brief moment, it produced 67% more energy from fusion reactions than the energy input required to sustain the plasma. It marked a significant step towards the goal of achieving sustained nuclear fusion for clean and abundant energy generation. TFTR was a pioneering fusion research facility in the United States from 1982 to 1997. It played a crucial role in validating the tokamak design for magnetic confinement fusion and achieved notable records in plasma confinement and temperature. TFTR significantly contributed to the understanding of plasma physics and fusion reactions, marking a milestone in the history of fusion research.

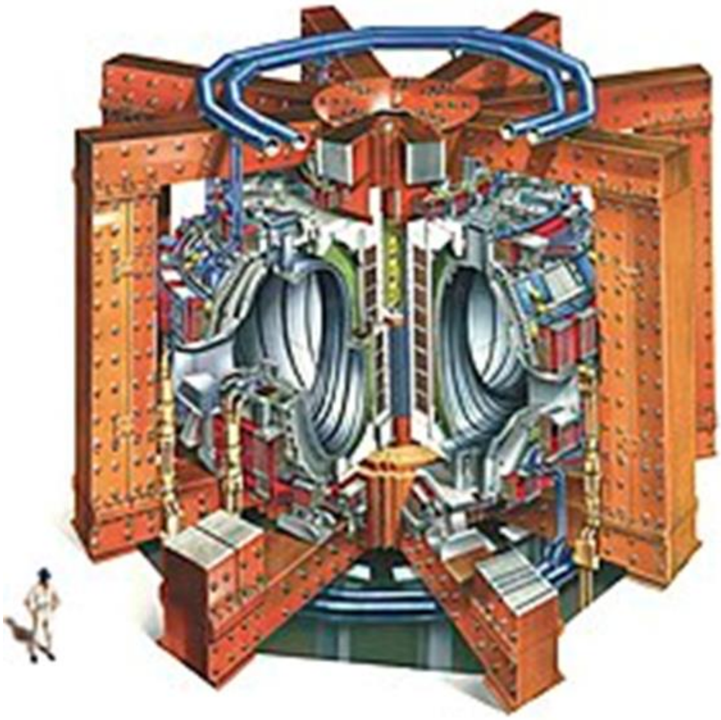


Figure 4.4: Joint European Torus (JET) [96]

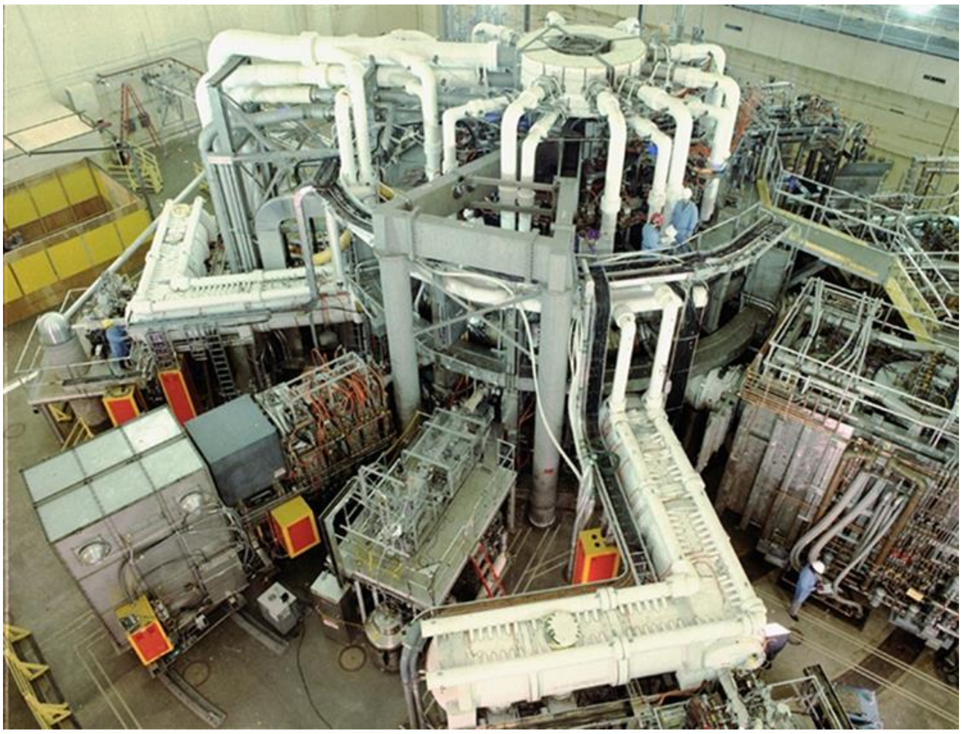


Figure 4.5: Tokamak Fusion Test Reactor [97]

ITER, the International Thermonuclear Experimental Reactor, emerged as the culmination of international collaboration and decades of research. The idea for ITER originated during the Geneva Superpower Summit in November 1985, where the U.S. and Soviet Union jointly proposed a collaborative international project focused on harnessing nuclear fusion for peaceful purposes. This proposal marked a significant shift towards international cooperation in fusion research, laying the foundation for the establishment of the ITER project and ongoing global partnerships in fusion research. ITER embodies the collective efforts of numerous countries to build a tokamak capable of achieving net energy gain - the point where the fusion reactions produce more energy than is input into the system. ITER's construction represents a testament to the enduring pursuit of controlled nuclear fusion, a journey that began with the pioneering ideas of individuals like Sakharov and Tamm and progressed through countless scientific breakthroughs and tireless dedication.

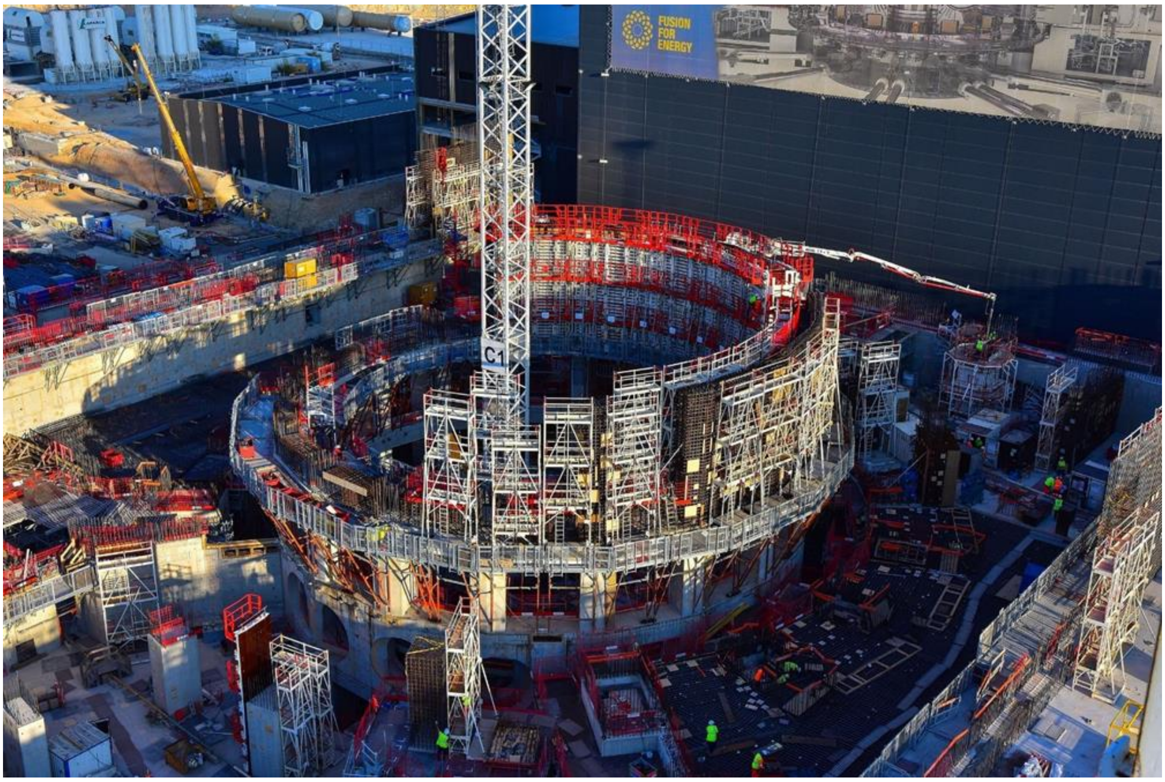


Figure 4.6: ITER [33]

5 Magnetic fusion power plants: state of the art

Since the initial stages of fusion research, significant advancements have been achieved in the science and technology of tokamaks. Periodically, important progress has been made as emerged by the establishment of new records in the triple product (i.e., the three plasma conditions to make fusion occur, that are reaching sufficient temperature, density and time [34]), which serves as the primary measure of plasma performance. Notably, TFTR[2] and JET[3] have further propelled these advancements by setting records in the triple product and D-T (i.e., Deuterium–Tritium) fusion gain [35]. Nonetheless, advancements in this field have largely plateaued since the 1990s. Despite notable advancements in plasma physics and fusion research during this period, the achievements in fusion gains recorded by TFTR and JET have (as well as the D-T equivalent performance record in JT-60U [35]) remained unchanged. To comprehend the reasons behind this slowdown, it is essential to consider the primary factors contributing to the triple product or fusion gain increase. As stated in the ITER Physics Basis [36], [37], the enhancements in fusion performance within ITER can primarily be attained through three main approaches. Firstly, it involves the exploration of novel operational regimes or the development of techniques to overcome existing physical constraints. Secondly, it entails the strengthening of the tokamak's magnetic field. Thirdly, it includes the enlargement of the physical dimensions of the tokamak [35]. In the absence of breakthroughs in new physics, improvements in machine performance must focus on increasing either the magnetic field strength or the machine size. As shown in Figure 5.1, that plot the achievable fusion gain Q against the toroidal field B_0 and major radius R_0, the gain aligns with the attainable fusion gain Q with the plotted Q contours, demonstrating the generality of the relationship between B_0, R_0, and Q and encouraging the pursuit of the highest field possible given technological limitations [35]. The vertical dashed gray line approximates the on-axis field limitation for machines relying on Low-Temperature Superconductors (LTS) [35].

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[2] The Tokamak Fusion Test Reactor (TFTR) operated at the Princeton Plasma Physics Laboratory (PPPL) from 1982 to 1997, setting a number of world records, including a plasma temperature of 510 million °C and achieving all of its hardware design goals, thus making substantial contributions in many areas of fusion technology development .

[3] The Joint European Torus is based at the UKEA (Culham, UK). It conducted the first experiments using tritium and in 1997 it set the world record of achieving Q=0.67

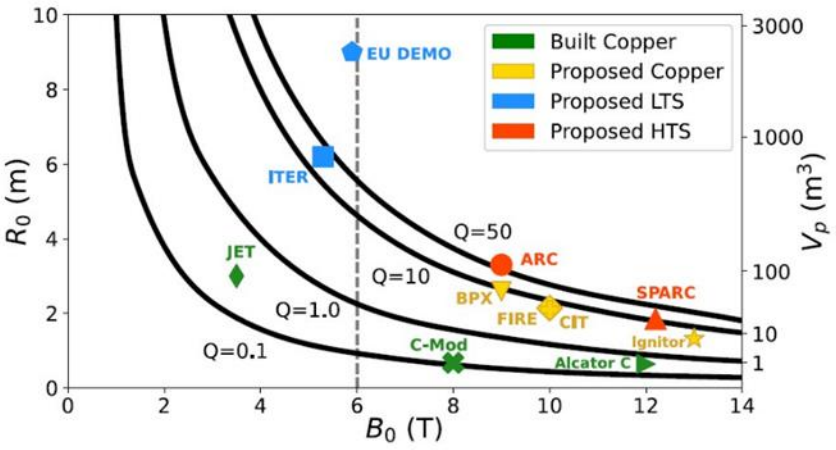


Figure 5.1: Fusion gain Q plotted against Bo and Ro [24]

At the time of ITER’s design, the state of-the-art superconductor was Nb3Sn. This field on coil limited the field on axis to roughly 5 or 6 Tesla (T), and as Figure 5.1 shows, limiting the toroidal field to 5.3 T requires a major radius of approximately 6m to achieve Q ≈ 10. It is noteworthy to acknowledge that plants of such magnitude inevitably entail substantial costs and time requirements [35]. These factors, combined with various political and organizational elements associated with the project's magnitude, have collectively led to the reduced pace of progress in achieving fusion gains over the last two decades [35]. Nevertheless, in recent years, novel high-temperature superconducting (HTS) materials have been discovered as viable alternatives to traditional low-temperature superconductors (LTS). Among these materials, REBCO has been previously recognized for its potential application in fusion magnets [35]. Starting from 2020, REBCO has become more widely available in substantial quantities and exhibits exceptional performance characteristics. This enables the attainment of much higher magnetic fields in comparison to Nb3Sn. This technological advancement opens up new possibilities for optimizing the design of a superconducting tokamak with a Q-factor greater than 1 and paves the way toward the development of a commercially feasible power plant. Although the new design introduces distinct engineering constraints, it remains firmly rooted in the fundamental physics principles utilized by the ITER project. By utilizing high-temperature superconducting (HTS) magnets, a significantly smaller device can be constructed, facilitating the rapid achievement of the Q > 1 goal at a relatively modest cost [35]. Furthermore, this technology holds the potential for the development of an economically attractive power plant which is crucial for the widespread adoption of fusion energy [26] [29] [38].

Nowadays, the plasma physics governing fusion devices is relatively well understood. However, it is important to note that no fusion device has yet demonstrated a gain value (Q) exceeding 1, which constitutes a pivotal milestone on the path to commercializing fusion as a viable energy source. Nevertheless, beyond achieving Q > 1 and establishing a pilot power plant, it is imperative that the progression towards commercial power generation through fusion remains both timely and cost-effective, in order to make magnetic fusion a front-runner in tackling the energy transition.

Indeed, as EUROfusion states [39], the realization of fusion energy must face a number of challenges:

1. Plasma must be confined at temperatures that are 20 times higher than the sun's core. Magnetic confinement configurations have been chosen in accordance with the need to minimize energy losses from turbulence and control plasma instabilities.

2. Heat exhaust: Plasma-facing materials and exhaust systems, deemed suitable for ITER, have already undergone development; nevertheless, their operational aspects require further refinement and validation. Addressing the substantial heat exhaust demands anticipated for DEMO remains a complex challenge, encompassing both experimental and theoretical facets. This necessitates the exploration of advanced plasma-facing components and strategic approaches aimed at distributing thermal power across the widest possible surface area through radiative processes within the main and divertor plasmas. These efforts must be seamlessly integrated with the primary plasma and the broader DEMO design. An assertive initiative is imperative to explore alternative solutions for heat exhaust, with a primary focus on enhancing plasma-facing materials and components, as well as devising novel divertor configurations.

3. Neutron tolerant materials that can resist the flux of neutrons (up to 14 MeV) and maintain adequate structural and physical properties for long periods over a sufficiently wide window of operation are fundamental to be developed for a commercial power plant, in order to ensure efficient electricity production and performing plant availability [40]. The achievement of this object is in the hand of the International Fusion Materials Irradiation Facility (IFMIF), which would provide the ideal fusion neutron source. At the same time, it is imperative that a DEMO Oriented Neutron Source (IFMIF-DONES, Europe) or the Advanced Fusion Neutron Source (A-FNS, Japan) be expeditiously constructed in order to furnish the scientific community with a neutron source possessing a spectrum relevant to fusion for the purpose of materials testing.

4. Tritium self-sufficiency is a key requirement for future commercial fusion power plants. Attaining tritium self-sufficiency necessitates the deployment of highly

efficient breeding and extraction systems aimed at reducing tritium inventory to a minimum. The choice of materials and coolants for the breeding blanket should be in harmony with the components designated for the conversion of high-grade heat into electricity, commonly referred to as the "Balance of Plant." Proper consideration of breeding is integral to the power plant's design and have numerous implications:

- The blanket design must be optimized in order to facilitate breeding and extraction of tritium, as well as fulfilling other functions.
- A strategic planning of the plant layout would be useful to maximize the available area for breeding. Moreover, certain technical aspects of the blanket, particularly the coolant, significantly impact the overall efficiency, plant design layout, integration, maintenance, and safety due to their interactions with key systems.
- The blanket must efficiently handle the dissipation of heat originating from the plasma, thereby averting excessive attenuation or loss of neutrons prior to their interaction with the breeding material.

5. Fusion has intrinsic safety features; any commercial power plant design should prioritize integrating these safety features of fusion into a cohesive architecture to prevent incidents and, in the worst-case scenario, the need for evacuation. To accomplish this, it is necessary to identify the most efficient techniques for disposal and recycling as well as ways to reduce the amount of tritium in the components recovered for disposal.

6. In the context of a commercial power plant, it is imperative to incorporate exceptionally reliable components, an optimized technical framework, a self-sustaining tritium-producing blanket, and a complete Balance of Plant, encompassing both heat transfer and associated electrical generation systems. The attainment of these milestones is instrumental in guaranteeing the requisite levels of reliability and availability, both of which hold paramount importance in shaping the overall cost-effectiveness and attractiveness of the power plant.

7. Achieving a competitive cost of electricity from fusion is fundamental to make fusion power plants play a significant role in the future energy supply. Although this is not the primary goal, target regarding electricity production costs needs to be set.

5.1 DEMO state-of-art

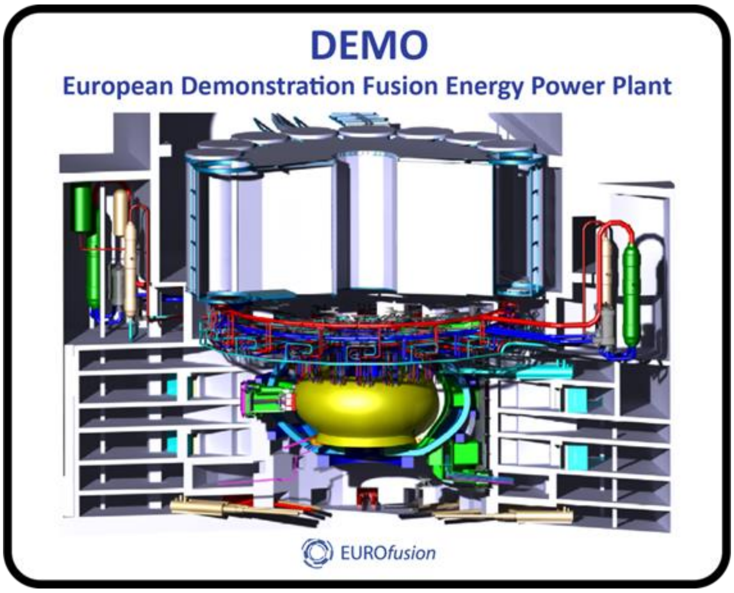


Figure 5.2: DEMO design [30]

DEMO is FOAK plant (i.e. First Of A Kind), that represents the commercialization of the global ITER fusion experiment [41].

As a central element of the Roadmap to Fusion Electricity, Europe is currently undertaking a conceptual design study for a DEMO Plant, anticipated to start operations by the mid-century. As stated by Eurofusion [41] (2022), “the primary objectives of DEMO include the generation of several hundred megawatts (MW) of net electricity, validating the viability of operating with a closed-tritium fuel cycle, and developing maintenance systems that meet the required safety standards”. DEMO design and construction is characterized by a strong correlation with ITER technological development. Indeed, the ITER experiments, scheduled to be conducted from 2025 to 2035 [41], are expected to incrementally furnish evidence of performance and valuable data that will serves as a foundation for the design of the DEMO power plant. As depicted in Figure 5.3, there exists a significant interdependence in terms of scheduling between ITER and DEMO. Of particular note is ITER's pivotal role, slated to commence demonstrating D-T burning plasma scenarios in 2037, serving as the foremost and conclusive validation input for the DEMO project [41].

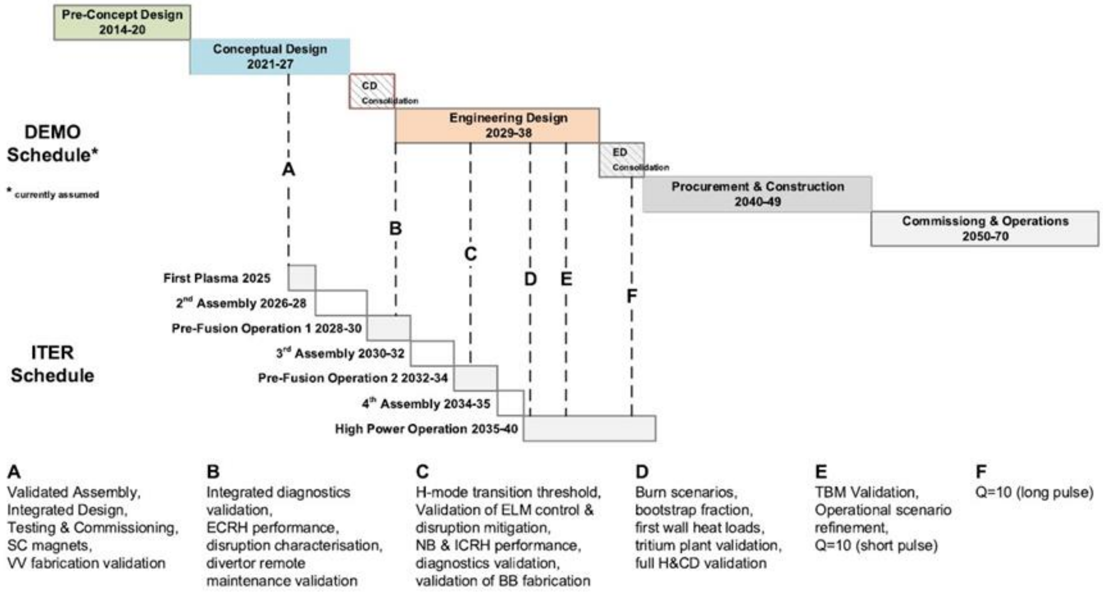


Figure 5.3: ITER schedule compared to DEMO schedule [31]

Nowadays, Europe is a front-runner in fusion research and development and can aim to be a key player in the fusion market. As EUROfusion states in the "European Research Roadmap to the Realisation of Fusion Energy" [41] (2022), to have electricity production from DEMO, in parallel with the construction and exploitation of ITER, there are four goals to achieve:

1. Demonstration of fusion power on a large scale from a technical perspective. ITER aims at achieving a fusion power of 500 MW for 400 seconds, validating that the burning plasma can be created and sustained [41].

2. Electricity supplied to the electrical grid through a DEMOnstration fusion power plant (DEMO), envisaged to commence generation by the year 2050, is expected to yield several hundred megawatts of electrical power for sustained durations, typically spanning multiple hours.

3. In parallel, it is essential to establish a foundation encompassing science, technology, innovation, and industry capabilities. This foundation will facilitate the transition from a demonstration fusion plant to economically viable devices suitable for widespread commercial deployment on a large scale.

4. Construction of fusion plants on large-scale.

The first three of these objectives are addressed in the European fusion roadmap, all in the context of the final goal.

By 2027, this strategy aims to develop initial conceptual designs for a European DEMO. Following the successful achievement of high-performance deuterium-tritium (D-T) operation in ITER and the availability of initial findings from the ITER Test Blanket Modules (TBMs) to validate the design choices, the plan will initiate an engineering design phase with the aim of making a decision on the construction of DEMO within a few years [41]. DEMO will be in operation about 20 years after ITER's demonstration of high-power burning plasmas [41].

The European Commission has updated its Strategic Energy Technology Roadmap, reaffirming the potential of fusion as an energy source by the end of this century and emphasizing the relevance of ITER. The plan focuses on three distinct time periods with separate primary goals.

- First period (<2030): during this period, ITER will start the operations and DEMO will complete the conceptual design(s);
- Second period (2030-2040): this period will focus on the achievement of the burning plasma on ITER and in the engineering design of DEMO;
- Third period (>2040): during the third period, DEMO will be constructed and the ITER’s plasma and technology will be optimized.

The realization of maximum performance in the ITER project, demonstrated by achieving a fusion gain value Q=10, needs concentrated efforts by scientists and engineers throughout the period leading up to the early 2040s [40]. Following this, ITER will fulfill its objectives through the validation of advanced operational regimes and the pursuit of specific technological advancements. These advancements include comprehensive testing of breeding blanket modules, refinement of plasma heating systems, and the advancement of measurement and control techniques [40]. Within the European strategic framework, DEMO assumes a unique role as the sole large-scale tokamak positioned between ITER and the realization of a commercially viable fusion power plant [40].

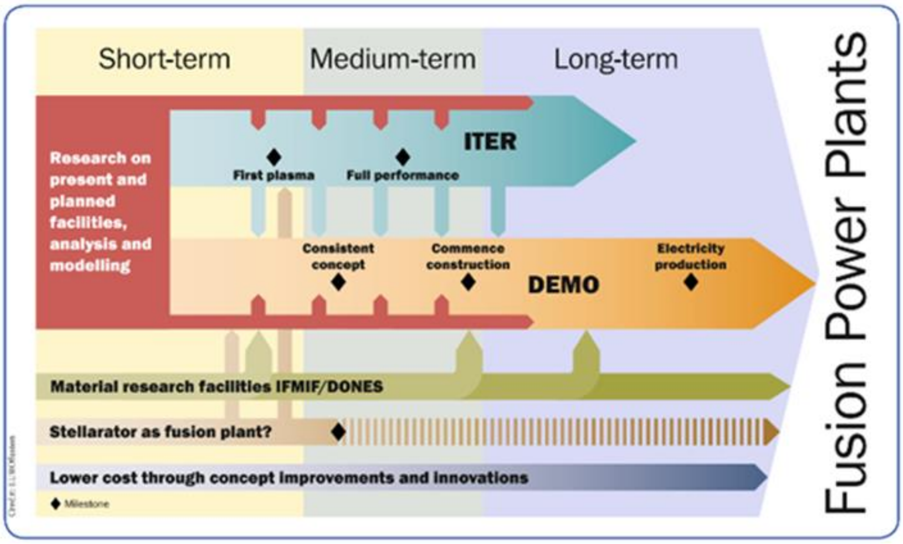


Figure 5.4: The European Roadmap, from ITER to DEMO [29]

5.1.1 DEMO design phases and gates

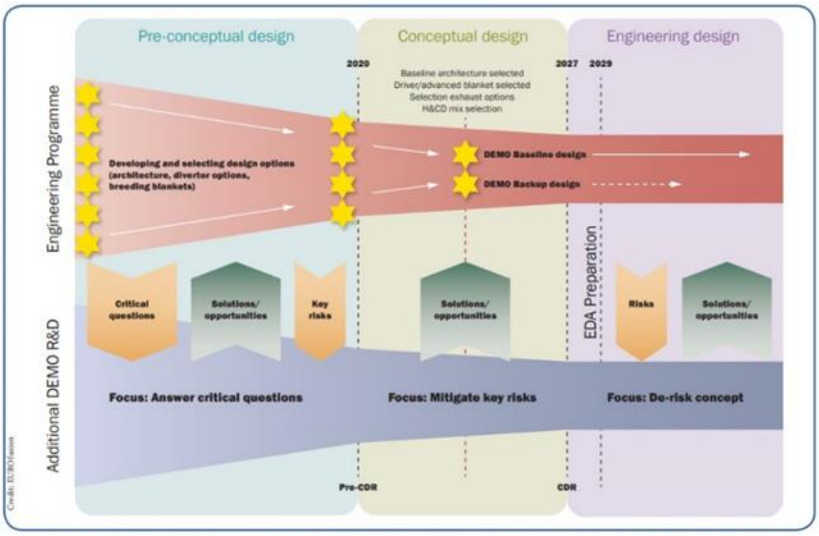


Figure 5.5: Flow diagram for the PCD, CD, and ED of DEMO [29]

The DEMO staged design approach encompasses three primary technical phases, of which the first phase is already completed [40]:

1. Pre-concept design phase (PCD) (up to 2020): this phase aimed at comparing different plant configuration to a reference plant, called the "baseline" plant. The main points of focus of this phase were the

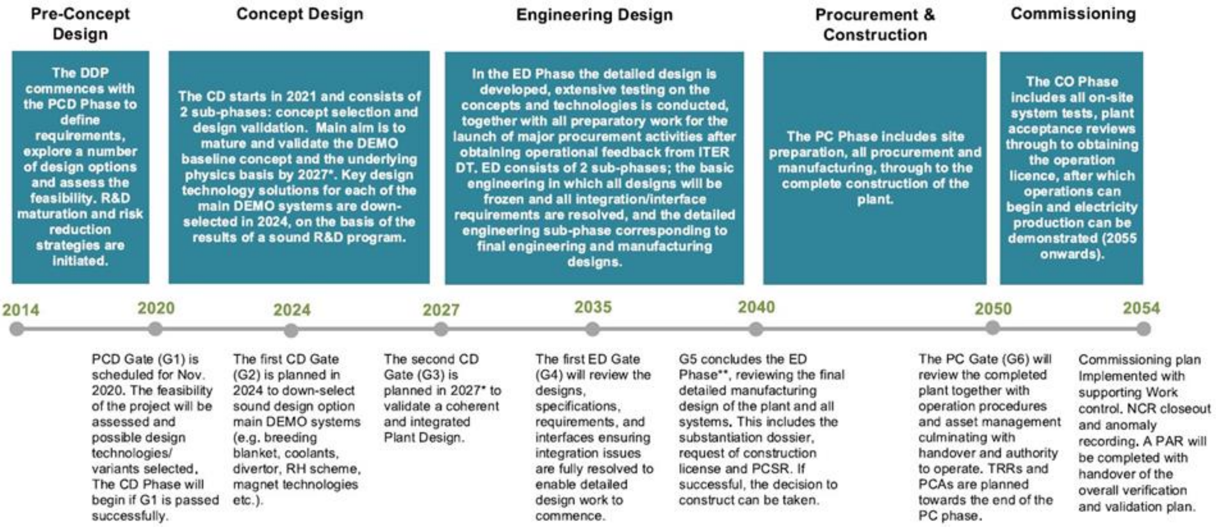
engineering, operational challenges, safety, power conversion aspects and reliability of the power plant. A plant configuration includes the major parameters, such as the size, aspect ratio, field and current, then the plasma configuration, whether pulsed or steady state (or both), coolant and BOP, and remote maintenance approach (e.g., vertical access). This phase ended with the selection of the optimal plants in terms of chance of success;

2. Concept design phase (CD) (2020-2027): during this period, the project configuration selected in phase 1 are taken and further developed and compared, trying to identify the optimum concept and architecture;
3. Engineering design phase (ED) (starting in 2029): The selected DEMO architecture progresses into this phase as system-level solutions are systematically selected and substantiated through comprehensive engineering assessments and technological research and development (R&D). This phase will also involve prototype testing to validate and refine the utilization of key components and systems.

To achieve fusion electricity early in the second half of the century, a European DEMO construction has to start in the early 2040s, shortly after ITER achieves the milestone of $Q = 10$ operations [40].

As shown in Figure 5.6, a decision gate process (DGP) has been established to assess and verify the advancement and accomplishments of the DEMO design development cycle, along with its associated technologies. Criteria are developed in order to assess if each DEMO design and technology piece met the technological, integration, and system readiness levels assigned to each decision gate.

Within the framework of the PCD Gate (G1), a comprehensive evaluation of primary design integration risks and their corresponding design and technology options was conducted, employing a methodical and traceable assessment approach. Simultaneously, a thorough examination of the technical maturation plan for each major tokamak system was carried out. The objective was to determine the most favorable technologies suitable for deployment during the concept design phase. Additionally, an intermediate gate (G2) has been introduced, approximately in 2024. This intermediate gate aims to make selections for the design solutions pertaining to critical systems, such as the breeding blanket, divertor configuration, remote maintenance scheme, and the heating and current drive (H&CD) mix. It also involves the establishment of main machine parameters and a reference plasma scenario, all of which are geared towards achieving a coherent and validated DEMO Conceptual Design by the year 2027 [42].



The DDP commences with the PCD Phase to define requirements, explore a number of design options and assess the feasibility. R&D maturation and risk reduction strategies are initiated.

The CD starts in 2021 and consists of 2 sub-phases: concept selection and design validation. Main aim is to mature and validate the DEMO baseline concept and the underlying physics basis by 2027*. Key design technology solutions for each of the main DEMO systems are down-selected in 2024, on the basis of the results of a sound R&D program.

In the ED Phase the detailed design is developed, extensive testing on the concepts and technologies is conducted, together with all preparatory work for the launch of major procurement activities after obtaining operational feedback from ITER DT. ED consists of 2 sub-phases; the basic engineering in which all designs will be frozen and all integration/interface requirements are resolved, and the detailed engineering sub-phase corresponding to final engineering and manufacturing designs.

The PC Phase includes site preparation, all procurement and manufacturing, through to the complete construction of the plant.

The CO Phase includes all on-site system tests, plant acceptance reviews through to obtaining the operation licence, after which operations can begin and electricity production can be demonstrated (2055 onwards).

PCD Gate (G1) is scheduled for Nov. 2020. The feasibility of the project will be assessed and possible design technologies/ variants selected. The CD Phase will begin if G1 is passed successfully.

The first CD Gate (G2) is planned in 2024 to down-select sound design option main DEMO systems (e.g. breeding blanket, coolants, divertor, RH scheme, magnet technologies etc.).

The second CD Gate (G3) is planned in 2027* to validate a coherent and integrated Plant Design.

The first ED Gate (G4) will review the designs, specifications, requirements, and interfaces ensuring integration issues are fully resolved to enable detailed design work to commence.

G5 concludes the ED Phase**, reviewing the final detailed manufacturing design of the plant and all systems. This includes the substantiation dossier, request of construction license and PCSR. If successful, the decision to construct can be taken.

The PC Gate (G6) will review the completed plant together with operation procedures and asset management culminating with handover and authority to operate. TRRs and PCAs are planned towards the end of the PC phase.

Commissioning plan Implemented with supporting Work control. NCR closeout and anomaly recording. A PAR will be completed with handover of the overall verification and validation plan.

Figure 5.6: DEMO phases and Decision Gate Process (DCP) [31]

Currently, the DEMO team has disclosed the findings from their Pre-Concept Design Phase (2014-2020) within a dedicated edition of the scientific journal Fusion Engineering & Design. This publication encompasses a wide array of topics, ranging from power exhaust and tritium breeding to the extraction of high-grade heat from the breeding blanket, remote maintenance procedures for in-vessel components, robust magnet designs, the selection of qualified structural and plasma-facing component materials, and comprehensive considerations regarding nuclear safety and system integration [40].

5.2 ARC state-of-art

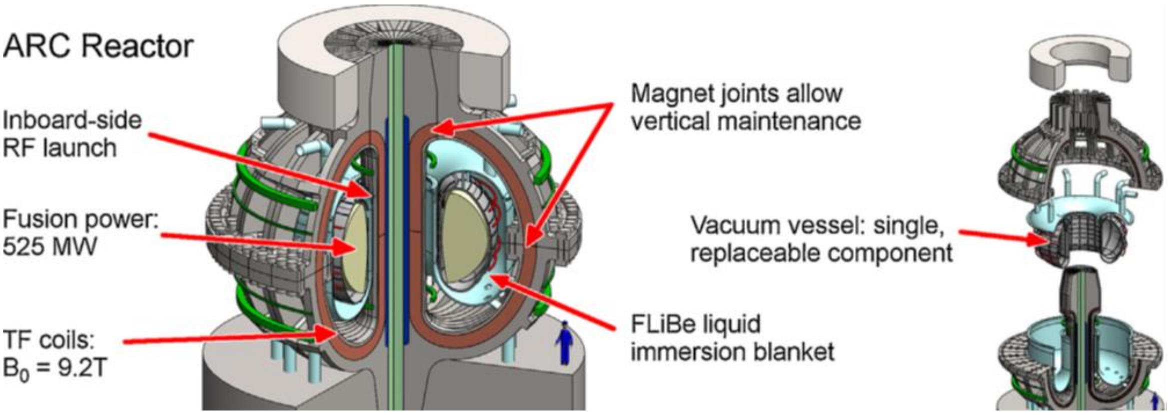


Figure 5.7: ARC reactor configuration [38]

ARC magnetic fusion power plant will be built on SPARC’s technology. As a crucial next step on the road to commercial fusion energy, SPARC is a magnetic fusion plant designed not for the purpose of producing electricity, but its primary mission goals are to demonstrate fusion energy generation from the plasma with a margin over break-even ($Q = 1$) and to achieve a fusion gain $Q > 2$ [38]. Moreover, SPARC seeks to open the way for the commercialization of magnetic fusion power plants (i.e. ARC power plant), by demonstrating the feasibility of rare earth barium copper oxide (REBCO) high-temperature superconducting (HTS) magnets in an integrated fusion confinement facility [38] [35]. As stated by Creely, et al. [35] (2020), “the SPARC project aims to show that the high magnetic fields possible with REBCO-based magnets allow one to reduce the size of fusion devices and facilitate the reduction of cost”. The ITER Physics Basis forms a substantial part of the performance predictions for SPARC. Additionally, SPARC's engineering design incorporates the technical advancement achieved in other machines and design studies, such as designs for ITER and knowledge gained from previous D-T devices like TFTR and JET. Following the SPARC project, the logical progression is to advance towards a high-temperature superconducting (HTS) based power plant, exemplified by the ARC design. Due to its substantially smaller size in comparison to larger designs utilizing low-temperature superconductors (LTS), it is expected that the ARC power plant will likely incur significantly reduced costs. [35]. The SPARC project is divided into two main phases.

Phase 1 (2018-2021) is divided in two major milestones:

- The construction and operation of a model coil for a toroidal field based on high-temperature superconductors (HTS) (i.e. Alcator C-Mod);
- Finalization of the SPARC design.

Phase 2 (2021-2025) involves the completion of the tokamak design and the subsequent commencement of device construction and commissioning.

Nowadays, Phase 1 has been completed, allowing the following milestones to be reached [43]:

- Testing high magnetic field plasmas within a compact configuration;
- Achieving a record-high plasma pressure in a tokamak;
- Attaining the highest magnetic field for a diverted tokamak;
- Qualifying the performance of high-temperature superconducting (HTS) tapes;
- Developing and testing HTS magnet components on a scale;
- Completing the design of HTS magnets;
- Constructing a large-bore magnet;

- Demonstrating the performance of full-scale magnets.

Regarding Phase 2, the SPARC construction site has been selected and the necessary permits have been obtained. At present, the SPARC plant is under construction in Devens (MA). The forthcoming objectives involve the initiation of the first plasma phase in SPARC and, subsequently, the achievement of net energy production from the SPARC facility [43]. After the last steps of the SPARC project, CFS intends to expeditiously embark on the construction and operation of a pilot commercial fusion power plant, based on the ARC design [38]. CFS aims at exploiting the knowledge gained from SPARC in order to complete the transition of fusion from the laboratory to the market. According to what A. J. Creely and the SPARC Team stated in the paper "Overview of the SPARC tokamak" [35] (2020), "ARC will create fusion energy for the grid while demonstrating the science and technology necessary for the cost-effective, mass generation of fusion energy. It will open the door for fusion power systems that can supply the entire planet with carbon-free, secure power that is endless." The construction of the ARC power plant will start in 2030s.

5.3 DTT state-of-art

The Divertor Tokamak Test (DTT) is an experimental plant located in Frascati. Its main objective is to tackle mission n. 2 that emerges from the European Fusion Roadmap [40], explained at the beginning of this Chapter. The objective n. 2 involves the Heat-exhaust system. DTT is focused on exploring alternative approaches to address the challenge of managing the heat load [44], by testing different divertor solutions that will be implemented in DEMO. For this reason, DTT plasma performance are considered comparable to the one of DEMO [44]. Currently, the construction phase of DTT is underway, with the reference standards being set in line with the state-of-the-art technologies employed in ITER and JT-60SA[4].

Figure 5.8: Design of the reference initial divertor for the proposed DTT. The left is the conceptual one. The right one is the first draft actual design [34]

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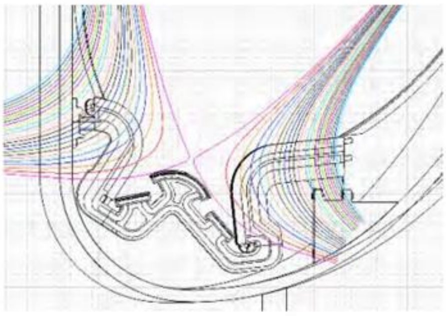
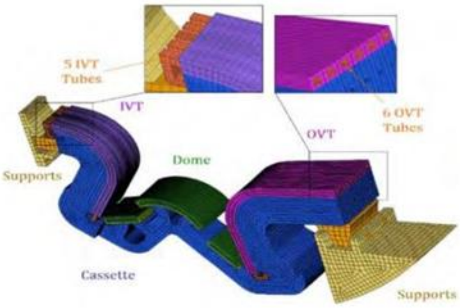
[4] JT-60SA, situated in Naka (Japan), is a collaborative international fusion experiment jointly established and constructed by Japan and Europe. This facility has been designed to facilitate ITER's operation by means of a coordinated research and development initiative. Moreover, it aims to explore the most effective approaches for enhancing the operation of future fusion power plants constructed subsequent to ITER [89].





5.3.1 DTT Operational program

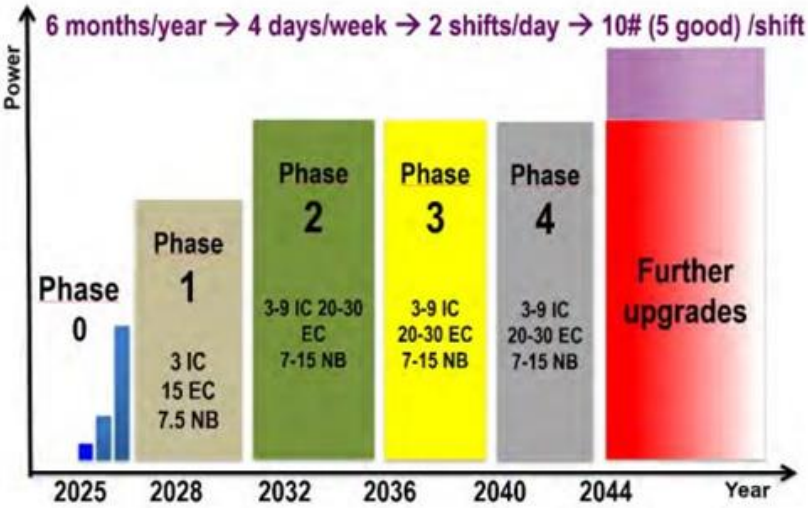


Figure 5.9: Schematic planning of DTT experimental program [34]

DTT will operate in parallel with ITER, serving as a supportive and complementary entity to the ITER experimental agenda. It will particularly concentrate on addressing high-priority concerns, including the prevention and mitigation of disruptions, research and development requirements pertaining to plasma-facing components, and plasma control [44].

The DTT operational phase comprehend Phase 1 (2025-2030) which aim at the construction and installation of the different components of the plant [44]. During Phase 2, spanning from 2030 to 2036, the machine will attain operational readiness. Subsequent phases will be dedicated to the evaluation of various alternative divertor solutions, encompassing novel magnetic configurations and pioneering technologies related to liquid metal [44].

5.4 Tokamak diffusion

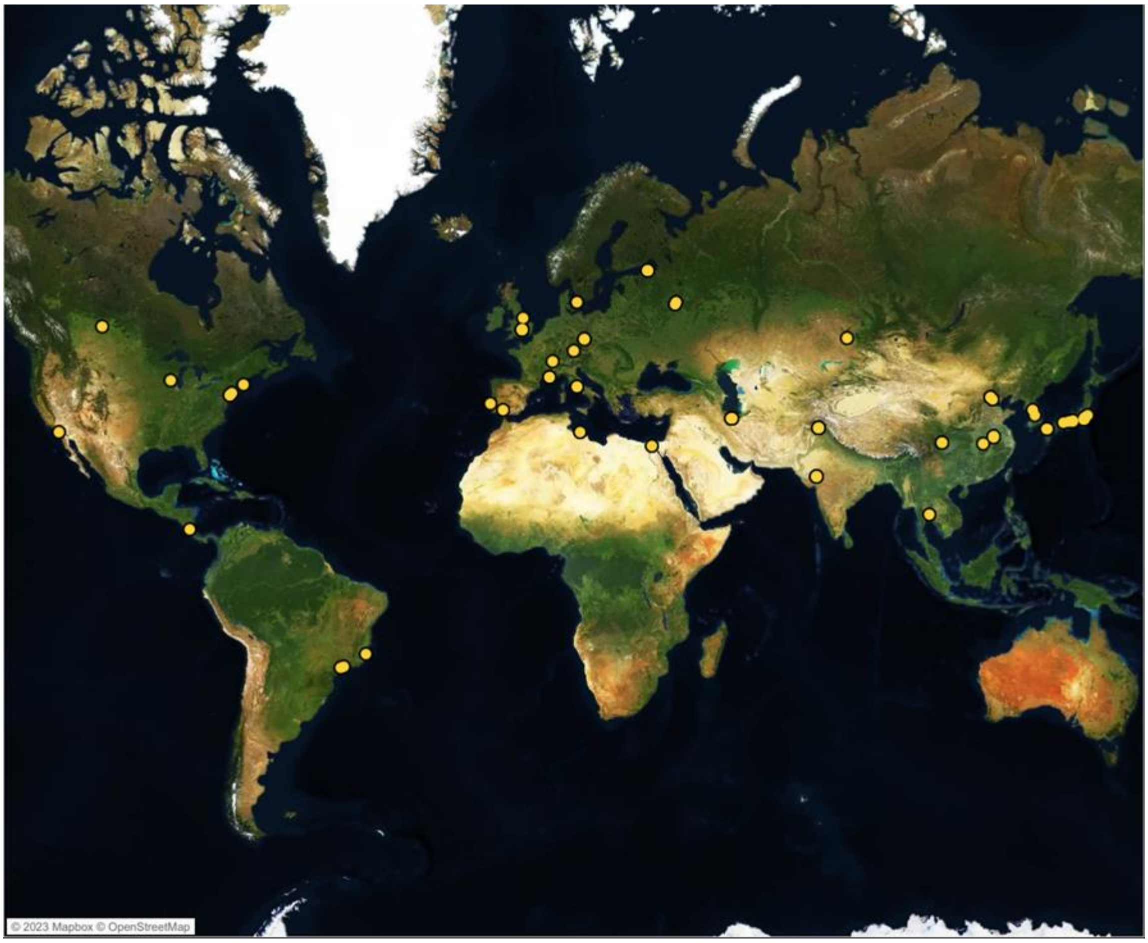
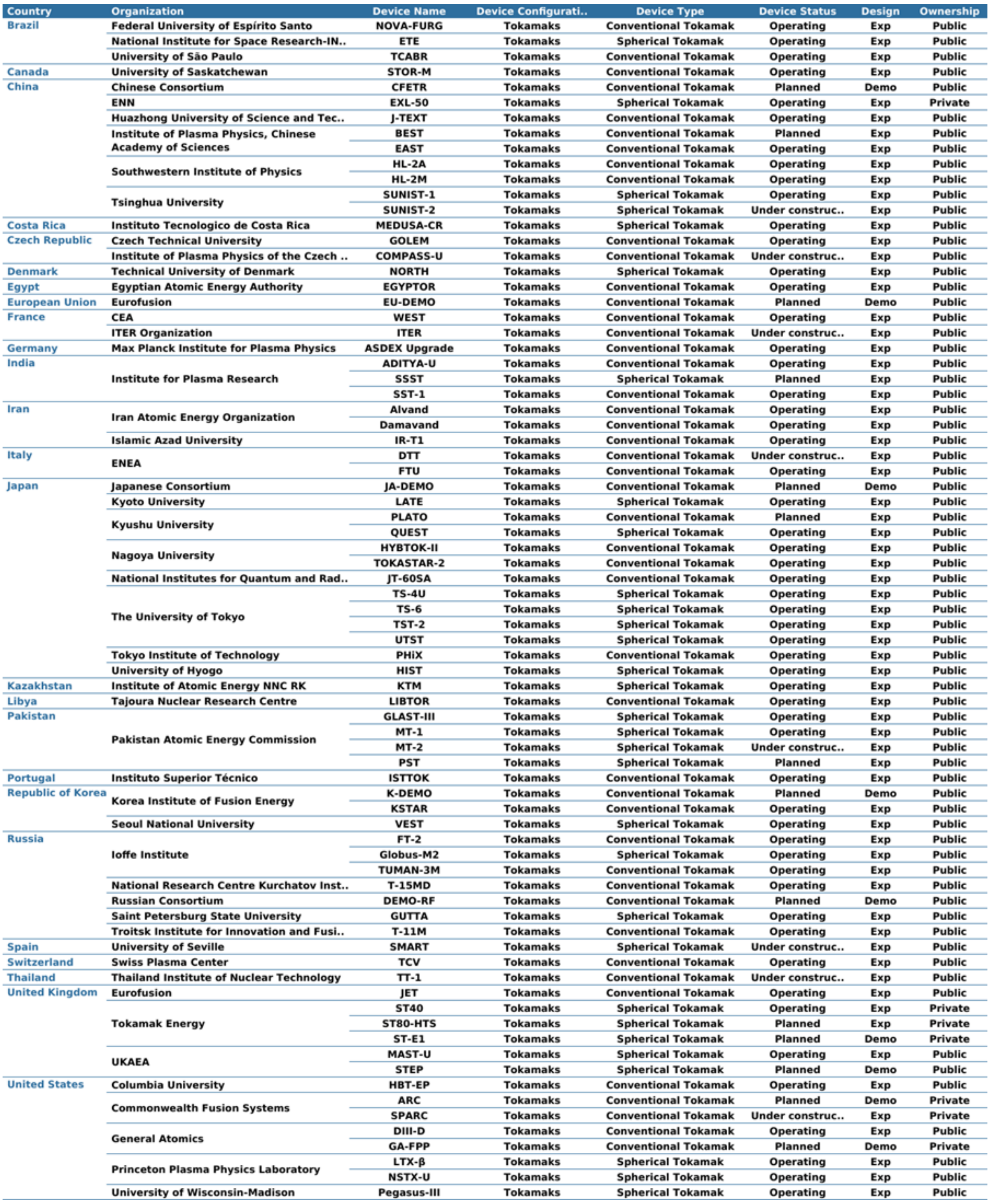


Figure 5.10: Worldwide diffusion of magnetic fusion plant with tokamak configuration [35]

Nowadays, there are 142 magnetic fusion plant globally, of which 77 are characterized by a tokamak configuration (See Figure 5.10), 15 are Stellarators/Heliotrons, 11 are Laser/Inertial and 39 follow alternative concepts [45]. Due to the purpose of this dissertation, the point of focus is on the tokamak configuration .

Figure 5.11 shows the different tokamak devices varying according to the location, organization, device type, device status, design, and ownership. Of the 77 tokamaks devices globally, 55 are in operations, 8 are under construction and 14 are planned. Moreover, 68 are in the experimental phase and 9 in the demonstration phase (3 characterized by a private ownership and 4 public) [45]. The country in which most of the tokamaks are located is Japan (13 devices), followed by China (9 devices), United States (8 devices) and Russia (7 devices) [45].



Country	Organization	Device Name	Device Configurati..	Device Type	Device Status	Design	Ownership
Brazil	Federal University of Espírito Santo	NOVA-FURG	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	National Institute for Space Research-IN..	ETE	Tokamaks	Spherical Tokamak	Operating	Exp	Public
	University of São Paulo	TCABR	Tokamaks	Conventional Tokamak	Operating	Exp	Public
Canada	University of Saskatchewan	STOR-M	Tokamaks	Conventional Tokamak	Operating	Exp	Public
China	Chinese Consortium	CFETR	Tokamaks	Conventional Tokamak	Planned	Demo	Public
	ENN	EXL-50	Tokamaks	Spherical Tokamak	Operating	Exp	Private
	Huazhong University of Science and Tec..	J-TEXT	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	Institute of Plasma Physics, Chinese Academy of Sciences	BEST	Tokamaks	Conventional Tokamak	Planned	Exp	Public
		EAST	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	Southwestern Institute of Physics	HL-2A	Tokamaks	Conventional Tokamak	Operating	Exp	Public
		HL-2M	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	Tsinghua University	SUNIST-1	Tokamaks	Spherical Tokamak	Operating	Exp	Public
		SUNIST-2	Tokamaks	Spherical Tokamak	Under construc..	Exp	Public
Costa Rica	Instituto Tecnologico de Costa Rica	MEDUSA-CR	Tokamaks	Spherical Tokamak	Operating	Exp	Public
Czech Republic	Czech Technical University	GOLEM	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	Institute of Plasma Physics of the Czech ..	COMPASS-U	Tokamaks	Conventional Tokamak	Under construc..	Exp	Public
Denmark	Technical University of Denmark	NORTH	Tokamaks	Spherical Tokamak	Operating	Exp	Public
Egypt	Egyptian Atomic Energy Authority	EGYPTOR	Tokamaks	Conventional Tokamak	Operating	Exp	Public
European Union	Eurofusion	EU-DEMO	Tokamaks	Conventional Tokamak	Planned	Demo	Public
France	CEA	WEST	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	ITER Organization	ITER	Tokamaks	Conventional Tokamak	Under construc..	Exp	Public
Germany	Max Planck Institute for Plasma Physics	ASDEX Upgrade	Tokamaks	Conventional Tokamak	Operating	Exp	Public
India	Institute for Plasma Research	ADITYA-U	Tokamaks	Conventional Tokamak	Operating	Exp	Public
		SSST	Tokamaks	Spherical Tokamak	Planned	Exp	Public
		SST-1	Tokamaks	Conventional Tokamak	Operating	Exp	Public
Iran	Iran Atomic Energy Organization	Alvand	Tokamaks	Conventional Tokamak	Operating	Exp	Public
		Damavand	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	Islamic Azad University	IR-T1	Tokamaks	Conventional Tokamak	Operating	Exp	Public
Italy	ENEA	DTT	Tokamaks	Conventional Tokamak	Under construc..	Exp	Public
		FTU	Tokamaks	Conventional Tokamak	Operating	Exp	Public
Japan	Japanese Consortium	JA-DEMO	Tokamaks	Conventional Tokamak	Planned	Demo	Public
	Kyoto University	LATE	Tokamaks	Spherical Tokamak	Operating	Exp	Public
	Kyushu University	PLATO	Tokamaks	Conventional Tokamak	Planned	Exp	Public
		QUEST	Tokamaks	Spherical Tokamak	Operating	Exp	Public
	Nagoya University	HYBTOK-II	Tokamaks	Conventional Tokamak	Operating	Exp	Public
		TOKASTAR-2	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	National Institutes for Quantum and Rad..	JT-60SA	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	The University of Tokyo	TS-4U	Tokamaks	Spherical Tokamak	Operating	Exp	Public
		TS-6	Tokamaks	Spherical Tokamak	Operating	Exp	Public
		TST-2	Tokamaks	Spherical Tokamak	Operating	Exp	Public
		UTST	Tokamaks	Spherical Tokamak	Operating	Exp	Public
	Tokyo Institute of Technology	PHiX	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	University of Hyogo	HIST	Tokamaks	Spherical Tokamak	Operating	Exp	Public
Kazakhstan	Institute of Atomic Energy NNC RK	KTM	Tokamaks	Spherical Tokamak	Operating	Exp	Public
Libya	Tajoura Nuclear Research Centre	LIBTOR	Tokamaks	Conventional Tokamak	Operating	Exp	Public
Pakistan	Pakistan Atomic Energy Commission	GLAST-III	Tokamaks	Spherical Tokamak	Operating	Exp	Public
		MT-1	Tokamaks	Spherical Tokamak	Operating	Exp	Public
		MT-2	Tokamaks	Spherical Tokamak	Under construc..	Exp	Public
		PST	Tokamaks	Spherical Tokamak	Planned	Exp	Public
Portugal	Instituto Superior Técnico	ISTTOK	Tokamaks	Conventional Tokamak	Operating	Exp	Public
Republic of Korea	Korea Institute of Fusion Energy	K-DEMO	Tokamaks	Conventional Tokamak	Planned	Demo	Public
		KSTAR	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	Seoul National University	VEST	Tokamaks	Spherical Tokamak	Operating	Exp	Public
Russia	Ioffe Institute	FT-2	Tokamaks	Conventional Tokamak	Operating	Exp	Public
		Globus-M2	Tokamaks	Spherical Tokamak	Operating	Exp	Public
		TUMAN-3M	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	National Research Centre Kurchatov Inst..	T-15MD	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	Russian Consortium	DEMO-RF	Tokamaks	Conventional Tokamak	Planned	Demo	Public
	Saint Petersburg State University	GUTTA	Tokamaks	Spherical Tokamak	Operating	Exp	Public
	Troitsk Institute for Innovation and Fusi..	T-11M	Tokamaks	Conventional Tokamak	Operating	Exp	Public
Spain	University of Seville	SMART	Tokamaks	Spherical Tokamak	Under construc..	Exp	Public
Switzerland	Swiss Plasma Center	TCV	Tokamaks	Conventional Tokamak	Operating	Exp	Public
Thailand	Thailand Institute of Nuclear Technology	TT-1	Tokamaks	Conventional Tokamak	Under construc..	Exp	Public
United Kingdom	Eurofusion	JET	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	Tokamak Energy	ST40	Tokamaks	Spherical Tokamak	Operating	Exp	Private
		ST80-HTS	Tokamaks	Spherical Tokamak	Planned	Exp	Private
		ST-E1	Tokamaks	Spherical Tokamak	Planned	Demo	Private
	UKAEA	MAST-U	Tokamaks	Spherical Tokamak	Operating	Exp	Public
		STEP	Tokamaks	Spherical Tokamak	Planned	Demo	Public
United States	Columbia University	HBT-EP	Tokamaks	Conventional Tokamak	Operating	Exp	Public
	Commonwealth Fusion Systems	ARC	Tokamaks	Conventional Tokamak	Planned	Demo	Private
		SPARC	Tokamaks	Conventional Tokamak	Under construc..	Exp	Private
	General Atomics	DIII-D	Tokamaks	Conventional Tokamak	Operating	Exp	Public
		GA-FPP	Tokamaks	Conventional Tokamak	Planned	Demo	Private
	Princeton Plasma Physics Laboratory	LTX-β	Tokamaks	Spherical Tokamak	Operating	Exp	Public
		NSTX-U	Tokamaks	Spherical Tokamak	Operating	Exp	Public
	University of Wisconsin-Madison	Pegasus-III	Tokamaks	Spherical Tokamak	Operating	Exp	Public

Figure 5.11: List of the global tokamak devices [35]

6 Grants & incentives

At present, there are not incentive schemes already designed for magnetic fusion. This lack is justified by the fact that to realize magnetic fusion and make it commercially viable, it is needed to overcome 7 technological milestones, described in Chapter 5. Nevertheless, it these challenges are assumed to be overcome, and electricity coming from magnetic fusion energy can be sell on the electricity market, it can be stated that the incentives and grants designed for nuclear fission power plants can serve as powerful precursors and valuable assets for future nuclear fusion endeavors. Indeed, while nuclear fission and nuclear fusion are distinct processes, the strategies and mechanisms employed to support fission can effectively pave the way for the development and success of fusion plants. The incentives and grants applied to nuclear fission power plants will create fertile ground for the nuclear fusion. They provide the critical elements of experience, policy frameworks, funding mechanisms, and safety standards that can significantly expedite the progress of fusion technology. The synergies between these two nuclear realms can be harnessed to accelerate the realization of fusion.

Governments globally are actively nurturing nuclear power plant growth through an array of grants and incentives, each playing a specific role in the evolution of this energy sector.

6.1 Grants & incentives for the construction phase

This paragraph aims at describing what are the most important nuclear incentives associated to the construction phase of a nuclear power plant.

At the outset, *Construction and Operation Grants* stand as crucial pillars. These grants alleviate the financial strain of creating and maintaining nuclear power plants, covering diverse costs from initial site preparation to essential infrastructure development and equipment installation.

Promoting innovation, *Research and Development Support* underpins technological advancements. This funding fosters progress in reactor design, safety protocols, waste management strategies, and advanced fuel technologies, driving the continuous refinement of nuclear power [46].

Financial facilitation takes center stage through *Loan Guarantees*. By mitigating financial risks, these guarantees streamline funding accessibility for both construction and operation phases, enhancing financial feasibility [47].

These types of incentive schemes would be fundamental for increasing the competitiveness of magnetic fusion. Indeed, as the time of construction of a magnetic fusion power plant varies between 8 and 10 years, both Construction and Operation Grants and Loan Guarantees are fundamental to lower the risk of shareholders. On the other hand, the Research and Development Support would be of paramount importance for magnetic fusion; from one side, it is important to support company in overcoming the technological milestones that would render magnetic fusion commercially viable, and, on the other side, this incentives would help the scientific research to increase the competitiveness of magnetic fusion, by investigating the factors that would reduce the LCOE.

6.2 Grants & incentives for the operational phase

This paragraph aims at describing what are the most significant incentives associated with the operational phase of a nuclear power plant.

Production Tax Credits act as powerful incentives for nuclear power generation. By rewarding operators based on electricity output, these credits significantly enhance the economic viability of nuclear plants [48].

Contract for difference (CfD) ensure revenue stability. Governments offer premium electricity rates for nuclear-generated power, ensuring consistent income for operators and driving clean energy production [49].

In regions with *Carbon Pricing and Emission Trading Systems*, nuclear power enjoys advantages due to its low carbon footprint. These systems place costs on high-emission processes, offering economic incentives for nuclear environmental attributes.

Moreover, governments can establish *Decommissioning and Waste Management Funds*. These funds secure resources for future decommissioning and safe management of radioactive waste [47].

Lastly, *Liability Limitation* strategies provide a controlled risk landscape. Governments cap operators' financial responsibility in accident scenarios, instilling investor confidence while mitigating potential financial shocks [47].

The first two incentive schemes are fundamental to increase the competitiveness of magnetic fusion on the electricity market. On the other hand, Carbon Pricing and Emissions Trading Scheme act in the decrease of competitiveness of the other energy sources, that have a high carbon footprint. This scheme would ultimately enhance the economic viability of magnetic fusion. Decommissioning and Waste Management Funds and Liability Limitation are powerful incentives for nuclear fission, but probably less important for nuclear fusion. Indeed, the percentage of nuclear waste produced by nuclear fusion is minimal, and consequently it is not needed a huge number of resources to decommission and manage the radioactive waste. Moreover, due to the intrinsically safety features of magnetic fusion, the likelihood of accident scenarios transpiring is minimal, making the Liability Limitation incentives less attractive for magnetic fusion.

Among this array of incentives, it's vital to understand that their form and availability depends on specific regional and national contexts. The complex dynamics of the nuclear sector drive governments to tailor these mechanisms in ways that ensure safety, environmental harmony, and economic growth while nurturing nuclear energy advancement.

6.3 Regulated Asset Base model

Differently from the incentive schemes described above, the regulated asset base model is a financing mechanism that cover both the construction and the operational phase of the plant. It allows investors to recover their costs and earn a return on investment over the lifespan of the asset. In the context of nuclear power plants, the UK government has considered implementing the RAB model to attract private investment for the construction of new nuclear facilities.

Under the RAB model, the capital costs of the nuclear plant would be funded by investors who would then earn a regulated return on their investment. This return would be recovered through the prices charged for electricity generated by the plant over an extended period, typically spanning several decades. The revenue required to cover the costs and provide the investor return would be collected from consumers through their electricity bills. Proponents of the RAB model argue that it can provide more certainty and stability to investors, which may help attract the necessary capital for large-scale infrastructure projects like nuclear power plants. By allowing investors to recover their costs over a long period, the RAB model mitigates the financial risks associated with upfront construction costs and lengthy payback periods.

However, the RAB model also has its critics. Some concerns raised include the potential impact on consumer energy bills, as the costs of the project would be passed onto consumers over an extended period. Critics argue that this could lead to higher electricity prices, potentially burdening households and businesses. Moreover, the RAB model relies on accurate cost estimates and revenue projections and any cost overruns or revenue shortfalls could have implications for both investors and consumers. There are also challenges in setting appropriate regulated returns and ensuring transparency in the process to avoid excessive profits for investors at the expense of consumers. It's worth noting that the implementation of the RAB model for nuclear power plants in the UK is still under consideration, and the final decision will depend on various factors, including policy considerations, regulatory frameworks, and stakeholder consultations [50] [52].

There are certain aspects of EU regulations and policies that can pose challenges to the RAB implementation. There are many reasons why the RAB model might face difficulties in an EU country:

1. The EU has strict regulations regarding state aid, which aim to prevent unfair competition and distortion of the single market. Any financial support provided to specific industries or companies, including nuclear power, could be subject to scrutiny under these rules. The RAB model, as a mechanism that involves long-term financial support and potentially guarantees a regulated return for investors, could be seen as state aid and would require careful assessment and approval from the European Commission.
2. The EU has been working towards creating a liberalized and competitive electricity market across member states. This involves promoting market-based pricing and reducing barriers to entry for new market participants. The RAB model, with its potential long-term cost recovery mechanism, might be perceived as contradictory to the principles of market liberalization, as it could create barriers to competition and distort price signals.
3. The EU has been prioritizing the transition to clean and renewable energy sources as part of its climate and energy objectives. Policies and support mechanisms are often geared towards promoting renewable energy technologies. The RAB model, primarily associated with large-scale infrastructure projects like nuclear power plants, might not align with the EU's emphasis on renewables and could face resistance or less favorable treatment within the policy framework.
4. The RAB model, which involves recovering costs from consumers over an extended period, can raise concerns about the impact on electricity prices and consumer bills. The EU emphasizes consumer protection and affordable energy prices. Implementing the RAB model would require a careful balance between ensuring financial viability for investors and safeguarding consumers from excessive cost burdens.

It's important to note that these challenges are not insurmountable, and some EU countries have implemented variations of financing mechanisms to support infrastructure projects. Each country's specific circumstances, legal frameworks, and policy priorities will influence the feasibility and potential obstacles associated with implementing the RAB model or any other financing mechanism for nuclear power plant. European countries have several other options for financing nuclear power projects or any other large-scale infrastructure projects.

Indeed, governments can choose to provide direct funding from their budgets to finance nuclear power projects. This approach would require allocating public funds to cover the construction and operation costs of the project. Direct government funding may be supported by national energy policies, strategic energy plans, or specific legislation.

Secondly, governments can establish partnerships with private companies or consortia to develop nuclear power projects. PPPs (public-private partnerships) allow for the sharing of risks and responsibilities between the public and private sectors. Private partners can bring in financing, expertise, and operational capabilities, while the government maintains a certain level of involvement and oversight.

The implementation of market reforms can be adopted to create a favorable investment environment for nuclear power. This may involve designing energy market mechanisms that provide long-term price stability or incentives for low-carbon energy sources, including nuclear. Reforms could include contract for difference Cfd), power purchase agreements (PPA), capacity mechanisms, or carbon pricing schemes that adequately value low-carbon attributes.

The European Investment Bank, as the lending arm of the EU, can provide financing and investment support for infrastructure projects, including nuclear power, through loans or guarantees. The EIB aims to support sustainable economic development within the EU and can offer favorable terms and conditions to eligible projects [53].

European countries can leverage funding programs and initiatives provided by the European Union. For example, the European Structural and Investment Funds (ESIF) and the Connecting Europe Facility (CEF) allocate resources to support energy infrastructure projects. EU countries can apply for funding under these programs, subject to specific eligibility criteria and compliance with EU regulations.

Furthermore, EU countries can explore issuing green bonds or accessing sustainable financing mechanisms to fund nuclear power projects. Green bonds are financial instruments specifically designed to raise capital for environmentally friendly projects. By aligning with sustainable finance frameworks, countries can attract investors seeking investments that contribute to climate objectives.

6.4 Contract for Difference (CfD)

The two ways contract for difference is an incentive scheme characterized by an hourly time frame in which the energy produced by a green energy plant and fed into the grid is sold by the producer itself. The plant owner and the State agree upon a tariff, called strike price, for the duration of the contract. If during the contract the zonal price is lower than the strike price, the State pays for the spread. If otherwise the zonal price is higher than the strike price, the plant owner pays for the spread.

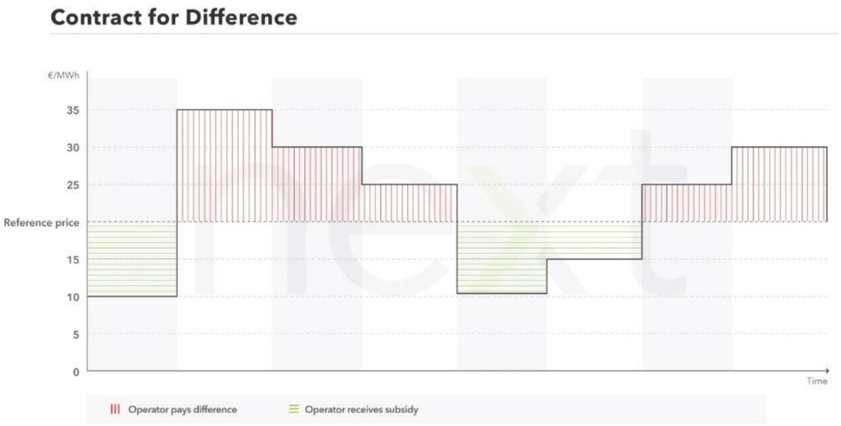


Figure 6.1: Contract for Difference [54]

This scheme guarantees energy producers a predictable and stable revenue stream. CfDs allow to mitigate the risks characterized by the fluctuations and volatility of the current electricity market. Moreover, in a context in which intermittent energy sources are increasing year-by-year their share in the energy mix, the price of electricity will be characterized by an increasingly high level of fluctuations. In this scenario, CfDs would become a fundamental incentive scheme in increasing the share of renewables and lower the dependance from fossil fuel, while maintaining a price stability.

6.5 Hinkley Point C

Figure 6.2: Hinley Point C [98]

For sake of completeness, it is useful to understand what the incentive schemes designed for a real nuclear fusion power plant are. Hinkley Point C is taken as reference. It is a major nuclear power project in Somerset, England, aims to generate a substantial amount of low-carbon electricity, but its gigawatt-scale construction comes with a substantial financial burden. Indeed, Hinkley Point C will be composed of two reactors, with a combined capacity of 3.26 GW [55]. The project's cost for planning and construction is estimated to be tens of billions of pounds (i.e., 40 billion dollars adjusted for inflation 2023) [56], and it has faced delays and cost overruns due to its complexity and long construction period. The plant's construction phase started in 2017 and, after the delays and overruns, it is expected that Hinkley point C will be in operation by 2028 [55]. Plants of such dimensions, with such an elevated time of construction, need incentive schemes to attract private investments and lower the risk for shareholders.

To attract private investments for such ventures, the Contract for Difference (CfD) model was introduced. Hinkley Point C was financed through a CfD with a fixed price of £92.50/MWh (in 2012 prices) (i.e., 112.85 US $/MWh = 148.95 $/MWh adjusted for inflation) [57]. While this model offers revenue stability to investors, it also places construction risk on private shareholders, decreasing their return on investment. In contrast, the Regulated Asset Base (RAB) model aims to make financing more cost-effective. However, the financial value of the construction risk borne by the public balance sheet can affect the return for shareholders, potentially reducing their earnings. Value for money is a critical consideration, as the financial burden of cost overruns and delays can affect the project's profitability and, consequently, shareholders' returns. The government must provide transparent financial figures for proper assessment, ensuring that consumers and taxpayers are not exposed to undue financial risks, while shareholders receive a reasonable return on their investment. The government is also encouraged to explore alternative partnerships with the private sector to find effective financing and risk-sharing arrangements, practiced in other countries, that balance the interests of shareholders and the public. In summary, Hinkley Point C exemplifies the challenges and complexities of financing highly complex nuclear power projects, where private shareholders' returns can be affected by construction risks and delays. Striking the right balance in financing and ensuring transparency is crucial for the success of such ventures while protecting shareholders' interests [58].

7 Literature review

7.1 Thesis objectives & research questions

Through the literature review conducted in support of the previous Chapters, it was evident that magnetic fusion holds the potential to revolutionize the energy mix in the near future. Thanks to its huge potential of producing a green baseload and safe source of electricity, magnetic fusion can actively contribute in tackling the energy transition. Nevertheless, there are seven technological challenges that need to be achieved to realize magnetic fusion and make it commercially viable. Upon successfully addressing these technological challenges, the construction of the first magnetic fusion power plant will commence, and the electricity generated from fusion will become available on the electricity market.

Despite the huge potential that magnetic fusion power plants can offer, it is essential to acknowledge that, at present, the literature do not provide a complete and updated cost estimation of the first magnetic fusion power plants (i.e., FOAK), with an ARC-like configuration. Indeed, having a complete cost estimate of an ARC-like power plant is fundamental to acknowledge the potential competitiveness of this technology on the electricity market. Moreover, once a complete cost estimation is built, sensitivity analyses can be done in order to understand where the scientific research has to canalize its effort, with the purpose of increasing the competitiveness of magnetic fusion.

Hence, the main purpose of this dissertation is to bridge the existing gap in the literature by providing a complete and updated cost estimation of an ARC-like magnetic fusion power plant and consequently conduct sensitivity analyses either on an item performance or on an item cost, in order to assess their potential impact the LCOE. These sensitivity analyses will be fundamental in understanding what are the areas in which the research must focalize to reduce magnetic fusion costs.

To achieve this goal, the following research questions have been raised, with the purpose of defining the theoretical background:

- **RQ0:** What is the current state of the art of magnetic fusion power plants and its potential role in the future?
- **RQ1**: What is the cost estimation of a magnetic fusion power plant?
    - **RQ1.1:** What is the Levelized Cost of Electricity of an ARC-like magnetic fusion power plant?

- **RQ2**: How a potential reduction of components' cost or an increase in the plant's performance can impact the LCOE?
    - **RQ2.2:** Where the scientific research has to canalize its effort to increase the competitiveness of magnetic fusion?

The literature review will delve into the existing body of research surrounding cost estimation methodologies, addressing both the technical and economic factors that influence the overall cost of constructing and operating fusion power plants. The literature review of this dissertation is undertaken by a comprehensive synthesis of paper materials sourced from Scopus, Research Gate, Google Scholar, and a collection of documents graciously provided by the Eni team. Once the literature review delved to analyze the role and the state of the art of magnetic fusion (i.e., RQ0), the existing cost estimations of magnetic fusion power plants (i.e., RQ1), and the components' impact on the LCOE (i.e., RQ2) have been completed and analyzed, an answer to RQ1.1 and RQ2.2 has been provided, throughout the construction of a model, able to compute the LCOE and sensitivity analyses to assess the impact that a component's variation has on the ARC-like magnetic fusion LCOE. Once having developed a complete analysis of the impact of the different components on the LCOE, strategic recommendations has been developed to canalize the R&D effort in the right direction, with the purpose of increasing the competitiveness of the ARC-like magnetic fusion power plant.

The objective of this research is to offer a guiding paradigm for the organizations that want to deepen the knowledge regarding the cost of an ARC-like magnetic fusion power plant, thereby facilitating further studies on the competitiveness of this design.

7.2 Research methodology

A methodical approach has been adopted to guarantee a comprehensive evaluation, which includes academic publication, scientific paper, and technical reports. Furthermore, direct interactions with the ENI magnetic fusion team and a formal interview with the Chief Engineer of ENEA DTT Gian Mario Polli have been fundamental in achieving a comprehensive evaluation of the research. Indeed, the research questions raised have been previously discussed with the ENI team, to identify a real gap in the literature utile at the same time for the research and for the magnetic fusion industry. Once the research questions have been defined, a comprehensive review of the literature has been drafted.

7.2.1 Model conceptualization

To conceptualize the model, an answer to RQ0, RQ1, and RQ2 has been given. The following workflow has been adopted:

- String definition to conduct the research;
- Definition of research filters based on the papers' language and year of publication;
- Formulation of exclusion criteria to enhance the precision of the initial database;
- Screening phase to refine the initial database by reading titles and abstracts of the selected papers;
- Snowball-effect research to deepen the analysis;
- Eligibility phase in which papers have been ranked by relevance;
- Analysis phase in which papers have been read completely in order to search for the necessary information to build the ARC-like plant cost estimation model.

This meticulous approach to literature acquisition and curation ensures that the review is grounded in a robust and diverse foundation of relevant academic discourse, thereby fostering a thorough examination of the research context and facilitating a nuanced exploration of the dissertation's central themes and objectives.

7.2.1.1 RQ0

In order to provide an answer to RQ0, Scopus and ReasearchGate have been the two primary source of documentation. This review types identifies themes, theoretical perspectives, and other qualitative material linked to the analysis of the potential role of fusion in the energy mix.

To select the most relevant articles in Scopus, the following string has been utilized, with the purpose of identifying the potential role of fusion in the future energy mix:

TITLE-ABS-KEY (fusion AND power AND contribution OR contribute OR in AND decarbonized OR decarbonize OR low AND carbon AND electricity OR system)

After conducting the research, 210 articles were initially retrieved. First of all, the research was limited to articles published from 2015 onwards. This decision was dictated by the necessity to base the analysis on more concrete and up-to-date research. Indeed, studies that evaluate the role of fusion before 2015 are nowadays too far from reality. Consequently, the database has been reduced to 106 articles. Moreover, the research was limited only to documents written in English, resulting in a database of 97 articles eligible for the screening process.

The screening process followed two-step procedure:

1. Screening of titles, in order to discard the articles that were not aligned with the scope of the study;
2. Reading of the abstract of the remaining record, to exclude those that were out of focus.

Concerning step one, articles that were completely out of scope were discarded. Then, all the articles that were too technical and do not provide an economic analysis of the role of fusion were discarded. These exclusions were made in order to ensure that the research remained focused on the key objectives and was consistent with the thesis's scope. Step one led to an exclusion of 64 articles.

In step two, the remaining articles' abstract (i.e., 31 articles) were examined. Articles were classified based on their level of alignment with the scope of the research question. Through this analysis, the most significant documents were analyzed, resulting in a total of 7 articles that were used as a reference for specific aspects of the study.

Subsequently, we applied the snowballing method to identify additional studies relevant to the research, resulting in the inclusion of 6 articles.

For what concerns the state of the art of magnetic fusion power plants, emerges from research of Google Scholar and through interview with ENI that only two plants are designed to be commercial and consequently to produce electricity: ARC and DEMO. For this reason, the state of the art of ARC and DEMO2 (i.e., the updated configuration of DEMO) have been analyzed. For sake of completeness, DTT state of the art has been analyzed, as it will be fundamental for the model development.

7.2.1.2 RQ1 & RQ2

To provide an answer to RQ1 and RQ2, Scopus was an important source of documentation. To select the most relevant articles the following strings have been utilized:

1. TITLE-ABS-KEY (magnetic AND fusion AND power AND plant OR plants OR reactor OR reactors AND cost OR costs)
2. TITLE-ABS-KEY (magnetic OR magnetically AND confined AND fusion AND reactors AND cost)

The keywords are chosen to have specific focus on the objective of the study, consequently, keywords were limited to magnetic fusion and to economic analysis. The first research generated 220 documents and the second one 31. Afterwords, a first limitation based on the exclusion of the documents that are not written in

English has been done, causing a reduction of the database to 203 and 28 documents, respectively. Then, only documents recently drafted were chosen for the literature, to guarantee updated information in an argument in continuous evolution. Indeed, documents from 2008 onwards were selected. This third selection phase brings to a limitation to 99 documents for the first string and 13 documents for the second string.

A title screening process of these documents was adopted. It has been chosen to limit the research only to economic analysis and not to scientific papers referred to technological aspect in detail. This step brings to a selection of 51 documents for the first string and 7 for the second one. Then, an abstract screening was adopted in order to select the documents which were relevant to the research questions, causing a reduction of the database to 32 documents. These 32 documents were carefully and completely read and analyzed. After this phase only 16 documents remained as a relevant source for the dissertation. From this phase onwards, the snowball effect has been exploited, bringing to a comprehensive set of papers of about 25 documents.

The knowledge gained from this literature review will contribute to enhancing the accuracy and reliability of the cost estimation for an ARC-like magnetic fusion power plants. It will serve as a foundation for the subsequent chapters of this thesis, which will focus on developing a comprehensive cost estimation model specific to the ARC design, considering the unique technical features that characterize this plant. By building upon the existing literature, this research aims to address the critical gap in cost estimation for ARC-like magnetic fusion power plant, thus facilitating the advancement of fusion energy as a sustainable and economically viable solution for meeting the world's future energy needs.

What emergers from the literature review is that only one paper estimates the cost of an ARC-like magnetic fusion power plant. The study of Sorbom, et al. [38] (2015), provides a bottom-up cost estimation of ARC investment costs, excluding the balance of plant, buildings, and indirect costs. The key parameters, assumptions, and methodology of this paper are described in Chapter 8.

For sake of completeness, the study of Lindley, et al. [49] (2023), published in 2023, refers to the detailed design data provided by Sorbom, et al. [38], but uses the power scaling method to provide cost estimations and LCOE for a NOAK (i.e., Next Of A Kind), 10th of a kind, and 75th of a kind ARC-like magnetic fusion power plants. The purpose of this document is to analyze what could be the competitiveness of magnetic fusion when the industry progresses, and the technology becomes mature. This document also provides a short analysis of the impact that different components have on the LCOE, through a tornado graph.

7.2.2 Model development

After conceptualizing the model by providing an answer to RQ0, RQ1, and RQ2, the focus of the study shifted toward model development. The development of the model served for estimating the total costs of an ARC-like magnetic fusion power plant and its LCOE. Once the LCOE has been drafted and an answer to RQ1.1 has been addresses, sensitivity analyses have been fundamental in order to provide an answer to RQ2.2.

The studies on which the model of this dissertation is based are the following:

1. "ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets" [38];
2. "Approximation of the economy of fusion energy" [17];
3. "DTT: Divertor Tokamak Test facility project proposal" [59];

The former served as the basis for estimating the volume, weight, and material requirements of ARC components. The second study was adopted as a benchmark for calculating the ARC's Balance of Plant, Buildings, and Indirect costs. The latter provides a reliable methodology for the estimation of the fabricated costs, which has been incorporated into the model presented in this thesis. As there are few documents that had previously analyzed the cost of a magnetic fusion power plant, especially for ARC, it is worth to provide a description of these three papers in which the model methodology is based, in order to have a comprehensive overview of the parameters, assumptions, and methodologies used in these papers. An analysis of these relevant documents is provided in Chapter 8.

7.3 Research gap

The existing literature is characterized by a paucity of data in the cost estimations of magnetic fusion power plant and subsequent sensitivity analyses, especially regarding ARC design. The only available document present in the literature is the paper of Sorbom, et al. [38] (2015). Furthermore, the methodology used by Sorbom for the estimation of the fabricated cost is based on Dale M. Meade analysis [60] (2002), which compare the costs and weight of reactors with information derived from documents dated between 1991 and 2002 that are not uploaded with the recent discoveries of fusion. For these reasons, the purpose of this thesis is to assess the economic viability of an ARC-like magnetic fusion power plant. It aims at bridging the existing gap in the literature by providing a comprehensive and updated methodology for the complete cost estimation of an ARC-like magnetic fusion power plant unparalleled and completely new. This methodology allows to compute the LCOE of an ARC-like magnetic fusion power plant and consequently draft sensitivity analyses to gain insight about the costs and technology uncertainties impacts on the LCOE. The development of sensitivity analyses has been fundamental to provide a direction for the R&D, with the purpose of rightly canalizing their effort to lower the LCOE of the ARC-like magnetic fusion power plant.

8 Previous cost estimation of magnetic fusion power plants

The aim of this Chapter is to report the main papers found in literature on which this dissertation is based. Subsequently, Chapter 9 will compare the results obtained from the model constructed in this thesis with the methodologies and estimation results reported in this Chapter.

Paragraph 8.1 describes the assumptions and methodology of the solely paper that provides cost estimation of ARC-like magnetic fusion power plant. Reporting the methodology used in this paper helps in better understand the research gap and the starting point of this thesis. Once gained information through the literature review, we had the opportunity to participate to the "ENI & MIT Accelerating Innovation meeting" in which the MIT researchers showed the main results of their studies regarding the ARC magnetic fusion power plant. This meeting helped the authors in gaining insight about the ARC project and its cost, but for non-disclosure agreements, they cannot be shown in this thesis.

Paragraph 8.2 and 8.3 report the most updated cost estimation of DEMO2 fusion power plant and the DTT experimental reactor, respectively. The former is the most complete cost estimation of a magnetic fusion power plant (i.e., DEMO2). It has been fundamental to retrieve data of components technologically similar to ARC (i.e., BOP and buildings), operational costs and indirect costs. The latter is the project proposal of the DTT experimental reactor. Differently from the previous cost estimation, the DTT project proposal is not an estimation, but a budget definition. Indeed, from the formal interview to the Chief Engineer Gian Mario Polli of ENEA DTT emerged that the plant is already in the pre-construction phase and the costs proposed in the document are the reference for tenders for the supply of components. The Chief Engineer Gian Mario Polli stated: "[…] we are in the pre-construction phase, meaning we are in the process of doing it. We have completed the surveys and are finalizing the detailed project to then go out for a tender for the buildings. However, there are many other contracts that have been launched and are in the execution phase. These relate to the supply of components that will need to be assembled on-site as soon as the experimental machine, the Hall, becomes available. Overall, we have issued tenders for approximately 200 M€ out of a total budget of 600 M€". Moreover, the authors had the opportunity to visit the ENEA site, where DTT will be constructed starting from 2025. Valerio Orsetti, Responsible Officer ASI (Assembly System Integration), showed us the area in which the plant will be build, the plant layout, and the digital twin of the plant. At present, the coring phase has been completed. For these reasons, the cost breakdown employed by DTT for the computation of the components' fabricated costs has been taken as a reference.

8.1 Cost estimation of ARC magnetic fusion power plant

The cost estimate built by Sorbom, et al. [38] (2015) is focused on ARC power plant, enhancing its powerful advantages, as the fact that it is a smaller, timelier, and lower-risk alternative. This is the unique paper that provides the ARC reactor's components material cost and fabricated cost. Nevertheless, the document focuses only on the reactor components, and consequently this cost estimation cannot be considered complete. Indeed, a cost analysis of the auxiliaries' components, as the BOP and buildings is missed. Moreover, operational expenses and indirect costs are not analyzed and estimated. As the cost estimation is not complete, even the ARC LCOE is not provided by this paper.

The plant in analysis is the baseline configuration of ARC, in which the most significant design parameters are outlined in Table 8.1.

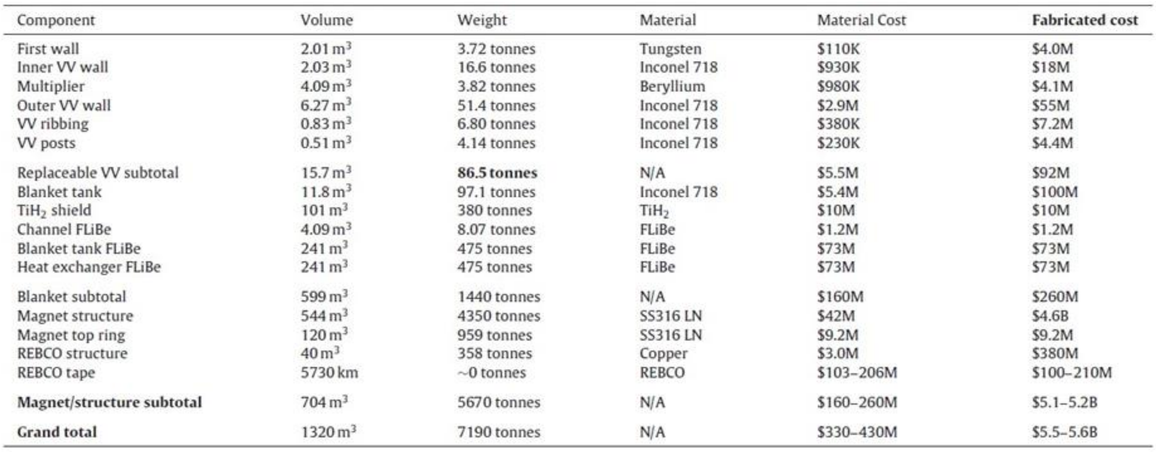
Table 8.1: ARC reactor characteristics [38]

Reactor characteristics	Symbol	Unit	Value
Fusion power capacity	Pf	MW	525
Thermal power capacity	Ptot	MW	708
Plant thermal efficiency	ηelec	%	40%
Net electric power	Pnet	MWe	190
Major radius	Ro	m	3.3
Tritium breeding ratio	TBR		1.1

In particular, the fusion power capacity (Pf) represents the power of the reaction inside the tokamak. The thermal power capacity (Ptot) is higher than the fusion power (Pf) as it includes also the heat released during the tritium production in the blanket and the power of the heating system. The net electric power (Pnet) of the plant resulted as the product of the plant thermal efficiency and the thermal power (Ptot) at net of the plant self-consumption. The major radius represents the length of the ARC reactor inboard radial build. Eventually, the tritium breeding ratio (TBR) represents the ratio between the tritium produced and the tritium in input. Indeed, as explained in Chapter 3, the plant is capable of producing tritium itself through the tritium breeding.

The paper provides a rough bottom-up cost estimate of the ARC reactor, followed by a list of the necessary research to enable a design like ARC. As stated in the paper, the primary motivation behind the efforts to downsize ARC is the aim of decreasing the construction expenses associated with the reactor [38]. The reactor was divided into three parts: the blanket, the vacuum vessel and the magnets/structure. Table 8.2 shows the volume, weight, and the material chosen for each component, followed by the material cost and the overall fabricated cost.

Table 8.2: Cost/weight breakdown for ARC reactor (excluding BOP and buildings equipment) [38]



Component	Volume	Weight	Material	Material Cost	**Fabricated cost**
First wall	2.01 m^3	3.72 tonnes	Tungsten	\$110K	\$4.0M
Inner VV wall	2.03 m^3	16.6 tonnes	Inconel 718	\$930K	\$18M
Multiplier	4.09 m^3	3.82 tonnes	Beryllium	\$980K	\$4.1M
Outer VV wall	6.27 m^3	51.4 tonnes	Inconel 718	\$2.9M	\$55M
VV ribbing	0.83 m^3	6.80 tonnes	Inconel 718	\$380K	\$7.2M
VV posts	0.51 m^3	4.14 tonnes	Inconel 718	\$230K	\$4.4M
Replaceable VV subtotal	15.7 m^3	**86.5 tonnes**	N/A	\$5.5M	\$92M
Blanket tank	11.8 m^3	97.1 tonnes	Inconel 718	\$5.4M	\$100M
TiH_2 shield	101 m^3	380 tonnes	TiH_2	\$10M	\$10M
Channel FLiBe	4.09 m^3	8.07 tonnes	FLiBe	\$1.2M	\$1.2M
Blanket tank FLiBe	241 m^3	475 tonnes	FLiBe	\$73M	\$73M
Heat exchanger FLiBe	241 m^3	475 tonnes	FLiBe	\$73M	\$73M
Blanket subtotal	599 m^3	1440 tonnes	N/A	\$160M	\$260M
Magnet structure	544 m^3	4350 tonnes	SS316 LN	\$42M	\$4.6B
Magnet top ring	120 m^3	959 tonnes	SS316 LN	\$9.2M	\$9.2M
REBCO structure	40 m^3	358 tonnes	Copper	\$3.0M	\$380M
REBCO tape	5730 km	~0 tonnes	REBCO	\$103–206M	\$100–210M
Magnet/structure subtotal	704 m^3	5670 tonnes	N/A	\$160–260M	\$5.1–5.2B
Grand total	1320 m^3	7190 tonnes	N/A	\$330–430M	\$5.5–5.6B

Table 8.3 shows the unitary materials cost, expressed in 2014 US dollars and were acquired through either estimation based on commodity prices or formal price quotations obtained from components' suppliers [38].

Table 8.3: Unitary materials cost in 2014 US dollar [38]

Material	**Material cost**	**Unit**
Beryllium	257.0	\$/Kg
Inconel 718	56.0	\$/Kg
Tungsten	29.0	\$/Kg
Stainless steel 316LN	9.6	\$/Kg
Copper	8.3	\$/Kg
REBCO tape	18-36	\$/m
FLiBe	154.0	\$/Kg
TiH2	26.4	\$/Kg

The analysis of the costs related to the replaceable vacuum vessel and the blanket involved the utilization of an automated model to estimate the material volume. Subsequently, this material volume was multiplied by the material densities and assigned a comprehensive cost based on the unitary cost of the raw materials [38].

With the purpose of estimating the cost of the magnet structure, a specific model was employed to evaluate the necessary volume of steel. Additionally, to determine the required length of REBCO tape, the area of REBCO needed to generate the specified magnetic field was calculated, considering the geometry of the coils [38]. This area was divided by the area of an individual tape to determine the quantity of tapes needed, which was subsequently multiplied by the perimeter of the superconducting coil [38]. Eventually, the total cost of material volumes/lengths was determined by applying the corresponding raw material costs.

To compute the fabricated cost, a rough scaling method based on the total cost per tonne was employed [38], following the study conducted by D. Maede, that compare the estimated cost per tonne across various projects [61].

Table 8.4: Cost/weight comparison of FIRE, BPX, PCAST5, ARIES-RS, ITER-FEAT, and ITER-EDA projects [61]

	FIRE	BPX	PCAST5	ARIES-RS	ITER-FEAT	ITER-EDA
Major Radius (m)	2.14	2.59	5.0	5.5	6.2	8.1
Weight (tonne)	1,371	3,099	9,607	12,678	18,812	41,968
$B (FY02)	1.2	2.2	7.1	11.2	5	10
$M / tonne	0.88	0.71	0.74	0.88	0.27	0.25

FIRE [62], BPX [63], PCAST5 [64], ARIES-RS [65], ITER-FEAT [36], and ITER-EDA [36] are all magnetic fusion experimental plant. As it can be seen in Table 8.4, the $M/tonne of FIRE, BPX, PCAST5 and ARIES-RS are similar. According to D. Meade, this similarity instills confidence that the scaling is not contingent on the specific characteristics of a machine [38]. As a simple approximation, the ARC study calculated the average of the four costs per tonne and adjusted for inflation, resulting in 1.06M/tonne[5] in FY2014 US dollars [38]. Consequently, to compute the fabricated cost, the total weight of the component was multiplied by 1.06 M$/tonne.

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[5] The average of the $M/tonne of the four plants without considering the outlier ITER is 0.8025 and it is adjusted for inflation from FY2002 US dollars to FY2014 US dollars through this calculator: CPI Inflation Calculator (bls.gov)

For components that do not necessitate machining (e.g., the FLiBe blanket), the fabricated cost remains identical to the material cost [38].

In summary, Sorbom employed the following methodology to estimate the cost of the reactor's components:

1. Definition of the unitary materials cost;
2. Estimation of the quantity (expressed in tons (t) or kilometers (km)) necessary to build each component;
3. Computation of the Material Cost (fifth column in Table 8.2) by multiplying the unitary material costs by the quantity necessary to build each component;
4. Computation of the Fabricated Cost (sixth column in Table 8.2) by multiplying the components' weight by 1.06 M$/tonne.

As Table 8.2 shows, the materials costs for ARC total 428 M$ and the total fabricated component cost estimates total 5.5 B$ - 5.6 B$ [38]. The range is justified by the fact that for what concern the REBCO tape, two different material cost were considered (i.e., 18-36 $/m), resulting in a range of REBCO tape material cost from 103 M$ to 206 M$. This choice causes a chain reaction on the Gran total. As indicated in the paper, it should be noted that these are simple approximations. Nevertheless, it is evident that the material costs associated with the "innovative" materials and components in the ARC reactor, such as REBCO tape, FLiBe, and TiH2 shielding, constitute only a minor portion of the total fabricated cost estimated by the fabricated component scaling method.

This paper has been utilized in the thesis as a reference point for the project configuration and consequently for the material chosen and dimensions of ARC components. Nevertheless, the thesis aims at utilizing a completely different methodology for the computation of the fabricated costs.

8.2 Cost estimation of DEMO2 commercial magnetic fusion power plant

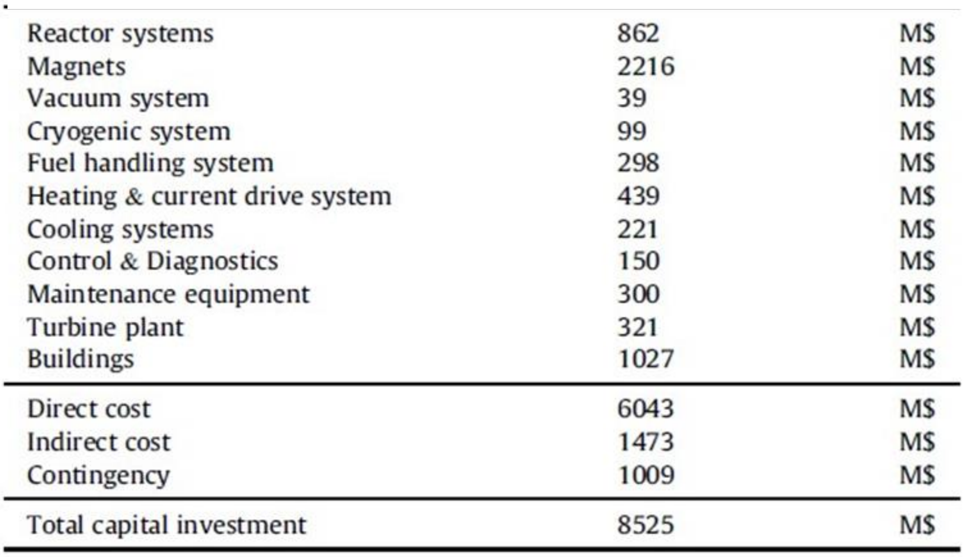
The study of Entler, et al. [17] (2018), brings the ex-ante economic analysis of the European demonstration fusion power plant model DEMO2. As stated in Chapter 5, DEMO2 is a First Of A Kind (i.e., FOAK) plant, which represents the commercialization of the global ITER fusion experiment. Differently from ARC, it has a major radius 2.3 times bigger and uses low temperature superconductors (LTS). At present, this paper is the most complete cost estimation of a magnetic fusion power plant, as an analysis of the capitalized and operational expenditure is done in order to build up the LCOE. The European reference model for the demonstration fusion power plant DEMO2, which was proposed by the EUROfusion consortium of fusion laboratories in 2015, was selected as the basis for the evaluation [17]. Table 8.5 shows what are the most significant DEMO2 reactor's characteristics.

Table 8.5: DEMO2 reactor characteristics [17]

Reactor characteristics	Unit	Value
Fusion power capacity	MW	3255
Thermal power capacity	MW	4149
Gross electric power	MWe	1660
Net electric power	MWe	953
Plant self-consumption	MWe	707
Plant availability fraction	% year	75%
Major radius	m	7.5

From Table 8.6 it can be seen what the estimated fabricated costs of the DEMO2 power plant are. The analysis employed the Net Present Value (NPV) approach, which is based on the Discounted Cash Flow (DCF) methodology, with an assumed discount rate of 7%. DEMO2 was selected as, for the author, it stands as the most pertinent prototype for future fusion power plants, offering one of the most precise approximations for both construction and operational costs associated with fusion power plant development [17]. The components considered are first-of-a-kind, signifying that they are presumed to be relatively costly to manufacture due to their unique nature. Specialized tools and machines may have been custom designed to produce these components [17].

Table 8.6: Investment costs of DEMO2 reference model [17]



Reactor systems	862	M$
Magnets	2216	M$
Vacuum system	39	M$
Cryogenic system	99	M$
Fuel handling system	298	M$
Heating & current drive system	439	M$
Cooling systems	221	M$
Control & Diagnostics	150	M$
Maintenance equipment	300	M$
Turbine plant	321	M$
Buildings	1027	M$
Direct cost	6043	M$
Indirect cost	1473	M$
Contingency	1009	M$
Total capital investment	8525	M$

In this cost estimation, the cost of Vacuum Vessel, Blanket and Divertor are grouped together in the Reactor system. Furthermore, all the items from Vacuum system to Turbine plant represent the Balance Of Plant. As emerges from Table 8.6, a major part of the investment cost sustains uniquely from the tokamak magnets made of low-temperature superconductors [17], which are more industrially established than high temperatures superconductors (i.e., REBCO) used in ARC.

Table 8.7: Operational costs of the DEMO2 reference model [17]

DEMO2 operational costs	Values [€/MWh]
Operation & Maintenance	9.81
Replaceable components cost	13.61
Waste disposal	0.56
Fuel cost	0.44
Decommissioning fund	0.78

The paper provides also an estimation of the operational costs of DEMO2. Table 8.7 shows the estimated operational cost in €/MWh. Operation & Maintenance cost, Waste disposal cost, Fuel cost, and costs associated to Decommissioning fund are costs incurred every year. Instead, the Replaceable components cost incur every 4.5 years for the replacement of Divertor, and every 10.5 years for the replacement of Banket and Vacuum Vessel. Although the replacement costs are not incurred yearly, the total replacement cost over the plant lifetime has been computed and they have been spread annually. Moreover, the investment costs have also been spread over the plant lifetime. This choice is inconsistent with the Discounter Cash Flow (DCF) method, which aims to calculate annual cash flows and discount them using the corresponding year's rate.

Once capital and operational costs have been estimated, the paper provides the LCOE as follow:

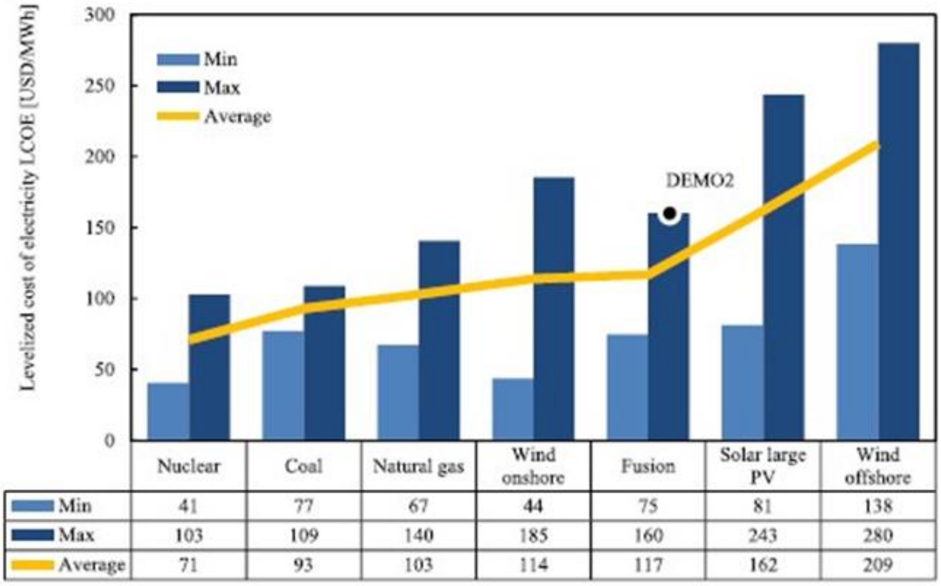
8.1

$$LCOE = \frac{\sum_{t=0}^{T_L-1}(IN_t + C_t + I_t) * (1+r)^{-t}}{\sum_{t=0}^{T_L-1} E_t * (1+r)^{-t}}$$

Where IN is the annual investment, C are the annual operating costs, I is the interest, E stands for the annual electricity production and r is the discount rate (fixed at 7%). Entler, et al. use the levered DCF method to compute the LCOE, meaning that financial interest has been taken into account and the discount rate is represented by the cost of equity in the computation of the NPV. The analysis was carried out at constant prices (in US dollar) of the year 2015, the plant lifetime was taken from the model as 40 years and the technical preparation phase, construction phase, and decommissioning phase were all taken as ten years duration [17]. The paper presents a Levelized Cost of Electricity (LCOE) between 75 $/MWh and 160 $/MWh (average 117 $/MWh) and identifies an upper limit for the selling price of electricity at around $175/MWh. The analysis underscores the substantial impact of investment costs and the net efficiency of electricity production on the economic viability of the fusion plant. Moreover, it highlights the considerable influence of a lower level of industry expertise in fusion technology and the associated risks on the project's investment costs [17]. On the basis of gradually acquired know-how, however, the document states that this cost will decrease (i.e., Learning factor) by up to 40%, as already demonstrated in high-tech novel industrial projects [17]. Furthermore, the intrinsic safety features of fusion reactors render any need for augmenting the expenses associated with nuclear safety unnecessary. Similarly, there is minimal escalation in the costs linked to environmental protection. Consequently, it is expected that the investment costs for fusion power plants will progressively decrease with the development, refinement, and standardization of fusion technology, commencing from the initial plant and onwards. [17].

The study shows a limit sale price of electricity (175 $/MWh) that is several times higher than the market price of electricity at the time of the estimation: ~34 $/MWh in 2015 on the EU stock market [17]. It is evident the need for incentives in order to make this technology competitive in the market. As the paper suggests, the necessary funding, which amounts to approximately 141 $/MWh, is in a comparable range to the subsidies allocated to offshore wind energy, which amounted to 136

$/MWh in the European Union in 2012, considering the price level of 2015. Moreover, it significantly falls below the subsidies extended during the same year for photovoltaic plants, which stood at 249 $/MWh, also adjusted to the 2015 price level [17].



	Nuclear	Coal	Natural gas	Wind onshore	Fusion	Solar large PV	Wind offshore
Min	41	77	67	44	75	81	138
Max	103	109	140	185	160	243	280
Average	71	93	103	114	117	162	209

Figure 8.1: LCOE comparison of different technologies [17]

In conclusion, the paper enhanced the potential that fusion energy can have in tackling climate change as, given the inexhaustible fuel with insignificant price, inherent nuclear safety as well as its negligible environmental impact, there will be great scope for reducing investment costs on the basis of technological research and development with high probability to become the cheapest and cleanest energy source since the end of this century for an unlimited time onwards [17].

8.3 DTT project proposal

Eventually, the study conducted by ENEA [59] estimates the cost of the Divertor Tokamak Test (DTT) project, a top priority project for the European research community, since it represents an important step towards the realization of a DEMO reactor [59]. DTT is an experimental reactor located in Frascati (Rome, Italy). Its main objective is to tackle mission n. 2 that emerges from the European Fusion Roadmap [39], which is the Heat-exhaust system. DTT is aimed at carrying out alternative solutions to the problem of disposing the heat load [44] by testing different divertor solutions that will be implemented in DEMO. The DTT magnetic fusion plant has the huge advantage of being a government project and, consequently, the level of data disclosure exhibits a significantly elevated magnitude with respect to the ARC one. In the DTT cost estimation methodology, the computation of the fabricated costs was estimated basing on analogous contracts for which ENEA and its partners were suppliers in preceding years for fusion ventures, the most relevant is JT-60SA.

JT-60SA (Japan Torus-60 Super Advanced) is a significant nuclear fusion research facility located in Japan. It is a superconducting tokamak in the commissioning phase, which is a device used to study and develop nuclear fusion as a potential future source of clean and virtually limitless energy. JT-60SA is a collaborative project between Japan and the European Union, with contributions from several other countries. The primary goal of JT-60SA is to advance the understanding of plasma physics and fusion energy production. It aims to demonstrate the feasibility of using magnetic confinement to achieve controlled nuclear fusion reactions [67].

Differently from the cost estimation of ARC and DEMO2 described above, this project proposal presents a relevant level of detail as it is the closest to the construction of the plant.

From the formal interview with the Chief Engineer Gian Mario Polli emerges that the components fabricated costs follow the breakdown presented in Table 8.8.

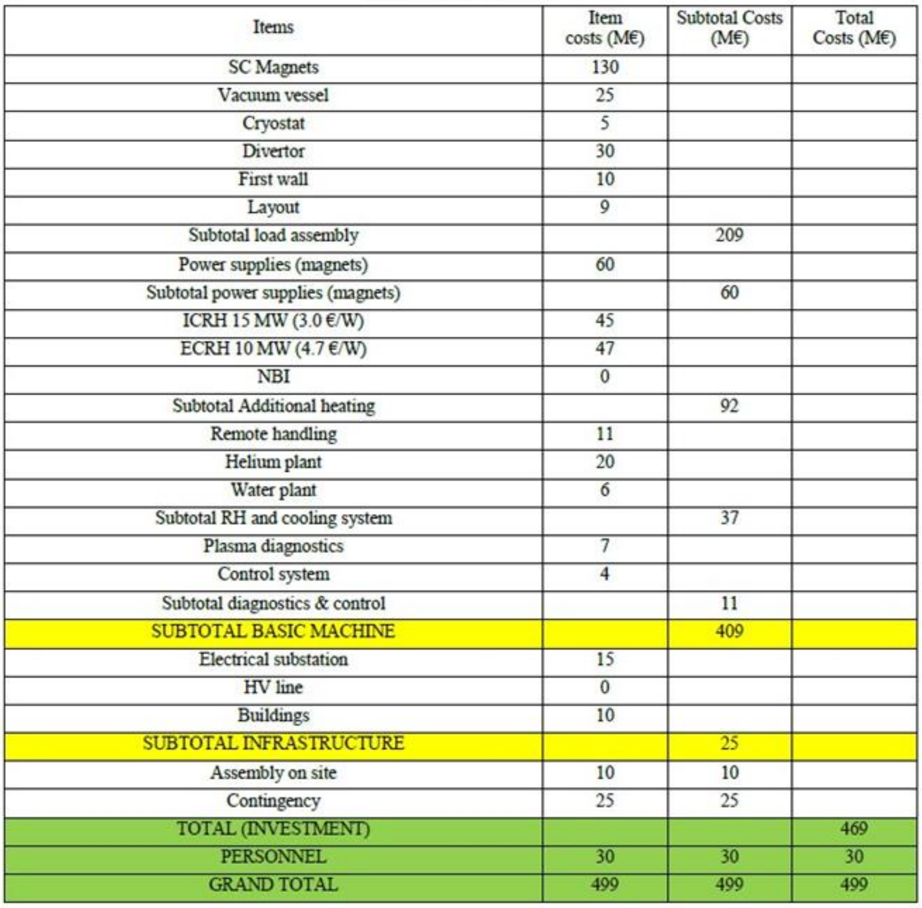
Table 8.8: DTT project proposal fabricated cost composition

Fabricated cost composition	Values
Engineering cost	15%
Material cost	25%
Labour cost	40%
Risk margin	20%

This breakdown was derived from the in-kind supplies provided by Europe and Italy for the JT-60SA magnetic fusion plant. Indeed, of the 800 M€ employed in the construction of JT-60SA, Europe was responsible for 400 M€ supply in-kind, of which 90 M€ comes from an Italian supply. As an example, Italy was responsible for the construction and supply of the TF coils. Henceforth, ENEA possessed comprehensive cost data at its disposal for this rationale. Concerning the assembly cost and the cost of components constructed directly on-site, ENEA possesses all the costs incurred by JT-60SA. These costs were adjusted by changing the unitary cost of Japan's manpower to the Italian one, taken from the "Ministero del Lavoro".

The breakdown shown in Table 8.8 was fundamental for the development of the model of this thesis. Indeed, once derived the material cost, by multiplying the material volume and weight needed for each tokamak component for the updated material costs in 2023, this breakdown was used for the composition of the tokamak components' fabricated cost.

Table 8.9: DTT cost breakdown [59]



Items	Item costs (M€)	Subtotal Costs (M€)	Total Costs (M€)
SC Magnets	130		
Vacuum vessel	25		
Cryostat	5		
Divertor	30		
First wall	10		
Layout	9		
Subtotal load assembly		209	
Power supplies (magnets)	60		
Subtotal power supplies (magnets)		60	
ICRH 15 MW (3.0 €/W)	45		
ECRH 10 MW (4.7 €/W)	47		
NBI	0		
Subtotal Additional heating		92	
Remote handling	11		
Helium plant	20		
Water plant	6		
Subtotal RH and cooling system		37	
Plasma diagnostics	7		
Control system	4		
Subtotal diagnostics & control		11	
SUBTOTAL BASIC MACHINE		409	
Electrical substation	15		
HV line	0		
Buildings	10		
SUBTOTAL INFRASTRUCTURE		25	
Assembly on site	10	10	
Contingency	25	25	
TOTAL (INVESTMENT)			469
PERSONNEL	30	30	30
GRAND TOTAL	499	499	499

Table 8.9 shows the DTT project cost breakdown, computed following the breakdown shown in Table 8.8. Nevertheless, from the interview to Engineer Gian Mario Polli emerges that nowadays the value of the grand total of DTT shifted from 500 M€ to 600 M€. DTT project proposal includes a detail of the cost composition of every single item shown in Table 8.9. As an example, for what concerns the cost of the SC magnets, that occupy the 62% of the tokamak cost (i.e., 130 M€ over 209 M€) the document provides a detailed cost estimation of every single component that constitute the SC magnets. In particular, the SC magnets has been divided into TF coils and PF coils. The TF coils include the cost of SC

cable (50 M€), winding (20 M€) and casing (15 M€), deriving a subtotal cost of 85 M€. The PF coils include the cost of the SC cable (33 M€), winding (10 M€) and rings (2 M€), deriving a subtotal cost of 45 M€.

The level of details shown in this document is due to the reliability of the cost data derived to supply in-kind components for the JT-60SA project. This cost reliability gives confidence that the components costs, and consequently the methodology used to determine these costs is reliable and it is the nearest to the costs effectively incurred to build up a tokamak.

9 Model description

9.1 Model objective

This dissertation aims to provide a complete and updated cost estimation of an ARC-like plant by building a model to estimate its capital and operational costs. The aim of the model is to bridge the existing gap in the literature by providing an answer to Research questions RQ1 and RQ1.1 presented in Chapter 7. Indeed, the existing literature provides only a complete cost estimation of DEMO2 power plant and a cost estimation of only the tokamak components of ARC. Consequently, the objective of the thesis is to provide a complete and updated cost estimation of an ARC-like magnetic fusion power plant, providing an answer to RQ1, and build up a model to estimate the LCOE of this plant providing an answer to RQ1.1.

Once the LCOE of the ARC-like magnetic fusion power plant is obtained, a further step involves analyses to optimize and canalize the research in what are the most important improvements to gain insight into the economic viability and competitiveness of magnetic fusion. These analyses aim to provide an answer to RQ2 and RQ2.2.

This chapter delineates the methodology utilized in constructing the cost estimation model. The development of this methodology stemmed from collaborative endeavors between the authors and key figures within the Italian magnetic fusion industry, alongside scientists from MIT involved in the ARC project. Notably, ENI stands as the main Italian entity to have invested in Nuclear Fusion, backing CFS, a spin-off of the Massachusetts Institute of Technology (MIT) and the originator of the ARC project. ENI's investment encompasses both financial resources and expertise, actively supporting CFS in the industrialization of magnetic fusion. This backing is facilitated by an entire team led by Dr. Francesca Ferrazza, the head of magnetic fusion at ENI. The pivotal role played by the ENI team significantly contributed to the thesis's development, offering technical support crucial in comprehending the technology and formulating a congruent model. Furthermore, the authors engaged with the Chief Engineer of ENEA, DTT Gian Mario Polli, and his associates and participated in various forums and conferences. Throughout their collaboration with ENI, the authors had the privilege of participating in the "ENI&MIT Accelerating Innovation" meeting, where significant advancements in magnetic fusion technology were unveiled by MIT researchers, as well as key representatives of CFS, including CEO Bob Mumgaard and Head of Tokamak operations Alex Creely.

The wealth of experience acquired from these engagements endowed the thesis authors with the knowledge and expertise necessary to construct a model coherent with the technology and design of the analyzed plant.

9.2 Cost estimation of ARC Power Plant founds in literature

Chapter 8, shows all the different methodologies employed in the literature to estimate the costs of a magnetic fusion power plant. Specifically, regarding ARC, a unique study in the literature conducted by Sorbom, et al. [38] (2015) presents a rough estimation of the ARC reactor costs (excluding the BOP, buildings, and indirect costs). Following Sorbom's publication, subsequent studies universally regard this document as a fundamental point of reference for conducting cost estimations pertaining to ARC. The main criticalities are that this cost estimation methodology is defined as "rough" by Sorbom himself and, to compute the reactor components' fabricated costs, it takes as a reference a study conducted in 2002 considering the estimation of plants design of 2002 and before.

9.3 Assumptions

The nuclear fusion industry is characterized by a high paucity of data, and consequently, the literature is scarce of studies related to the costs of this technology. For these reasons, the cost model presented in this Chapter is a first draft, which can be updated when future costs and data will become more available.

The assumptions made during the construction of the model are described below:

1. The analysis focuses solely on magnetic fusion, specifically tokamak technologies;
2. It has been considered a magnetic fusion power plant oriented only to the production of electricity as a revenue stream. This is justified by the fact that all the project configuration of magnetic fusion power plants nowadays are oriented to the production of electricity, even considering that electrification is one of the major milestones of the decarbonization of the energy system. Furthermore, the production of electricity is necessary for the functioning of the plant itself. Nevertheless, the production of thermal energy will be a strategic decision for future plants when magnetic fusion will be a mature technology;

3. It is assumed that all technological milestones have been achieved, and the plant is deemed prepared for operation;
4. The cost data found with proportions with DEMO2 plant have been assumed technologically equal. This assumption has been made solely for components that are conceivably equal across different plants, such as buildings or supporting systems;
5. The plant lifetime (40 years), the turbine efficiency (40%) and the tritium breeding ratio (TBR=1.1) are assumptions taken from the literature as described above. Indeed, usually in the studies related to cost estimation of magnetic fusion power plants, these data are assumed. The availability fraction of the plant (75%) and the structural availability (95%) are assumption analyzed with the ENI team that will be described below;
6. For the computation of the LCOE, the unlevered DCF methodology has been used. Consequently, the discount rate (r) represents the opportunity cost of capital and, since an energy investment is financed both from internal and external sources, the discount rate is equal to the so called Weighted Average Cost Of Capital (WACC). For sake of simplicity, the tax rate is assumed to be equal to 0;
7. As the model encompasses a lifetime of 40 years, it is presumed that to account for fluctuations in the exchange rate during this period, the equivalence of 1 dollar to 1 euro shall be maintained as a simplifying assumption.

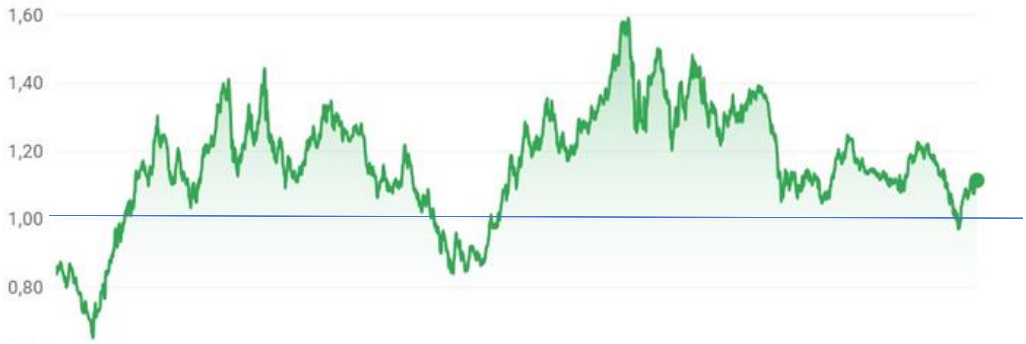


Figure 9.1: Dollar-Euro exchange [99]

9.4 Methodology

The Levelized Cost of Electricity (LCOE) is often cited as a convenient summary measure of the overall competitiveness of different generating technologies. It represents the unit cost (i.e., €/MWh) of building and operating a generating plant over an assumed financial life and duty cycle. It is useful measure as it provides a standardized way of comparing the costs of different energy technologies. Key inputs to compute the LCOE include capital costs (direct and indirect), ongoing operational and maintenance (O&M) costs, and an assumed availability. It also considers the expected energy output of the system over its lifetime. To compute the LCOE it has been used the Discounted Cash Flow (DCF) unlevered methodology in which has been calculated the Net Present Value (NPV) of the costs and the Net Present Value (NPV) of the electricity production over the project lifetime. The LCOE was computed as follows:

$$LCOE = \frac{\sum_t((Investment_t + O\&M_t + Replacement_t + Waste\ disposal_t + Decommissioning_t) * (1+r)^{-t})}{\sum_t((Electricity\ production_t * (1+r)^{-t})} \quad (9.1)$$

In which “r” is the cost of capital of the project.

The first step is the computation of the capital cost of the plant. Table 9.1 shows the main components of a magnetic fusion power plant as well as the most impacting cost objects. These items are described in detail in Chapter 3. Vacuum Vessel, Blanket and Divertor build the reactor system, that, with the magnets represents the tokamak, which is the core part of the magnetic fusion plant in which the reaction occurs. In Table 9.1 these components are represented in a simplified way, in order to guarantee a grade of flexibility when comparing the costs of different magnetic fusion power plant. These items’ composition will be shown in-depth when analyzing the specific costs of ARC. The Balance of Plant (BOP) is composed of the sum of all the auxiliary systems (i.e., vacuum system, cryogenic system, fuel handling system, heating and current drive system, cooling systems, control and diagnostics, maintenance equipment) and the Turbine plant. In the Buildings, it can be found buildings for civil works and civil structures and support buildings on the site (e.g., pipe/electrical tunnels, warehouses, reactor service (auxiliary) building). Direct costs are the results of the sum of all the costs already described, instead, indirect costs regard all costs not directly associated with the construction of the plant (e.g., field indirect, construction supervision, design services, Program Management (PM) and Construction Management (CM) services) [66]. It has been chosen to include the contingency in every item and not as a comprehensive value (as in the Entler, et al. study [17]) to differentiate it for each item. The contingency is an adder to account for uncertainty in the cost estimate. To compute these costs, it is important to have a comprehensive view of all the costs of the plant. For this reason, the starting point of the model are the investment costs of the plant.

Table 9.1: Capital cost items [17]

Component
Vacuum Vessel
Blanket
Divertor
Reactor systems
Magnets
Vacuum system
Cryogenic system
Fuel handling system
Heating & current drive system
Cooling systems
Control & Diagnostics
Maintenance equipment
Turbine plant
Buildings
Direct cost
Indirect cost
Contingency
Total investment costs

Once computed the CAPEX, an in-depth examination of magnetic fusion power plant operations outlined in literature and supported by ENI's provided narrative, enabled a comprehensive understanding of the operational costs encompassing the entire lifecycle of the plant.

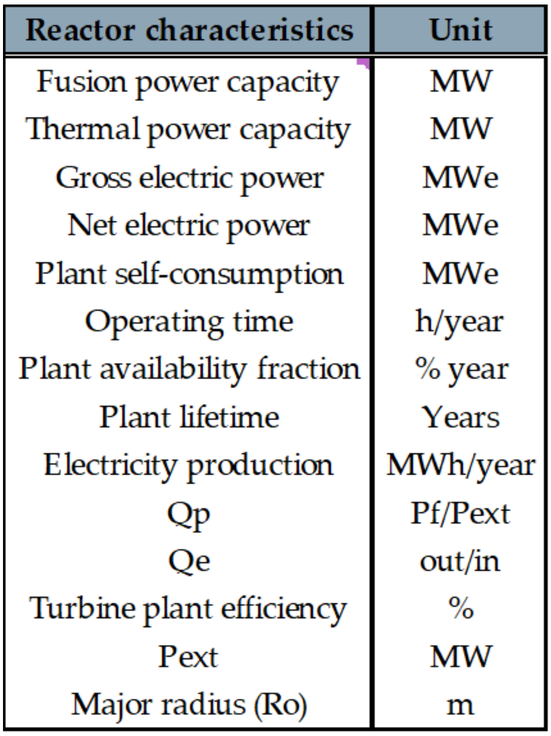
Table 9.2: Operational cost items [Own production]

Operational costs
Waste disposal
Maintenance
Components replacement
Decomissioning
Total

Table 9.2 shows what are the most impactful operational costs of a magnetic fusion plant. Waste disposal refers to the costs related to the disposal of radioactive waste. Indeed, the major share of the cost associated with the ongoing plant's operational phase is occupied by the components' replacement cost, that during the plant's lifetime have been activated by neutrons impacts, causing degradation of components. Other important operational costs are the general maintenance of the plant and the costs related to the decommissioning fund that covers the management and technical actions associated with the end of operation and withdrawal from service.

Eventually, it is needed to compute the amount of electricity produced by the plant. To do that, it is fundamental to understand what the reactor characteristics are, which are shown in Table 9.3.

Table 9.3: Reactor characteristics [Own production]



Reactor characteristics	Unit
Fusion power capacity	MW
Thermal power capacity	MW
Gross electric power	MWe
Net electric power	MWe
Plant self-consumption	MWe
Operating time	h/year
Plant availability fraction	% year
Plant lifetime	Years
Electricity production	MWh/year
Qp	Pf/Pext
Qe	out/in
Turbine plant efficiency	%
Pext	MW
Major radius (Ro)	m

The fusion and thermal power capacity, the plant self-consumption, plant lifetime and turbine plant efficiency, the external heating power (Pext) and the Major Radius (R0) are all data found in literature and depends on the different plant chosen.

The gross electric power is computed through the product between the thermal power capacity and the turbine plant efficiency.

$$Gross\ electric\ power = Thermal\ power\ capacity * Turbine\ plant\ efficiency\ (9.2)$$

The net electric power is the result of the difference between the gross electric power and the plant self-consumption.

$$Net\ electric\ power = Gross\ electric\ power - Plant\ self\ consumption\ (9.3)$$

Qp (i.e., plasma gain) is the ratio between the fusion power (i.e., Pf) and the external power (i.e., Pext), namely it is the ratio between the fusion output over the fusion input.

$$Q_p = \frac{P_f}{P_{ext}}\ (9.4)$$

Qp is a fundamental metric for assessing the viability of magnetic fusion. According to the scientific research, a commercial fusion power plant will need to achieve a plasma gain (i.e., Qp) equal to 10 [67]. At present, the world record has been set by JET magnetic fusion plant, which in 1997 achieved a Qp of 0.67 [25]. The plasma gain of the ARC power plant is 13.8.

Eventually, Qe (i.e., electric gain) is computed as the ratio between the gross electric power and the plant self-consumption.

$$Q_e = \frac{Gross\ electric\ power}{Plant\ self\ consumption}\ (9.5)$$

In order to understand the amount of electricity produced by the plant it has been considered the thermal power capacity of the plant in relation to the turbine plant efficiency. Furthermore, there is a difference between the net and the gross electric power related to the plant self-consumption in the operation phase. To compute the amount of electricity produced it has been considered the plant's availability fraction over the year. This data is fundamental as it takes into account the time to cool down the magnets before starting the process for the reaction, the time to substitute the activated components and every other pause for maintenance. The amount of electricity produced is the result of the product between the net electric power, the plant availability fraction, and the number of hours in the year.

$$Electricity\ production = Plant\ availability\ fraction * 8760 * Net\ electric\ power\ (9.6)$$

9.4.1 Availability

Plant availability refers to the extent to which a manufacturing or production facility is operational and able to perform its intended functions during a specified period. In this model, two different types of availability are performed:

- Structural availability: It comprehends the unscheduled downtimes caused by equipment failures, component failures, software and control system failures, power supply interruptions, instrumentation issues, human error, ageing infrastructure, quality control issues and others. The structural availability is assumed to be 95%;
- Tokamak availability: This availability includes all the planned stops of the plant in which the replacement of the components and the scheduled maintenance occur. To compute the tokamak availability, firstly the replacement time has been calculated. According to the ENI team, for the replacement of the vacuum vessel and blanket tank, the magnetic fusion power plant needs to stop from 1 to 3 months per year. This data was also validated through the literature. In the base case 3 months/year is chosen, meaning 2190 h/year. Consequently, the operating time has been computed by the difference of the total hours in a year and the replacement time. Eventually, the tokamak availability was computed through the ratio between the operating time and the total hours in a year.

$$Replacement\ time\ \left[{}^{h}/_{year}\right] = \frac{365\,\frac{days}{year}}{12\,\frac{months}{year}} * 24\,{}^{h}/_{day} *\ 3\,\frac{months}{year}\,(9.7)$$

$$Operating\ time\ \left[{}^{h}/_{year}\right] = 8760\ [h] - Replacement\ time\ \left[{}^{h}/_{year}\right](9.8)$$

$$Tokamak\ availability\ [\%] = \frac{Operating\ time\ \left[{}^{h}/_{year}\right]}{8760\ [h]}\ (9.9)$$

The total plant availability is computed as follow:

$$Availability\ [\%] = Structural\ availability\ [\%] * Tokamak\ availability[\%]\ (9.10)$$

9.4.2 ARC data research & validation

The second phase in building the cost estimation model is data research and validation. The only available data in the literature regarding the ARC costs are provided through the paper of Sorbom, et al., [38] (2015). As shown in Chapter 8, the ARC fabricated costs are computed using a rough scaling based on the total cost per weight of four different plants' cost estimation that refers to papers redacted between 1991 and 2002. On the other hand, the estimation of materials' volume and weight were estimated using estimation models and the experience gained through the years. Hence, given that the fabrication of components has a high impact on the total cost and the material cost weight only a small portion of the fabricated cost, it has been decided to take as reference only the components' raw material used, volume and weight. Building upon this foundation, a more dependable and punctual methodology has been taken as a reference to estimate the ARC fabricated cost. Indeed, the fabricated cost estimation methodology was elucidated through an interview conducted with the Chief Eng. Gian Mario Polli specifically assigned to the Divertor Tokamak Test Facility (DTT). In the DTT methodology, the computation of the fabricated costs was estimated basing on analogous contracts for which ENEA and its partners were suppliers in preceding years for fusion ventures, the most relevant is JT-60SA. Indeed, a direct cost comparison was conducted, whenever feasible, by employing size and technological disparities as criteria for comparison with JT-60SA. The selection of JT-60SA as a reference point was based on the following rationales:

1. Italy, particularly ENEA, actively contributed to the project through in-kind supplies, thus possessing actual supply cost data;
2. Among the completed projects, JT-60SA stands as the most recent endeavor;
3. The technologies employed in JT-60SA closely resemble those envisioned for DTT;
4. JT-60SA and DTT share a common classification as Category A radiogenic machines, necessitating comparable quality assurance (QA) systems.

As point 1. states, DTT holds, or has made estimations, regarding the fabricated cost associated with each component comprising JT-60SA. Indeed, of the 800 M€ employed in the construction of JT60SA, Europe was responsible for 400 M€ supply in-kind, of which 90 M€ comes from an Italian supply. Indeed, as stated by Chief Eng. Gian Mario Polli: "JT-60SA was an enterprise in which Europe contributed a total investment of about 400 M€ in-kind to the supply of equipment components for these supplies, of which Italy contributed about 90 M€. We practically have the detail, because for the Italian ones we certainly made them.". As an example, Italy was responsible for the construction and supply of the TF magnets. Henceforth, ENEA possessed comprehensive cost data at its disposal for this rationale. Concerning the assembly cost and the cost of components constructed directly on-site, ENEA possesses all the costs incurred by JT-60SA. These costs were adjusted by changing the unitary cost of Japan's manpower to the Italian one, taken from the "Ministero del Lavoro".

Table 9.4: Fabricated cost composition [Own production]

Fabricated cost composition	Values
Engineering cost	15%
Material cost	25%
Labour cost	40%
Risk margin	20%

Consequently, starting from the composition of each cost item, it has been built a breakdown of the fabricated costs. Table 9.4 shows the breakdown used to compute the fabricated costs. Given 100% the total fabricated cost of components, the table shows the different % related to each phase of the value chain. This breakdown does not encompass transportation costs due to their low significance in the overall cost distribution. Chief Eng. Gian Mario Polli stated: "There is a separate item of transportation costs, which typically do not significantly affect the overall cost of supplies".

The unitary material costs are taken from the paper Sorbom, et al. [38] (2015) and adjusted for an annual inflation of 2% from 2014 to 2023, except for the REBCO tape cost that has been increased from 18-36 €/m to 90 €/m. This is justified through the statement of two more recent papers, [68] (2022) and [69] (2023), which states that REBCO tape cost is between 80-100 €/m. Furthermore, in Chapter 10, a sensitivity analysis on material costs and REBCO cost have been performed, in order to analyze the impact that material costs have on the finale LCOE.

Furthermore, the risk margin shown in Table 9.4 has been adjusted in order to have a different risk among the items, basing on their level of uncertainties. In particular, for the tokamak components a contingency of 20% plus an alpha of 10% for a total of 30% of contingency has been taken into account for the high level of uncertainty of such innovative devices. For the auxiliaries (BOP), that are devices that already exist in other industries like robot arms for diagnostic system or cooling systems, a contingency of 20% has been taken as a standard value of infrastructure projects, as highlighted by the ENI team. Finally, a contingency of 10% has been taken for buildings and indirect costs as their costs are more reliable in the experience of project managers. Table 9.5 shows the different risk margin chosen for every plant component.

Table 9.5: Risk margin [Own production]

Component	Risk margin
Tokamak components	30%
Balance of Plant	20%
Buildings	10%
Indirect costs	10%

Table 9.6 illustrates the main components capital costs associated with the ARC reactor system, which have been segmented into significant subgroups that are elaborated upon in Chapter 3. These subgroups encompass the replaceable vacuum vessel, the blanket, the divertor, and the magnet/structure.

Table 9.6: Tokamak components costs [Own production]

Component	Volume	Weight [Tons]	Material	Material cost [M€]	Engineering cost [M€]	Labour cost [M€]	Risk margin [M€]	Fabricated cost [M€]
First wall	2.01 m3	3.72	Tungsten	0.13	0.08	0.21	0.18	0.59
Inner VV wall	2.03 m3	16.6	Inconel 718	1.11	0.67	1.78	1.52	5.08
Multiplier	4.09 m3	3.82	Beryllium	1.17	0.70	1.88	1.61	5.36
Outler VV wall	6.27 m3	51.4	Inconel 718	3.44	2.06	5.50	4.72	15.73
VV ribbing	0.83 m3	6.8	Inconel 718	0.46	0.27	0.73	0.62	2.08
VV posts	0.51 m3	4.14	Inconel 718	0.28	0.17	0.44	0.38	1.27
Replaceable VV subtotal	**15.7 m3**	**86.5**		**6.59**	**3.95**	**10.54**	**9.03**	**30.10**
Blanket tank	11.8 m3	97.1	Inconel 718	6.50	3.90	10.40	8.91	29.71
TiH2 shield	101 m3	380	TiH2	11.99	0.00	0.00	5.14	17.13
Channel FLiBe	4.09 m3	8.07	FLiBe	1.49	0.00	0.00	0.64	2.12
Blanket tank FLiBe	241 m3	475	FLiBe	87.42	0.00	0.00	37.47	124.89
Heat exchanger FLiBe	241 m3	475	FLiBe	87.42	0.00	0.00	37.47	124.89
Blanket subtotal	**599m3**	**1440**		**194.81**	**3.90**	**10.40**	**89.62**	**298.73**
Divertor			Tungsten	0.50	0.30	0.80	0.69	2.29
Reactor system				**201.90**	**8.15**	**21.73**	**99.34**	**331.12**
Magnet structure	544 m3	4350	Stainless steel 316LN	49.91	29.94	79.85	68.44	228.15
Magnet top ring	120 m3	959	Stainless steel 316LN	11.00	6.60	17.60	15.09	50.30
REBCO structure	40 m3	358	Copper	3.55	2.13	5.68	4.87	16.23
REBCO tape	5730 km	0	REBCO tape	515.70	309.42	825.12	707.25	2357.49
Magnet/structure subtotal	**704 m3**	**5670**		**580.16**	**348.10**	**928.26**	**795.65**	**2652.16**
Main components total	**1320 m3**	**7190 tonnes**		**782.06**	**356.25**	**949.99**	**894.99**	**2983.28**

For what concerns the balance of plant (BOP) and buildings, a third pillar was utilized, namely the cost estimation study on DEMO2 shown in Chapter 8. The study was deemed reliable as it is the most recent cost estimation on DEMO2 and as it relies on data provided by EUROfusion, a European consortium dedicated to the advancement of fusion energy. Consequently, this study exhibits a greater degree of disclosure compared to the Commonwealth Fusion System (CFS), the company entrusted with the construction of ARC. The DEMO2 cost model was used to estimate the BOP, buildings, and indirect costs. Table 9.7 shows the composition of the balance of plant (BOP) considered.

To compute the BOP of ARC based on DEMO2 cost estimation it has been utilized a proportion based on the major radius of the plasma (R_0). Indeed, while the reactor systems of ARC and DEMO2 are very different, as shown in Chapter 3, the auxiliaries' components can be considered the technologically comparable. Obviously, as the size of the two plants is very different, they have been adjusted through a proportionality to their respective plasma radius. The major radius is an effective proportionality index, as the BOP cost is strictly correlated to the dimension of the tokamak. The known data are the DEMO2 BOP cost and the DEMO2 and ARC major radius. Consequently, the ARC BOP was computed as follow:

Table 9.7: Balance of Plant [Own production]

Balance of Plant
Vacuum system
Cryogenic system
Fuel handling system
Heating & current drive system
Cooling systems
Control & Diagnostics
Maintenance equipment
Turbine plant

$$BOP_{ARC} = \frac{BOP_{DEMO2} * R_{0_{ARC}}}{R_{0_{DEMO2}}} \quad (9.11)$$

The same reasoning and formula have been used to compute the value of the buildings of ARC.

$$Buildings_{ARC} = \frac{Buildings_{DEMO2} * R_{0_{ARC}}}{R_{0_{DEMO2}}} \quad (9.12)$$

Table 9.8: BOP, buildings, and indirect cost estimations + grand total [Own production]

Component	Risk margin [M€]	Fabricated cost [M€]
Main components total	**894.99**	**2983.28**
Vacuum system	4.29	21.45
Cryogenic system	10.89	54.45
Fuel handling system	32.78	163.90
Heating & current drive system	48.29	241.45
Cooling systems	24.31	121.55
Control & Diagnostics	16.5	82.50
Maintenance equipment	33	165.00
Turbine plant	35.31	176.55
BOP subtotal	**205.37**	**1026.85**
Buildings	50.21	502.09
Total direct costs	**1150.56**	**4512.22**
Indirect costs	91.05	910.46
Grand total		**5422.68**

The indirect costs are associated with costs incurred by the firm, which are not considered “hands-on” construction. The indirect costs associated with the construction of a magnetic fusion power plant surpass those of a conventional energy plant primarily due to extended construction timelines. According to the estimate of the build timescale for a FOAK DEMO plant, the study conducted by Maissonnier, et al. [70] has projected a construction period of 8 years, followed by an additional 2 years for commissioning, for a substantial fusion power design with a 9-meter radius and a power generation capacity of 5000 MW. Similarly, the study conducted by Cook, et al. [71] has also estimated an 8-year construction duration for a fusion power facility with similar specifications, featuring a 9-meter radius and a 5000 MW power output. Furthermore, the study conducted by Federici, et al. [72] has indicated a construction timeframe of 10 years for their fusion power design, which, despite a slightly lower power output of 2000 MW, still incorporates a substantial 8.4-meter radius. Given its lower dimension compared to those plant analyzed, an ARC-like magnetic fusion power plant could incur in a lower construction time. Nevertheless, the construction timelines of a magnetic fusion power plant, even of a small dimension, surpass the timelines of construction of a conventional energy plant.

The indirect costs associated with a magnetic fusion power plant closely resemble those of nuclear fission [66], and a comprehensive delineation of these costs follows:

1. *Field Indirect Costs:* This account includes costs of construction equipment rental or purchase, temporary buildings, shops, laydown areas, parking areas, tools, supplies, consumables, utilities, temporary construction, warehousing, and other support services. It includes also the construction of temporary facilities (e.g. site offices, warehouses, shops, trailers, portable offices, portable restroom facilities, temporary worker housing, and tents), tools and heavy equipment used by craft workers and rented equipment, transport vehicles rented or allocated to the project, expendable supplies, consumables, and safety equipment, cost of utilities, office furnishings, office equipment, office supplies, radio communications, mail service, phone service, and construction insurance, construction support services, temporary installations, warehousing, material handling, site cleanup, water delivery, road and parking area maintenance, weather protection and repairs, snow clearing, and maintenance of tools and equipment;
2. *Construction Supervision*: This account covers the direct supervision of construction (craft-performed) activities by the construction contractors or direct-hire craft labor. It includes work done at the site in what are usually temporary or rented facilities;
3. *Commissioning and Start-up Costs*: This account includes costs for startup of the plant which are startup procedure development, trial test run services, commissioning materials, consumables, tools, and equipment;
4. *Demonstration Test Run*: This account includes all services necessary to operate the plant to demonstrate plant performance values and durations, including operations labor, consumables, spares, and supplies;
5. *Design Services Offsite*: This account covers engineering, design, and layout work. Often pre-construction design is included here. This account also includes site-related engineering and engineering effort (project engineering) required during the construction of systems, which recur for all plants, and quality assurance costs related to design;
6. *PM/CM Services Offsite*: This account covers the costs for project management and management support on the above activities (i.e. Field Indirect costs);
7. *Contingency on Support Services*: This account includes an assessment of additional cost necessary to achieve the desired confidence level for the support service costs not to be exceeded .

The indirect costs have been estimated by building the ratio between the indirect cost and the direct cost of DEMO2 and applying the ratio to the total direct costs of ARC.

$$Ratio = \frac{Indirect\ costs_{DEMO2}}{Direct\ costs_{DEMO2}}\ (9.13)$$

$$Indirect\ costs_{ARC} = Ratio * Direct\ costs_{ARC}\ (9.14)$$

Table 9.9 shows the model grand total. It can be seen that the tokamak components have been estimated following a bottom-up cost estimation, and the auxiliaries' components (i.e., BOP and buildings) and the indirect costs do not follow a bottom-up methodology but have been estimated through a proportionality with the DEMO2 reference plant.

Table 9.9: Model grand total [Own production]

Component	Volume	Weight [Tons]	Material	Material cost [M€]	Engineering cost [M€]	Labour cost [M€]	Risk margin [M€]	Fabricated cost [M€]
First wall	2.01 m3	3.72	Tungsten	0.13	0.08	0.21	0.18	0.59
Inner VV wall	2.03 m3	16.6	Inconel 718	1.11	0.67	1.78	1.52	5.08
Multiplier	4.09 m3	3.82	Beryllium	1.17	0.70	1.88	1.61	5.36
Outler VV wall	6.27 m3	51.4	Inconel 718	3.44	2.06	5.50	4.72	15.73
VV ribbing	0.83 m3	6.8	Inconel 718	0.46	0.27	0.73	0.62	2.08
VV posts	0.51 m3	4.14	Inconel 718	0.28	0.17	0.44	0.38	1.27
Replaceable VV subtotal	**15.7 m3**	**86.5**		**6.59**	**3.95**	**10.54**	**9.03**	**30.10**
Blanket tank	11.8 m3	97.1	Inconel 718	6.50	3.90	10.40	8.91	29.71
TiH2 shield	101 m3	380	TiH2	11.99	0.00	0.00	5.14	17.13
Channel FLiBe	4.09 m3	8.07	FLiBe	1.49	0.00	0.00	0.64	2.12
Blanket tank FLiBe	241 m3	475	FLiBe	87.42	0.00	0.00	37.47	124.89
Heat exchanger FLiBe	241 m3	475	FLiBe	87.42	0.00	0.00	37.47	124.89
Blanket subtotal	**599m3**	**1440**		**194.81**	**3.90**	**10.40**	**89.62**	**298.73**
Divertor			Tungsten	0.50	0.30	0.80	0.69	2.29
Reactor system				**201.90**	**8.15**	**21.73**	**99.34**	**331.12**
Magnet structure	544 m3	4350	Stainless steel 316LN	49.91	29.94	79.85	68.44	228.15
Magnet top ring	120 m3	959	Stainless steel 316LN	11.00	6.60	17.60	15.09	50.30
REBCO structure	40 m3	358	Copper	3.55	2.13	5.68	4.87	16.23
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Magnet/structure subtotal	**704 m3**	**5670**		**580.16**	**348.10**	**928.26**	**795.65**	**2652.16**
Main components total	**1320 m3**	**7190 tonnes**		**782.06**	**356.25**	**949.99**	**894.99**	**2983.28**
Vacuum system							4.29	21.45
Cryogenic system							10.89	54.45
Fuel handling system							32.78	163.90
Heating & current drive system							48.29	241.45
Cooling systems							24.31	121.55
Control & Diagnostics							16.50	82.50
Maintenance equipment							33.00	165.00
Turbine plant							35.31	176.55
BOP subtotal							**205.37**	**1026.85**
Buildings							50.21	502.09
Total direct costs							**1150.56**	**4512.22**
Indirect costs							91.05	910.46
Grand total								**5422.68**

Due to the paucity of data that describe the magnetic fusion operational costs, the methodology used for their computation was the same as the methodology adopted for the estimation of BOP and Buildings, described above. They have been taken as reference the operational costs of DEMO2 showed in the study of Entler, et al. [17] (2018) described in Chapter 8. Since the replacement costs of ARC are known, it is easy to proportionate all the other costs to this item. It has been taken the relative percentage of replacement costs of DEMO2 (55% as in Table 9.10) and applied it as a reference for ARC. Therefore, if the total operational costs are 100% and replacement costs are 55% of the total, the other operational costs are respectively the percentages shown in Table 9.10.

Table 9.10: Operational costs proportionality [Own production]

ARC operational costs	**Values**	**Unit**	**% on total**	**DEMO2 operational costs**	**Values**	**Unit**	**% on total**
Operation & Maintenance	37.70	$/MWh	40%	Operation & Maintenance	9.81	$/MWh	40%
Replaceable components cost	52.31	$/MWh	55%	Replaceable components cost	13.61	$/MWh	55%
Waste disposal	2.15	$/MWh	2%	Waste disposal	0.56	$/MWh	2%
Decommissioning fund	3.00	$/MWh	3%	Decommissioning fund	0.78	$/MWh	3%
Total costs	**95.16**	**$/MWh**	**100%**	**Total costs**	**24.76**	**$/MWh**	**100%**
tot op costs	**112.97**	**M€**		**tot op cost**	**154.96**	**M€**	
%capex	2.08%			%capex	1.82%		

The computation of replacement costs for ARC entails an analysis of both the expenses and frequency associated with the items necessitating replacement. In the case of ARC, the components requiring replacement consist of the Vacuum Vessel, the Divertor and the Blanket tank, with an annual replacement requirement. Therefore, the total annual replacement costs are the sum of the costs of these three items. To compute the cost per Megawatt-hour it has been done the ratio between the annual replacement cost and the annual electricity production.

$$Replacement\ cost\ [\frac{M€}{MWh}] = \frac{Annual\ replacement\ cost\ [M€]}{Annual\ electricity\ production\ [MWh]} \quad (9.15)$$

9.4.3 Model output

In this paragraph the output results of the model are shown. Table 9.11 shows the ARC reactor characteristics taken into account in the model.

Table 9.11: ARC reactor characteristics [Own production]

Reactor characteristics	**Unit**	**Value**
Fusion power capacity	MW	525
Thermal power capacity	MW	708
Gross electric power	MWe	283.2
Net electric power	MWe	190.2
Plant self-consumption	MWe	93
Operating time	h/year	6241.5
Plant availability fraction	% year	71.25%
Plant lifetime	Years	40
Electricity production	MWh/year	1187133.3
Qp	Pf/Pext	13.8
Qe	out/in	3.0
Turbine plant efficiency	%	40%
Pext	MW	38
R0	m	3.3

Table 9.12 shows the capital costs of an ARC-like magnetic fusion power plant. All items include the material cost, the engineering, labour cost, and risk margin.

Table 9.12: ARC-like plant capital costs [Own production]

Component	Cost [M€]
Vacuum Vessel	30.10
Blanket	298.73
Divertor	2.29
Reactor systems	**331.12**
Magnets	2652.16
Vacuum system	21.45
Cryogenic system	54.45
Fuel handling system	163.90
Heating & current drive system	241.45
Cooling systems	121.55
Control & Diagnostics	82.50
Maintenance equipment	165.00
Turbine plant (Rankine cycle)	176.55
Buildings	502.09
Direct cost	**4512.22**
Indirect cost	910.46
Total investment costs	**5422.68**

Table 9.13 shows the operational cost of the ARC-like magnetic fusion power plant.

Table 9.13: ARC-like plant operational costs [Own production]

Operational costs	Value [M€/year]
Waste disposal	2.56
Maintenance	44.76
Components replacement	62.10
Decomissioning	3.56
Total	**112.97**

The resulting LCOE of ARC plant is 437.53 €/MWh. The LCOE has been computed through the formula:

$$LCOE = \frac{\sum_t((Investment_t + O\&M_t + Replacement_t + Waste\ disposal_t + Decommissioning_t) * (1+r)^{-t})}{\sum_t\ ((Electricity\ production_t * (1+r)^{-t})} \quad (9.1)$$

The formula is based on the discounted cash flow (DCF) unlevered method, which aims at discounting cos ts and electricity production for the cost of capital taken as discount rate. Essentially it is the ratio between the net present value (NPV) of the discounted costs and the net present value (NPV) of discounted electricity production of the project. For the sake of completeness, the values are substituted in the formula obtaining:

$$\mathrm{LCOE} = \frac{\sum_s 62.1_s \sum_{\mathrm{t}}((5422.68_{\mathrm{t}} + 44.76_{\mathrm{t}} + 2.56_{\mathrm{t}} + 3.56_{\mathrm{t}}) * (1 + 0.07)^{-\mathrm{t}})}{\sum_{\mathrm{t}}((1187133.3_{\mathrm{t}} * (1 + 0.07)^{-\mathrm{t}})} \quad (9.16)$$

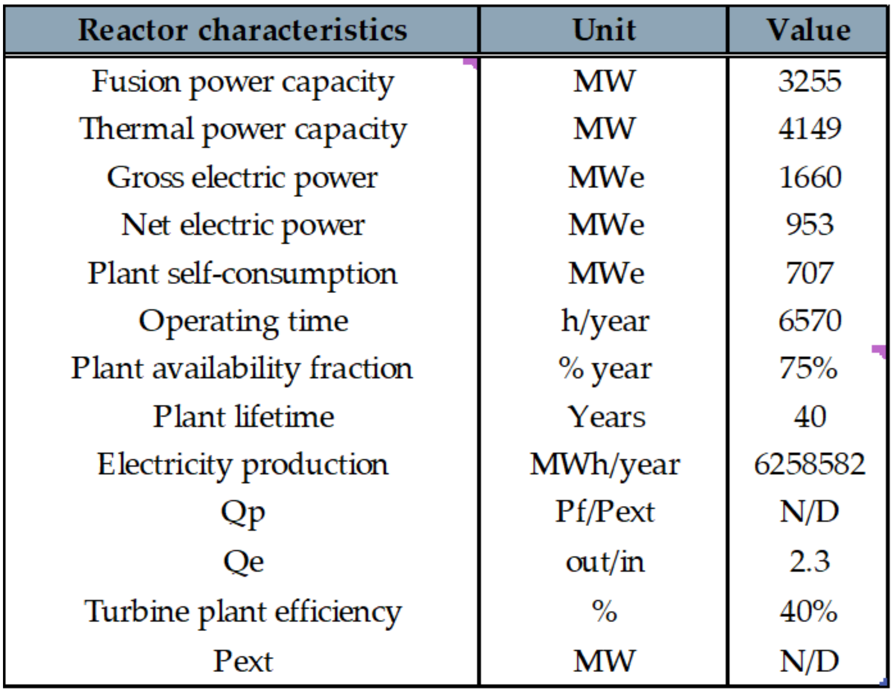
With t ranging from 1 to 40 and s ranging from 1 to 39. These values represent the lifetime of the plant assumed at 40 years. The reason why the ranges start from 1 is due to the construction phase of the plant assumed to elapse in t,s=0. Therefore, the plant operates from t,s=1 to 40. The range s represents the rate of substitution of components that must be substituted once per year until the last year of operation starting in t,s=39. Hence at the end of t=40 the components are not to be replaced because will start the decommissioning phase of the plant.

9.4.4 Model validation

In order to validate the accuracy and reliability of the model, it was applied to DEMO2 to assess whether the resulting Levelized Cost Of Electricity (LCOE) falls within the range stipulated by existing literature, as resented by the work of Entler et. al [17] (2018) (i.e., min=75 \$/MWh, average=117 \$/MWh, max=160 \$/MWh).

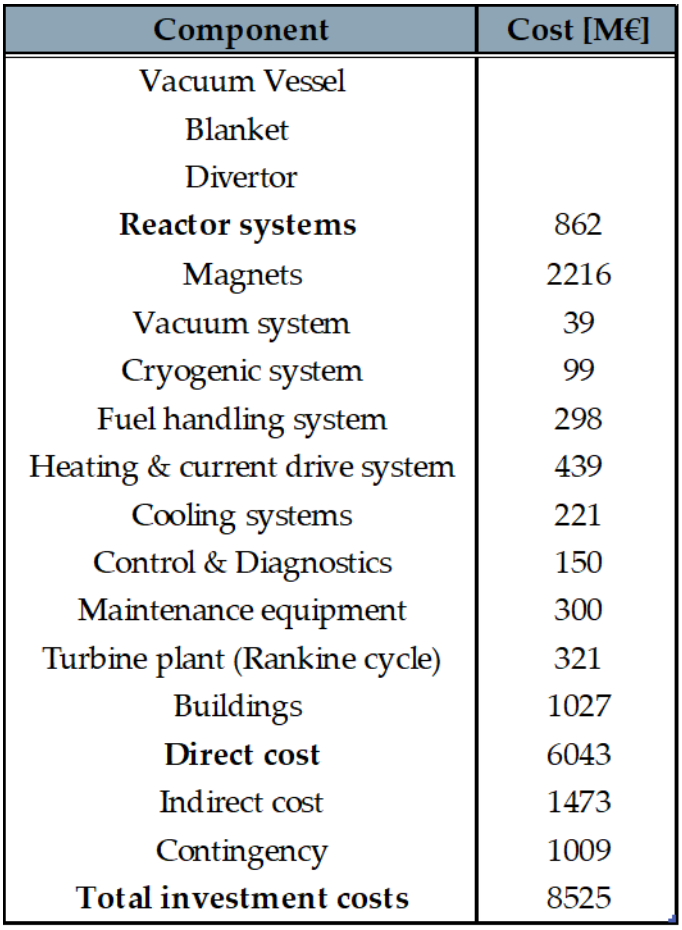
Starting from DEMO2 reactor's characteristics and investment costs, pertinent data extracted from the literature have been employed as inputs for the model. Table 9.14 and Table 9.15 show DEMO2 reactor characteristics and the investments costs, respectively.

Table 9.14: DEMO2 reactor characteristics [17]



Reactor characteristics	Unit	Value
Fusion power capacity	MW	3255
Thermal power capacity	MW	4149
Gross electric power	MWe	1660
Net electric power	MWe	953
Plant self-consumption	MWe	707
Operating time	h/year	6570
Plant availability fraction	% year	75%
Plant lifetime	Years	40
Electricity production	MWh/year	6258582
Qp	Pf/Pext	N/D
Qe	out/in	2.3
Turbine plant efficiency	%	40%
Pext	MW	N/D

Table 9.15: DEMO2 Capex [17]



Component	**Cost [M€]**
Vacuum Vessel	
Blanket	
Divertor	
Reactor systems	862
Magnets	2216
Vacuum system	39
Cryogenic system	99
Fuel handling system	298
Heating & current drive system	439
Cooling systems	221
Control & Diagnostics	150
Maintenance equipment	300
Turbine plant (Rankine cycle)	321
Buildings	1027
Direct cost	6043
Indirect cost	1473
Contingency	1009
Total investment costs	8525

Due to the absence of literature papers that explicitly present the absolute values of Operation & Maintenance (O&M) costs, but only the cost per Megawatt-hour ($/MWh), a more intricate method was employed to calculate the operational costs. Costs related to the maintenance, waste disposal and decommissioning fund were estimated using the cost per Megawatt-hour taken from the literature multiplied for the plant electricity production. Instead, regarding the replacement costs, it was considered inaccurate to compute the overall replacement costs over the plant's lifetime and spread it annually, as it would not take into consideration the right discount factor in the computation of the costs' present value. Therefore, it was considered crucial to compute the replacement cost for each single year. Notably, in the case of DEMO2, the components requiring replacement consist of the Blanket, the First Wall, and the Divertor. Replacement intervals are set at 10.5 years for the former two components and 4.5 years for the Divertor. Hence, starting from the annual cost, it has been identified the number of times in which these components must be replaced during the plant's lifetime (i.e., 40 years). The result is that the first wall and the blanket must be replaced 3 times and the divertor 9 times. Unfortunately, the literature consolidates the costs of these three components into a singular entity referred to as the reactor system, thereby impeding the ability to discern the specific cost associated with each individual component. To estimate the single component's cost, it has been computed firstly the total cost of replacement over the lifetime, by multiplying the replacement costs found in literature (in \$/MWh) for the annual electricity production and for the lifetime (40 years). Secondly, the specific cost of the components was estimated through this formula:

$$\begin{aligned}&Tot\ replacement\ cost\\ &\quad = replacement\ \left[\frac{\$}{MWh}\right] * electricity\ production\ \left[\frac{MWh}{year}\right]\\ &\quad * lifetime\ [years]\ (9.17)\end{aligned}$$

$$Divertor = \frac{(Total\ replacement\ cost - 3 * reactor\ system\ cost)}{9-3}\ (9.18)$$

where the numerical values 3 and 9 correspond to the respective frequencies of replacement for the first wall and blanket, and the divertor over the entire operational lifespan.

First wall and blanket have been computed just as the difference between the reactors system cost and the divertor. It is enough to have a cumulated value because the frequency of replacement is the same.

Table 9.16: DEMO2 operational costs [Own production]

Operational costs	Value [M€/year]
Waste disposal	3.50
Maintenance	61.40
Components replacement	85.18
Decomissioning	4.88
Total	**154.96**

Once all the costs have been estimated, the model computes the Net Present Value of the costs and the Net Present Value of total electricity production to find the Levelized Cost Of Electricity (LCOE). The resulting LCOE from the developed model stands at 125.94 €/MWh, which falls well within the prescribed range presented in the literature.

9.5 Comparison with existing estimations

As can be seen the ARC LCOE is much higher than the DEMO2 LCOE and the estimated costs with the new methodology are different respect to Sorbom study results. This paragraph aims to explain the reason why there is such a difference in the values of the previous studies on cost estimation of a magnetic fusion power plant.

Looking at cost of the main components shown in Table 9.6, they can be compared with what was presented by Sorbom. The result is different showing a total of 5.5-5.6 B€ for Sorbom study and of about 3 B€ for the thesis model. This difference is due to the different methodologies utilized in the studies. Indeed, Sorbom, as shown in Chapter 8, to compute the fabricated costs used a Cost on Tonn methodology based on the ratio between the total cost of the plant and his weight, obtaining a coefficient and multiplying it for the weight of each component of the plant. This methodology was considered rough by Sorbom himself. Although different modern studies rely on it, the result obtained cannot be considered reliable because the methodology considers the heaviest component as the more difficult and expensive to fabricate. This statement is not coherent with reality. Furthermore, a value of 5.5 B€, considering only the tokamak components, would bring an enormous Grand total cost of the plant. Indeed, considering the Balance of Plant, Buildings, and Indirect Costs according to the methodology of the thesis model, the Sorbom costs would arrive at a Grand total of about 8 B€ (5.5 B€ + 2.5 B€) without consider the contingency of the tokamak components, as assumed already included in the cost of each component. With the same performances and same operational costs, the LCOE of this cost configuration would be 718.17 €/MWh, a completely out of the range and far from affordable. The methodology provided by Sorbom very conservative, but nowadays the beginning of work on the ARC plant is getting closer and a more realistic cost estimation is needed, also with the purpose of attracting investments and grants from governments.

For what concerns the comparison with the study conducted by Entler, it can be seen that the LCOE provided by the model is higher than the Entler's LCOE. Indeed, if the study conducted by Sorbom is conservative, the study on DEMO2 is optimistic. Firstly, looking at the contingency used by Entler, it is calculated at 12%, instead according to the reference cost breakdown proposed by ENEA (see Table 9.4), the contingency is taken at 20%. Moreover, this data was confirmed in a meeting with ENI, in which emerged that a contingency of 12% is too optimistic for such a complex project. Furthermore, the replacement rate of the components exposed to the neutron flux is assumed to be one every 4.5 years for the Divertor and 10.5 years for the Vacuum Vessel and the Blanket. In this case there is an incoherence in different scientific publications (i.e., Sorbom and Entler) providing very different lifetimes of components to be replaced. To explain why the Sorbom study is conservative, instead the DEMO2 study is optimistic, it is possible to look at the substitution rate and at the contingency. The contingency of DEMO2 is assumed to be at 12%, although the construction time is longer than ARC and the beginning of construction is more distant than the ARC plant beginning of work. Furthermore, DEMO2 is bigger due to the utilization of Low Temperature Superconductor that has a magnetic field weaker than the High Temperature Superconductor magnets needs a larger area of field to contain the plasma. DEMO2 is bigger but also more powerful, the high fusion power brings to high thermal power as show in Table 9.14 and high thermal power means higher neutrons flux. This effect is in contrast with the replacement rate chosen. It is useful to see what the effect on the DEMO2 LCOE is, when inserting more conservative assumption in the model. Indeed, adjusting the contingency at 20% and the replacement rate to one per year for every component, the resulting DEMO2 LCOE increases from 125.94 €/MWh to 260.79 €/MWh. The value is still lower but more realistic. Furthermore, a factor that influences the ARC LCOE is the cost of the magnet structure that occupies the 79% of the tokamak total and therefore has a huge impact. Hence, it is important to notice that the cost of the REBCO tape (the high temperature superconductor utilized in ARC) taken as reference is updated with today's cost from Lindley, et al. [69] that proposed a cost between 80-100 €/m. It can be noticed that in the literature there are esteems of the future cost of REBCO of about 10 €/m. Furthermore, the ARC LCOE is higher than the DEMO2 one as the ARC plant produces less electricity than DEMO2. Nevertheless, insights emerged from a meeting with ENI indicate that the ARC possesses the capacity to operate also at 1001 MW of fusion power, surpassing the initial assessment of 525 MW. Such an enhancement in power output could result in a doubled electricity production, consequently leading to a substantial reduction in the LCOE. Further reasonings and quantitative results on such improvement are deepened in Chapter 10. Eventually, the LCOE in the Entler study is computed through the Levered DCF methodology considering the cost of debt as an operational expenditure and not in the discount rate, which is instead associated only to the cost of equity. In the thesis model the discount rate considers both the cost of debt and the cost of equity (DCF unlevered). Given that the discount rate is considered at 7% for both studies, it can be understood that in the Entler study there is another underestimation of the LCOE compared to the one presented in the thesis model.

9.6 Limitations

The model's limitations are presented below:

1. In the computation of the operational costs, it has been decided with the ENI team to consider negligible costs that occupy a share of less than 1% of the total operational costs, such as fuel and electricity costs to start the plant operation. Specifically, the fuel cost pertains to the supply of deuterium and tritium, both of which can be considered negligible due to the relatively low cost of deuterium and the plant's capability to auto-produce tritium through tritium breeding process. Indeed, a tritium storage is necessary only at the beginning of the life of the first operational plant, as for the subsequent plants an internal tritium supply chain will be built sharing tritium among different plants. Regarding the electricity cost, it should be taken only the initial cost related mainly to the cooling phase of the magnets at the beginning of the operational phase of the plant. During this phase, explained in detail in Chapter 3, it is important to cool the magnets down to extremely low temperatures, necessitating a time frame ranging from one week to one month for completion. This process is very slow and requires a small but constant amount of electricity to prepare the magnets. For this reason, it has been decided with ENI team to not consider these costs;
2. In the computation of the Net Present Value, it has been assumed that all investment costs are incurred at t=0, a phase encompassing construction and plant preparation (e.g., cooling of the magnets), while electricity production starts at t=1;
3. The model does not incorporate the land footprint of the plant, nor does it account for potential issues concerning land rights and costs associated with soil occupation. On the other hand, it can be considered as an advantage for fusion in terms of MWh/land occupied ratio.

10 Sensitivity analyses

Once computed the costs and the LCOE of the ARC-like magnetic fusion plant, sensitivity analyses evaluate the prospective cost reduction opportunities inherent in magnetic fusion. The main focus of the sensitivity analyses is to provide a direction for the R&D efforts. These opportunities may materialize through technological advancement, the utilization of more cost-effective materials, the exploitation of economies of scale and economies of multiples, learning rates, and the development of a more structured supply chain.

The results gained from this Chapter aim to answer to the research questions RQ2 and RQ2.2.

10.1 Assumptions

1. Due to the paucity of data that characterize fusion industry, either the literature, nor the ENI team can state quantitatively what are the implications that an increase of a component's performance has on the increase/decrease of the other plant's performance. For this reason, this implication has been described in a qualitative way, and sensitivities has been made through a percentage variation to have an approximation of the implications.
2. Since there are no data available regarding the impact that a component's variation has on the other plant performances, it is necessary to analyze at maximum the variation of two items on the LCOE, through a matrix analysis. Indeed, components performance variations need to be made through a fixed variation of +/- 20% and +/- 40%. This analysis permits to have a range of 25 values of LCOE and gain insight about what is the pool of the LCOE variation.
3. The most relevant and uncertain items have been analyzed and are described below:
    - Thermal power capacity: it is an input variable with a base value of 708 MW, it determines the electric power and, consequently, the electricity production;
    - Efficiency: it refers to the turbine plant efficiency. The turbine plant will be a Joule-Bryton cycle or a Rankine cycle, with a reference efficiency of 40%. In the plant configuration it has been chosen a proven technology, as the main focus of researchers is to demonstrate the technological feasibility of fusion and not improvements in auxiliary technologies. Nevertheless, more efficient turbines have

been developed and could be included in the configuration to make the plant more efficient. This variable impacts on the electricity production;

- Availability: it refers to the availability fraction of the plant, also called capacity factor. It represents the number of hours in which the plant is in operation over the year. As explained in the Chapter 9, it is influenced by the rate of replacement of the activated components;
- Capex: they are referred to the project's capital expenditure. A fusion power plant is a high capital project, meaning that capex is the most important variable that could change the final LCOE;
- Cost of capital: it represents the project's discount rate. It is linked to the risk of the project. It represents the return for shareholders and debtholders that is proportional to the risk in which they incurred.

10.2 Methodology

With the aim of developing the right direction to optimize the research and development efforts to realize an ARC-like magnetic fusion power plant that will be cost efficient and competitive on the market, it is fundamental to understand what the plant cost items that impact the most on the LCOE are. The methodology for the analysis starts with a tornado graph in order to understand, with the same percentage variation (i.e., +/- 20%), what is the impact of each variable analyzed on the LCOE. Once understood what the most impacting items are, it has been conducted an independent analysis in order to show the space of improvement of each single item with a real reference. Afterwards, if two items are strictly correlated together, a double variable analysis has been conducted to see the combined impact on the LCOE.

10.3 Sensitivity analyses on performances

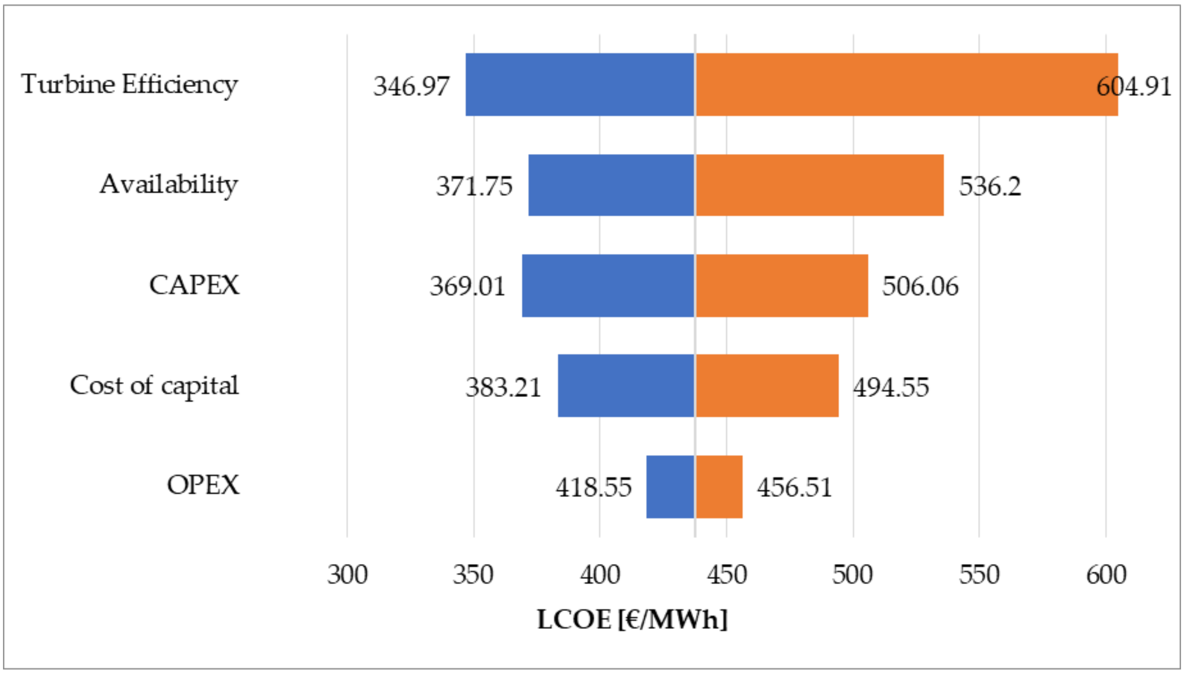


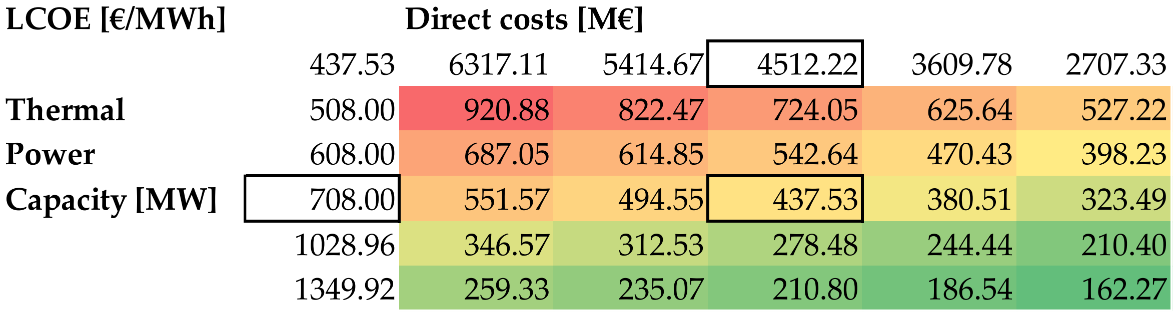
Figure 10.1: Tornado graph sensitivity [Own production]

Figure 10.1 shows what is the impact that a +/- 20% variation of the most significant cost items on the LCOE. From the graph emerges that turbine efficiency, availability, CAPEX and cost of capital are key cost drivers for the LCOE. This means that the R&D effort must be firstly directed into an improvement of the turbine plant efficiency, then plant availability, in which the highest impact is represented by the high replacement rate (i.e., 3 months/year). Subsequently, a reduction in CAPEX needs to be achieved, through the usage of new cheaper materials, learning rates, and exploitation of economies of scale and economies of multiples. Furthermore, magnetic fusion power plants are characterized by high capital costs and low operational costs, making the latter relatively low impactful on the LCOE.

In the next analysis, both the actual and prospective enhancements in performance have been leveraged to gain insights into the tangible potential reduction in the LCOE in the upcoming years.

10.3.1 Thermal power analysis

In the first analysis, the thermal power capacity has been analyzed. Indeed, one of the most promising improvements for magnetic fusion is the achievement of a higher point of fusion. It means to bring the plant's fusion power capacity from 525 MW (i.e., 708 MW thermal power) assumed to 1001 MW (i.e., 1349.92 MW thermal power). The achievement of this performance does not depend on the plant configuration but only on the contingencies related to the performances of the plasma inside the reactor. In fact, if the plasma is heated to higher temperatures than those assumed by Sorbom and more deuterium and tritium fuels are injected, the plant's performance would improve to the fusion power of 1001 MW. At the same time, in the Sorbom study it has been assumed a fusion power capacity of 525 MW in order to be more conservative and coherent with the material chosen. Indeed, with a higher fusion power, component materials would undergo a larger neutron flux and thus greater degradation. For these reasons, it is worth investigating the combined impact of Direct costs and Thermal Power Capacity.



LCOE [€/MWh]		**Direct costs [M€]**				
	437.53	6317.11	5414.67	4512.22	3609.78	2707.33
Thermal	508.00	920.88	822.47	724.05	625.64	527.22
Power	608.00	687.05	614.85	542.64	470.43	398.23
Capacity [MW]	708.00	551.57	494.55	437.53	380.51	323.49
	1028.96	346.57	312.53	278.48	244.44	210.40
	1349.92	259.33	235.07	210.80	186.54	162.27

Figure 10.2: Thermal power capacity – Direct costs sensitivity [Own production]

Figure 10.2 shows the impact of the effect described above on the LCOE. The framed values represent the baseline values. Direct costs have been varied of +/- 20% for each column. Thanks to the technical support of the ENI team, it has been understood that to increase thermal power capacity, it is needed to invest in more durable components, stronger magnetic field but also more sophisticated control systems. For this reason, it has been chosen to vary only the direct costs of the plant comprehending the components to be replaced, the magnets and the Balance of Plant and not consider the buildings and indirect costs, as they would not be impacted by such an improvement in performances. Consequently, it has been conducted a cross analysis with the Direct costs to understand the premium of such investments in the performances of the plant. Indeed, increasing direct costs until + 40% against an increase in the thermal power, would still lead to a relevant reduction of the LCOE.

10.3.2 CAPEX analysis

A fundamental variable to consider is the investment cost. As stated by Lindley et. al (2023), "Like other low-carbon plants, fusion plants are expensive to build and, hopefully, relatively cheap to operate, making capital cost a key cost driver" [69].

Deepening the key cost driver that causes the high CAPEX cost, from Figure 10.3 easily emerges that the key component in which effort must directed are the Magnets. Indeed, magnet cost accounts for 58.78% of all the direct cost, making this item the key cost driver for the CAPEX.

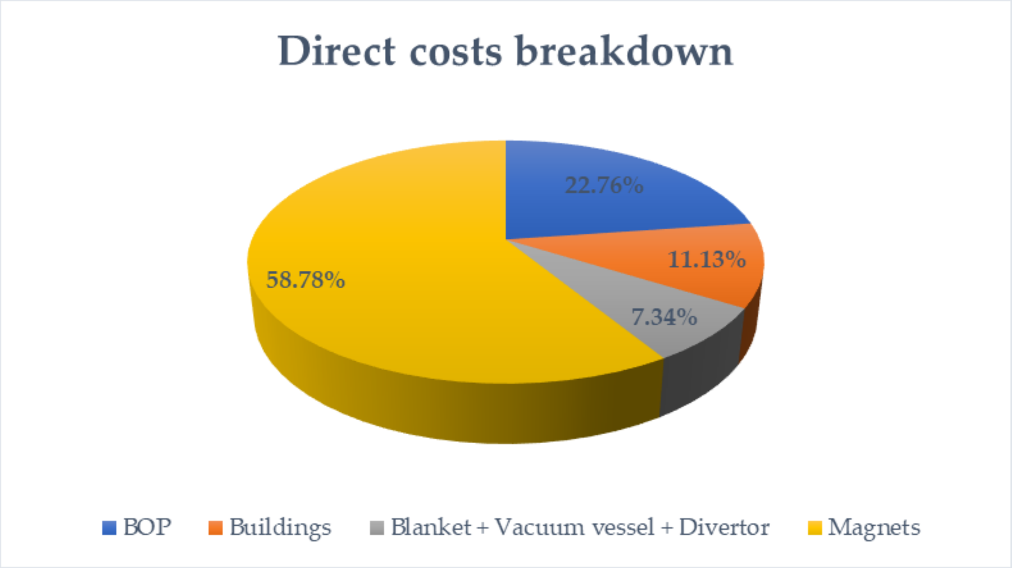


Figure 10.3: Direct costs breakdown [Own production]

Investigating the magnet cost composition, from Figure 10.4 easily emerges that magnet costs are occupied by 89% by the REBCO tape cost. This data states itself that REBCO tape is undeniable the key driver in reducing the LCOE. REBCO tapes are critical components in magnetic fusion research and technology, as they enable the creation of superconducting magnets that play a key role in confining and controlling the plasma necessary for nuclear fusion reactions.

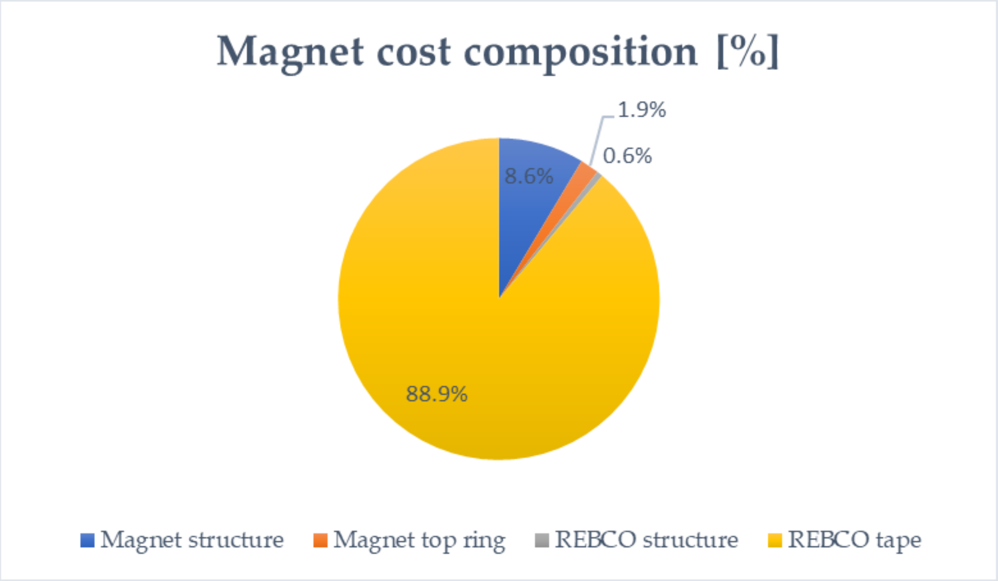


Figure 10.4: Magnet cost composition [Own production]

Although the magnet cost has the highest impact on capital expenditures, the REBCO conductor has significant room for cost reduction. From the literature emerges that cost of REBCO conductors can be reduced by an order of magnitude from today's 80-100 €/m to below 10 €/m [68]. By investigating what are the main causes that brings to such a reduction in cost, emerges that REBCO conductor do not suffer criticalities in the availability or costs of raw materials, but the high cost is associated only with the manufacturing process of tapes. Indeed, there are only few established companies, such as SuperOx [73] and SuperPower [74]. They do not produce in scale and consequently, their production capacity is low. Hence, this relevant reduction in cost will be enabled by the creation of a competitive market for the REBCO tape. Indeed, REBCO superconducting magnets can be potentially used in many industries different from magnetic fusion industry; REBCO magnets can be used for medical application, such as the magnetic resonance imaging (MRI) [75], but also for the construction of Gyrotron [76], superconducting magnetic energy storage (SMES) [77], MHD generator and long-distance transmission lines. If demand for REBCO increase, the probability that the production would consequently increase is high, creating a market for REBCO and reducing its cost. For this reason, a sensitivity analysis that shows the impact of the REBCO cost reduction on the LCOE has been drafted. Figure 10.5 shows the relevant impact that the REBCO tape cost has on the LCOE reduction.

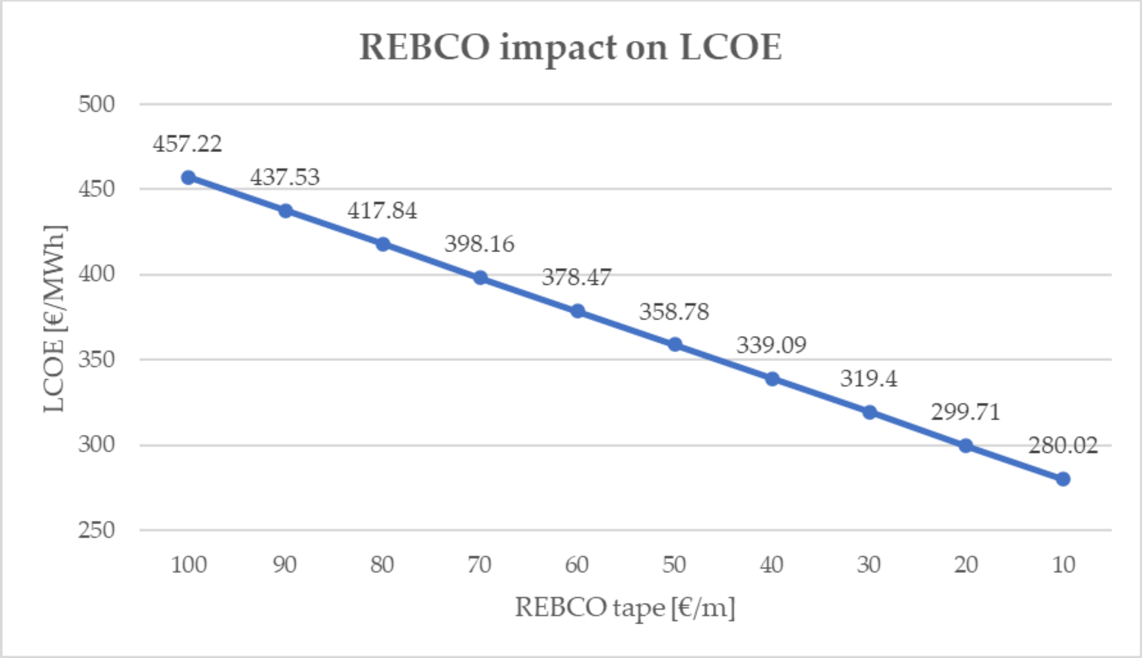


Figure 10.5: REBCO tape cost impact on LCOE [Own production]

From Figure 10.5 emerges the relevant impact of the reduction of the REBCO tape cost, indeed, the LCOE can be reduced of about 36% if REBCO tape cost will be reduced to 10 €/m.

10.3.3 Availability analysis

The availability is a relevant parameter for the reduction of the LCOE. It is strictly correlated with the frequency of the components' replacement, as it represents the number of hours in which the plant can operate, after deduction of the time needed to replace the components and to restart the reactor. During these stops, all the scheduled maintenance occurs. With the current plant configuration, the frequency of replacement is one time per year. As described in Chapter 9, the availability has been assumed at 71.25% in which it has been considered 95% of structural availability for non-predictable stops and 75% (i.e., time to replace equal to 3 months per year) for predictable stops to replace components. To understand if an increase of availability can bring to a relevant reduction of the LCOE, the frequency of replacement of components has been reduced, passing from 1 time per year to 1 time every 3 years and 1 time every 5 years which correspond to 87.08% and 90.25%, respectively.

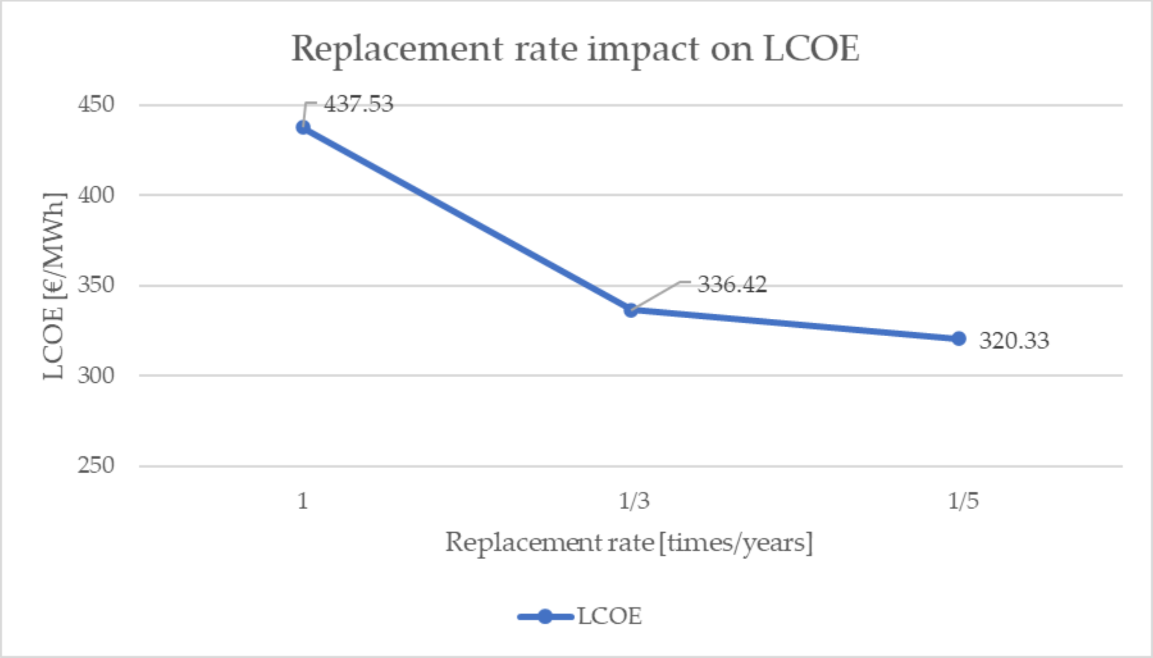


Figure 10.6: Replacement rate impact on LCOE [Own production]

Figure 10.6 shows that the replacement rate has a high impact on the increase of competitiveness of magnetic fusion. Indeed, replace the components once every 3 years and once every 5 years bring to a reduction of the LCOE of 23% and 27%, respectively. Nevertheless, reducing the replacement rate means increasing the robustness of materials to be replaced (i.e., Blanket tank, Vacuum vessel, Divertor). For this reason, investment in R&D must be made, with the purpose of making the component more resilient to the flux of neutrons.

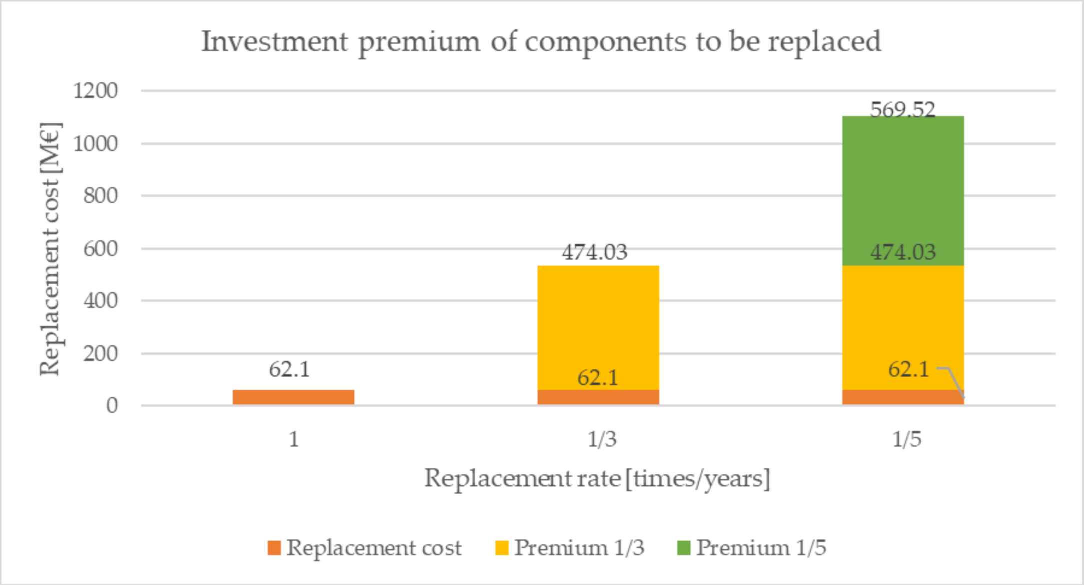


Figure 10.7: Investment premium of components to be replaced [Own production]

Figure 10.7 shows what is the amount of investment that can be done in more robust materials. Defining I_0, the baseline investment (i.e., 62.1 M€), the investment premium is defined as the portion of investment that can be done in addition to I_0, without reducing the fusion competitiveness and consequently maintaining the LCOE fixed. Indeed, if 62.1 M€ represent the replacement cost when the frequency of replacement is once per year, 474.03 M€ and 1043.55 M€ (i.e., 474.03 M€ + 569,52 M€) represent the amount of investment that can be additionally made in more robust materials, without reducing the LCOE competitiveness, in the cases in which the replacement rate is one every 3 and 5 years, respectively. To be more specific, the values of investments represent the maximum additional cost that can be spent to have the same LCOE. This analysis brings to the conclusion that investment in more robust material, with the purpose of reducing the replacement rate, create value for the project.

10.3.4 Materials cost sensitivity

With the aim of understanding where the research must canalize its efforts to invest and discover more resilient materials, it is useful to analyze the impact of materials cost on the LCOE. From Figure 10.8, it can be seen that a market distortion of +/-20% on the material cost has not a huge impact on the LCOE, with the exception of the REBCO tape and Inconel 718.

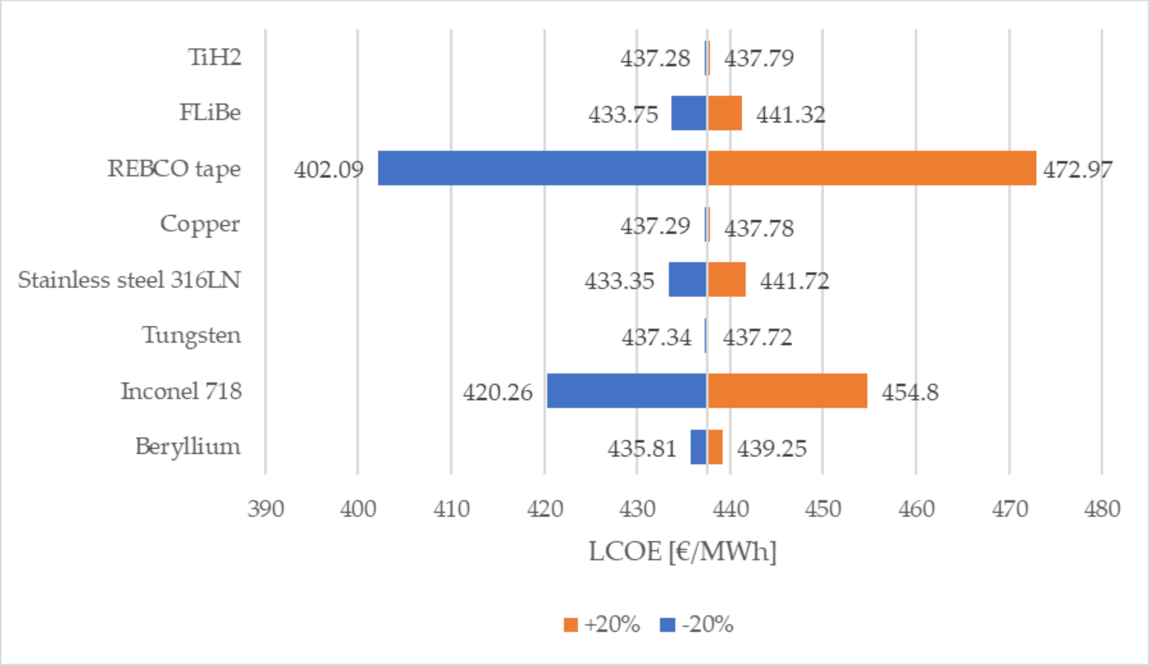


Figure 10.8: Materials cost sensitivity analysis [Own production]

Nevertheless, considering that the REBCO tape impact does not depend on its robustness, but only on the high costs and high amount of tape utilized in the reactor, the main research efforts must focalize on the Inconel 718, which is the material used for Blanket tank and Vacuum vessel.

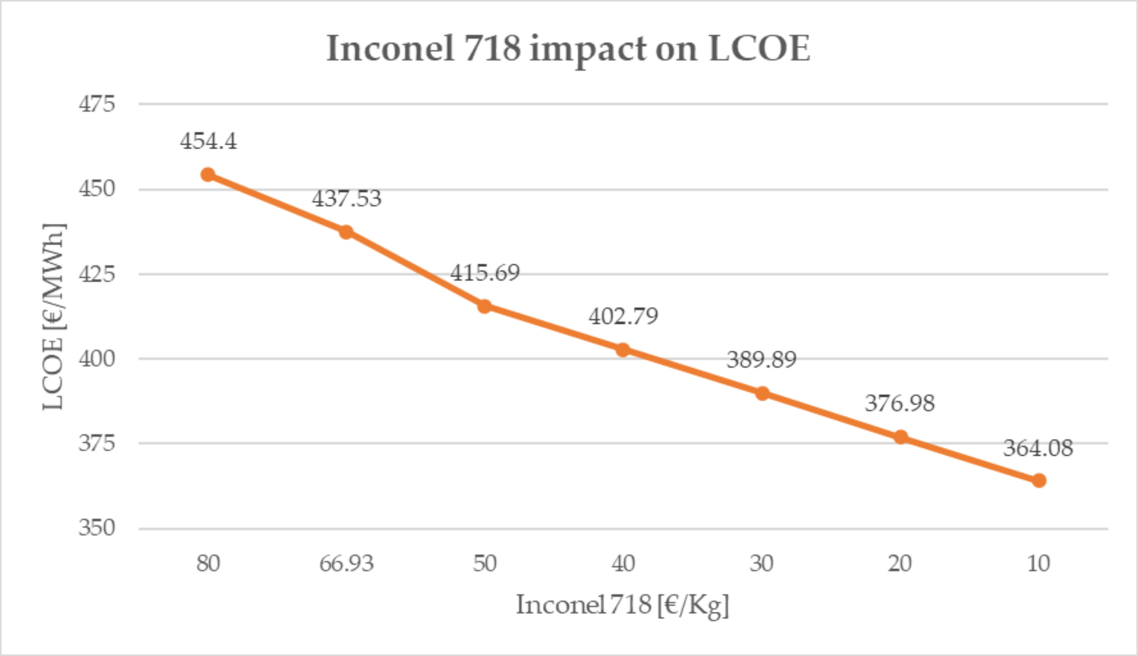
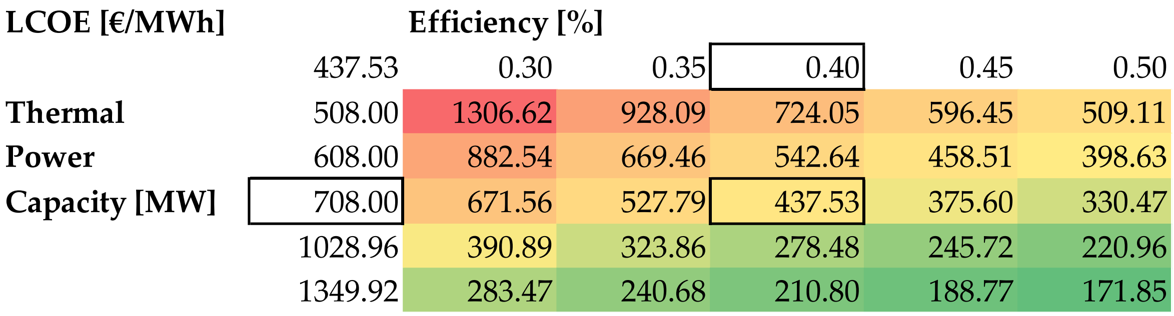


Figure 10.9: Inconel 718 analysis [Own production]

For this reason, it is worth analyzing the impact of Inconel 718 on the LCOE, as it is the first candidate to be substituted with other cheaper and/or more resistant materials. From Figure 10.9 emerges that if the cost of the material chosen to build the components to be replaced fell to 10 €/kg, the LCOE would be reduced of about 17%.

10.3.5 Turbine plant efficiency analysis

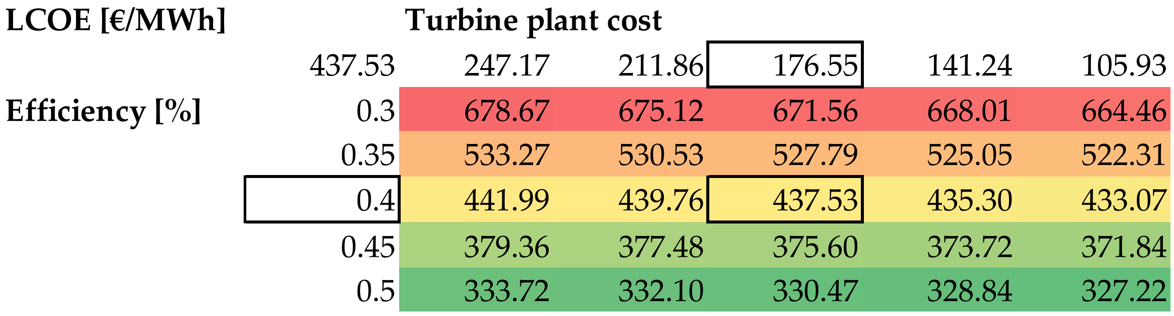
The turbine plant is responsible for the transformation of the thermal energy produced by the plant into electricity, through a thermodynamic cycle (i.e., Rankine cycle and Joule-Bryton cycle). In the plant design under analysis, it has been chosen a proven technology with an efficiency of 40%. According to the ENI team, this choice has been taken in order to reduce the technological risk variability. Moreover, the turbine plant was not the primary focus of magnetic fusion researchers, which prefer to concentrate their efforts in the internal reactor performances. Nevertheless, there are further technologies that could bring higher performance in the turbine plant up to 50% efficiency.



LCOE [€/MWh]		**Efficiency [%]**				
	437.53	0.30	0.35	0.40	0.45	0.50
Thermal	508.00	1306.62	928.09	724.05	596.45	509.11
Power	608.00	882.54	669.46	542.64	458.51	398.63
Capacity [MW]	708.00	671.56	527.79	437.53	375.60	330.47
	1028.96	390.89	323.86	278.48	245.72	220.96
	1349.92	283.47	240.68	210.80	188.77	171.85

Figure 10.10: Thermal power capacity - Efficiency sensitivity [Own production]

Figure 10.10 shows the combined effect that thermal power capacity and efficiency have on the LCOE. The framed values represent the baseline performances of the plant. Efficiency has been varied of +/- 5% each column. This analysis has been made as, theoretically, an increase of thermal power capacity would bring an increase in the turbine plant efficiency. Indeed, physics theory states that increasing temperatures enhance the efficiency of the thermodynamic cycle. The result on the LCOE is a significant combined effect reduction of about 61%, in the case of a 50% efficiency of the turbine plant and a 1350 MW of thermal power capacity.



LCOE [€/MWh]		**Turbine plant cost**				
	437.53	247.17	211.86	176.55	141.24	105.93
Efficiency [%]	0.3	678.67	675.12	671.56	668.01	664.46
	0.35	533.27	530.53	527.79	525.05	522.31
	0.4	441.99	439.76	437.53	435.30	433.07
	0.45	379.36	377.48	375.60	373.72	371.84
	0.5	333.72	332.10	330.47	328.84	327.22

Figure 10.11: Efficiency - Turbine plant cost sensitivity [Own production]

This LCOE reduction cannot be seen as a free reduction for research achievement, it has a cost derived from the turbine plant cost. Figure 10.11 analyses the impact of investing in a more efficient turbine on the LCOE. In the analysis the framed values represent the baseline and the costs have been varied by +/- 20% each column. As it is shown in Figure 10.11, an increase of 40% of the turbine plant cost with an increase of the efficiency to the 50% would keep the LCOE below the baseline. Consequently, it would be convenient to invest in the turbine plant to gain higher efficiency. The scientific research is currently focusing on internal reactor performances without considering the efficiency of the turbine plant yet. Nevertheless, it is important to highlight the real performances of magnetic fusion power in order to understand what the impact of such technology in the energy mix would be. Nowadays researchers are not focused on the of this technology but more on the realization of it and it is important to note how the two depend on each other.

10.4 Cost of capital sensitivity

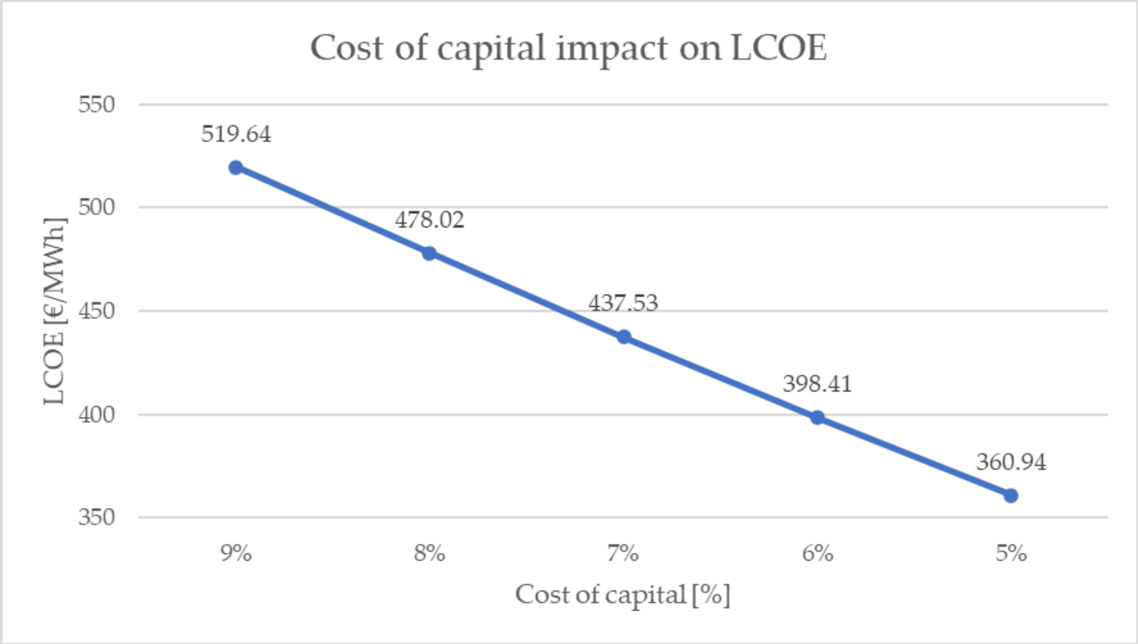


Figure 10.12: Cost of capital analysis [Own production]

Given the capital-intensive nature, extended construction timelines, and prolonged operational lifespans of the magnetic fusion power plant, it is imperative to emphasize the importance of the financing discount rate. Therefore, the conversation surrounding their financing, specifically regarding the responsible parties and the applicable interest rate, warrants significant attention from policymakers and decision-makers. Indeed, increasing the incentives would reduce the risk for shareholders and consequently reduce the cost of capital. Form Figure 10.12 emerges that reducing the cost of capital even of 2% can reduce the LCOE of about 18%.

10.5 Tritium breeding ratio (TBR) analysis

The Tritium breeding ratio TBR>=1 is a fundamental assumption for the construction and operation of the ARC magnetic fusion power plant. As stated by the literature, the assumed TBR is fixed at 1.1 in the model. Nevertheless, if this value is not achieved in the first commercial plant, an increase in the operational cost and consequently in the LCOE is expected. From the paper [78] emerges that a commercial tokamak needs an amount of 150 gr/day for 1 GW plant. This means that for ARC, the tritium needed is 78.75 gr/day (525 MW). The cost of tritium is fixed at 30.000 €/gr. Figure 10.13 shows the increase in operational costs bring by a reduction of 10% for each column of the TBR.

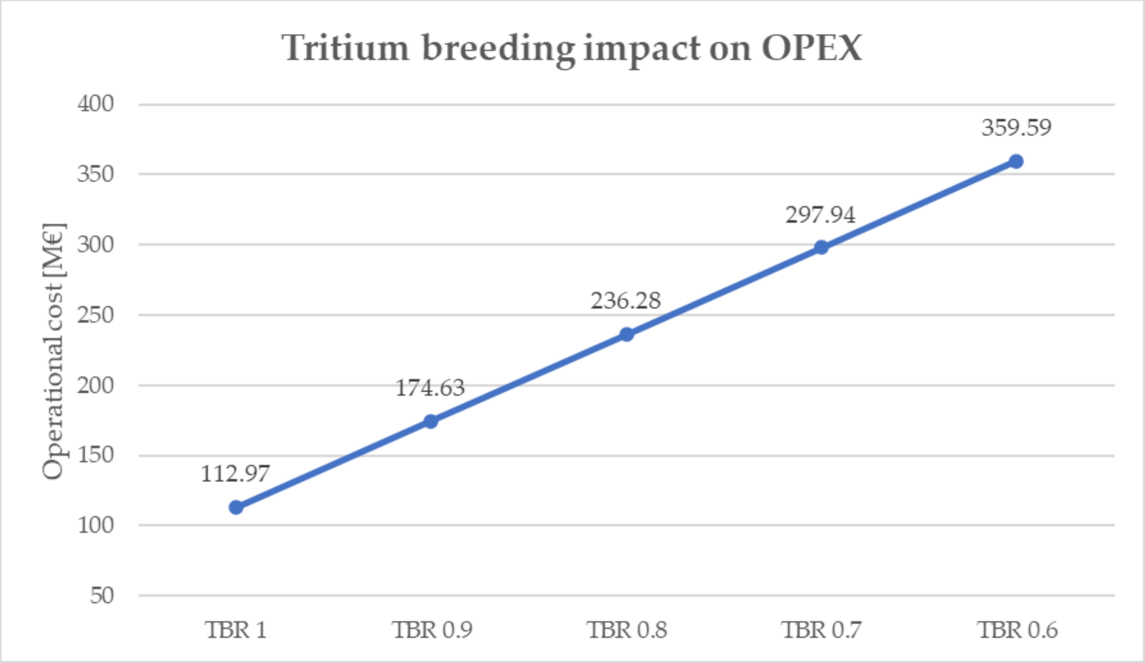


Figure 10.13: TBR impact on operational costs [Own production]

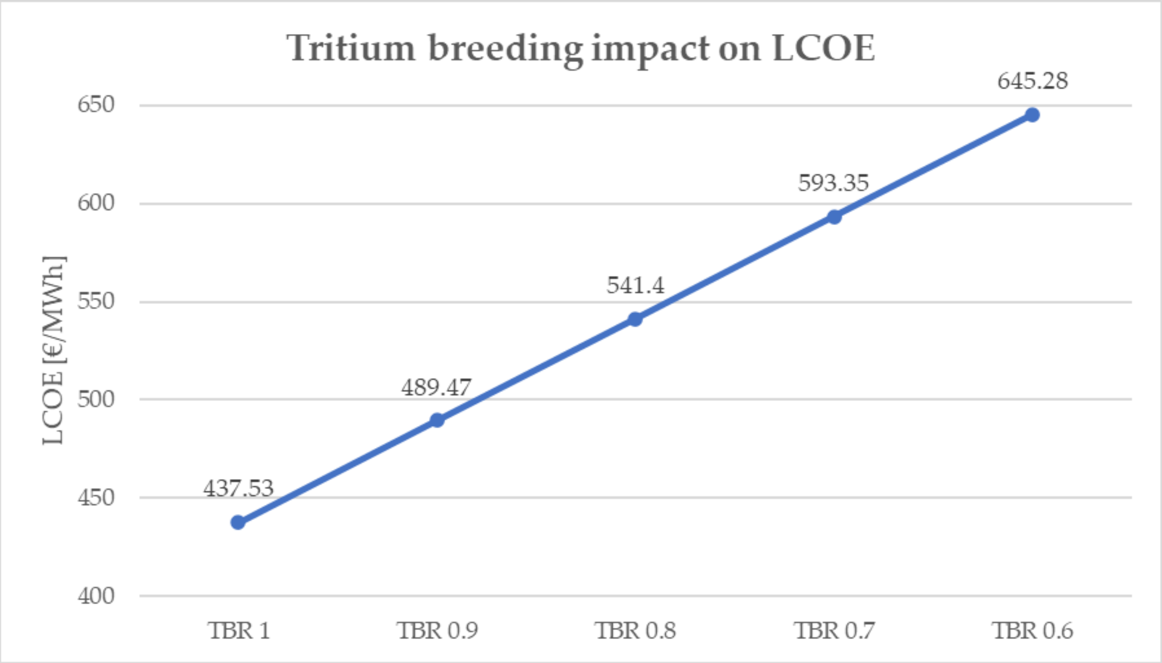


Figure 10.14: TBR impact on LCOE [Own production]

Figure 10.14 shows the impact that a reduction of the TBR has on the increase on the LCOE. It can be concluded that a TBR different from 1 causes a detrimental increase in the OPEX and LCOE, increasing 218% the OPEX and of 47.5% the LCOE.

10.6 Best case scenario

The sensitivity analyses showed that there are several areas of improvement for magnetic fusion to be more competitive on the energy market. It is interesting to see what are the performances that impact the most on the LCOE. Across all analyses conducted, it becomes evident that augmenting the plant's performance outweighs an increase in investment to achieve this result. To accurately ascertain the effect on the LCOE resulting from all potential enhancements achievable through increased investments in the plant, a comprehensive global sensitivity analysis was performed, adjusting all associated inputs accordingly. Indeed, the fusion power capacity has been increased from 525 MW to 1001 MW with a consequent increase in the thermal power capacity from 708 MW to 1349.92 MW. As explained above, an increase in thermal power brings higher temperatures that involve a higher neutrons flux and a higher degradation of components. Furthermore, with this change the plant would become more complex in general because it requires: stronger magnetic field, stronger heating systems, more reliable control systems and maintenance equipment and a more structured turbine plant to accept higher temperatures inside the cycle. For this reason, all the direct costs have been increased by about +920 M€ (i.e., +20%) also comprehending an increase in the cost of the components to be replaced and consequently an increase in the operational costs. For sake of completeness, the availability cannot be varied, as the investment in components to be replaced would increase their robustness for withstanding the higher temperatures but cannot exceed the previous performances in terms of replacement rate. Regarding the turbine plant, in the sensitivity analyses emerges that with a certain investment it is possible to increase its efficiency from 40% to 50% so it has been varied of about +53 M€ (i.e., +30%). The resulting LCOE is 194.25 €/MWh. Furthermore, as shown before, the cost of the REBCO tape can vary depending on the development of the industry from the price of 80-100 €/m to 10 €/m. As shown in Figure 10.15, such an improvement would make fusion very competitive bringing the LCOE to 135.06 €/MWh. It demonstrates that if researchers, companies, and governments would focalize their efforts in the right directions, magnetic fusion could be competitive on the market. Further reasonings are deepened in Chapter 11.

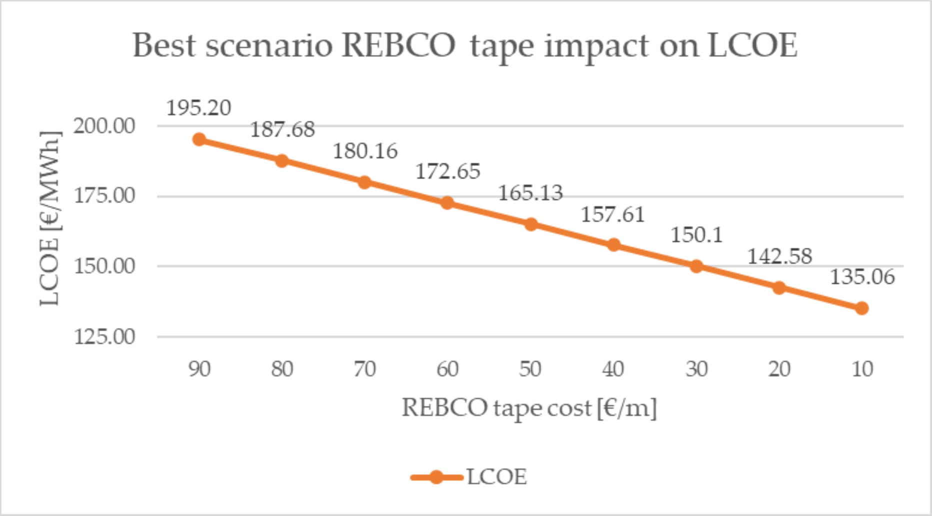


Figure 10.15: REBCO impact on best case scenario

10.7 Results analysis

The Levelized Cost Of Electricity [€/MWh] summarizes the overall competitiveness of different generating technologies. It assesses the unitary cost [€] per MWh of building and operating a generating plant. This paragraph aims at analyzing what are the mandatory and competitive milestones that, from one side contribute to the realization of magnetic fusion power plant, and on the other side contribute to increase the competitiveness of such a technology.

10.7.1 Mandatory milestones

Nowadays, there are no operational commercial magnetic fusion power plants. All the tokamaks, already constructed or in construction, are experimental machines aimed at demonstrating the technological feasibility of generating energy from fusion reaction. As stated in Chapter 5, in order to realize fusion energy, 7 technological milestones must be achieved. In particular:

1. Plasma confinement at high-temperature;
2. Management of the heat exhaust system;
3. Exploration of neutron-tolerant materials that can resist the flux of neutrons (14 MeV);
4. Achievement of the tritium self-sufficiency (tritium breeding ratio (TBR) >1);
5. Safety features management;
6. Inclusion of a Balance of Plant in order to generate electricity;
7. Achievement of a competitive price of electricity.

Within the framework of the thesis model, it is presumed that these milestones have been successfully attained, as the operational status of the plant is a prerequisite for electricity production. Indeed, to estimate the cost of an ARC-like plant, the plant configuration studies already assume that these technological challenges have been achieved and the plant is in operation, producing electricity. Nevertheless, if only one of these seven objectives is not obtained, it would be detrimental to the realization of magnetic fusion and/or to its competitiveness. As an example, the tritium breeding ratio (objective n. 4) sensitivities (see Figure 10.13 and Figure 10.14 in Chapter 10) shows that if this milestone is not achieved, a huge increase in the operational expenses, and consequently, in the LCOE, would negatively impact the competitiveness of this energy source.

10.7.2 Competitive milestones

Behind the mandatory milestones, there are several improvements that could enhance the performance of the ARC-like plant, positively contributing to the reduction of the LCOE. From the sensitivity analyses emerges that there are various areas of improvement with respect to the design and performances provided by the literature. Sensitivity analyses conducted in Chapter 10 are fundamental in understanding where the R&D needs to concentrate its efforts, in terms of time and cost, in order to make the electricity produced from an ARC-like plant more competitive on the market.

The most impactful cost drivers on the LCOE are the Thermal Power Capacity, the CAPEX, the availability, and the turbine plant efficiency. In order to achieve an increase in the performance of these items there are some factors to take into account. To achieve a higher thermal power capacity, it is imperative to achieve a higher fusion point, implying the necessity to confine the plasma at elevated temperatures. Nevertheless, upon reaching this milestone, it is anticipated that electricity production will nearly double, resulting in a significant reduction in the LCOE, from 437.53 €/MWh to 210.8 €/MWh (i.e., -52%) (see Figure 10.2). Furthermore, due to the capital intensiveness of this project, CAPEX is one of the key drivers for the reduction of the LCOE. Once conducting an analysis of the primary factors influencing capital costs, it becomes readily apparent that magnet costs play a fundamental role, accounting for 58.78% (see Figure 10.3) of the direct costs. Furthermore, REBCO tape accounts for 89% of the total expenditure of magnets (see Figure 10.4), meaning that R&D effort must concentrate on the cost reduction of this item. Indeed, the high cost of REBCO lies primarily from the limited scale of current production, rather than any issues related to its availability and supply. To address this issue, a global market for REBCO needs to be built. Starting from the establishment of a global demand for REBCO would result in increased production, subsequently unlocking the potential for the exploitation of economies of scale and cost reduction.

In the analysis of plant availability, it becomes crucial to emphasize that to enhance plant availability, the frequency of component replacements must be reduced. Increasing the plant availability from 71.25% (i.e., 3 months stop every year) to 87.08% (i.e., 3 months stop every 3 years) and 90.25% (i.e., 3 months stop every 5 years) results in a substantial reduction in the LCOE (i.e., 23% and 27%, respectively), but at the same time, entails allocating investments towards more durable materials for the vacuum vessel, blanket tank, and divertor, with the aim of reducing their rate of degradation. However, when assessing whether investing in more robust materials remains cost-effective, it becomes evident that there is a huge space of investment in more robust materials, without reducing the competitiveness of magnetic fusion.

For what concern the turbine plant efficiency, it is known that it is possible to achieve a higher level of efficiency (i.e., from 40% to 50%) thanks to more technologically advanced turbine plants. Concurrently, increasing efficiency necessitates higher investments in this technology, leading to an escalation in costs. However, when evaluating the return on this investment, it becomes evident that the value generated justifies the expense, even in the face of a substantial 40% increase in the turbine plant costs.

These analyses have the aim of identifying critical factors impacting the LCOE in ARC-like plants. Achieving higher thermal power capacity, addressing capital costs (particularly magnet costs), extending component replacement intervals, and improving turbine plant efficiency are key drivers for LCOE reduction. These insights offer a roadmap for future research and development efforts to enhance the competitiveness and sustainability of ARC-like plant technology in the energy market. To confirm this result in a quantitative way, a best-case scenario sensitivity has been conducted. Indeed, inserting the values of thermal power, turbine efficiency and increasing the amount of investment in the plant, the LCOE would decrease from 437.53 €/MWh to 195.2 €/MWh. Furthermore, if the cost of the REBCO tape would decrease to the value announced of 10 €/m, the LCOE would decrease to 135.06 €/MWh. It means a reduction between -55% and -69% of the LCOE if all the competitive milestones would be achieved.

11 Magnetic fusion competitiveness

11.1 European energy market

Technology costs are crucial in determining how demand for energy services is met in each sector or country. Comparing the fusion energy LCOE with the electricity price is fundamental to understand this energy source's potential attractiveness in the future. At present, in the current scenario of uncertainties and volatility of prices that characterizes the European energy market, estimating the forward price of electricity by 2030 cannot ignore a series of relevant issues.

The European electricity market has experienced fluctuations, uncertainties, and rising prices by Q1 of 2022. The price of both electricity and natural gas increased of four times during the Q3 of 2022 in comparison to 2021. This surge has raised significant concerns about the potential steep rise in energy expenses for both consumers and businesses. Fortunately, from the peak of Q3 2022, prices started declining, thanks in part to the higher temperatures that characterized winter. Figure 11.1 shows the detrimental increase of both European gas and power in the third quarter of 2022, followed by an unexpected price decrease.

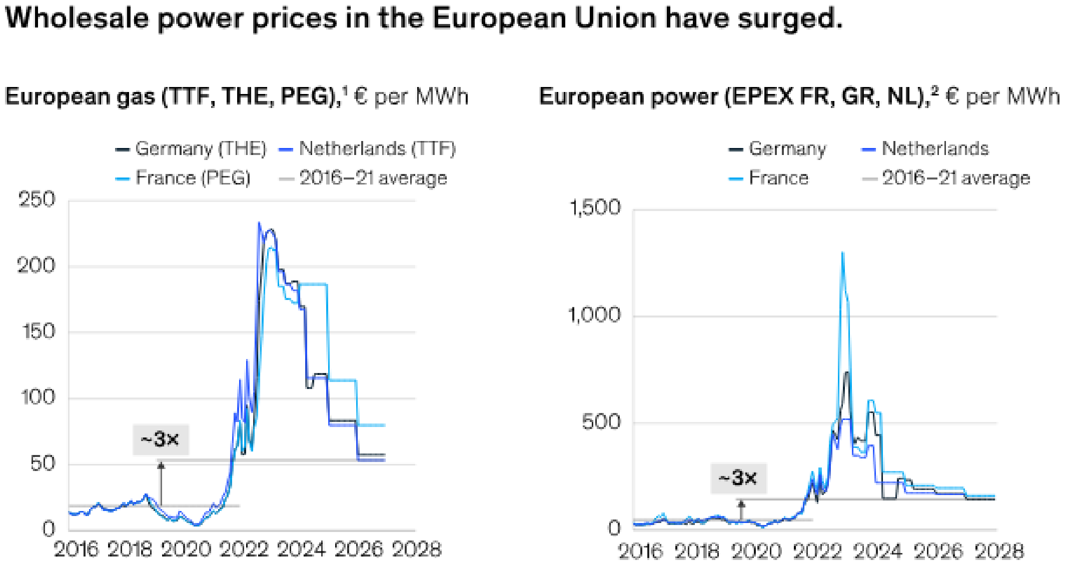


Figure 11.1: Wholesale power prices in the EU [79]

Such volatility highlights the challenges that Europe is facing in shifting away its energy supply from fossil fuels. At the same time, the stringent decarbonization targets are boosting electricity demand, increasing the need of extending the current energy supply constraints. Nevertheless, the war in Ukraine, shutdown of nuclear facilities in France, and low output from hydroelectric plants, have contributed in the opposite way by reducing EU dispatchable power [79]. Of these three events, certainly the most impactful was the Ukrainian war; before the war, Russia imports occupied the 30% of the total Europe's natural gas demand. To tackle the power shortage, many European utilities have increased coal production.

11.2 Forward price of electricity

Given the volatilises and uncertainties that characterize the European energy system, a dramatical change is expected in the coming years. Besides the impact of climate change and an outdated power plant infrastructure, the current geopolitical tensions forced and are forcing European Union to revolutionize their energy policies. In this scenario Energy Brainpool has estimated in the "EU EnergyOutlook 2060" [80] the forward price of electricity from 2023 to 2060 for European countries.

Energy Brainpool analyses four different scenarios, based on the evolution of the geopolitical tensions, and change in source of electricity supply.

In the *"Central"* scenario Europe will stop importing gas from the Russian pipeline by 2027 due to the current tension with Russia. Consequently, the gas price become highly dependent to the world market price for LNG. In the long term, green hydrogen and synthetic fuels will replace natural gas. A decentralization of the energy system, with a significant expansion of renewables occur, in order to lower the dependence on imports.

The *"Tensions"* scenario presumes that the existing tensions between Russia and Europe will persist and increase in the forthcoming years. For this reason, Europe stops the imports of Russian gas and, as in the Central scenario, the price of natural gas is based on the world market price for LNG.

In the *"Relief"* scenario, the tension between Europe and Russia will gradually diminish in the upcoming years. Hence, imports from the Russian pipeline gas will continue in the medium run. Nevertheless, policies fostering the decarbonization will lead to reduce the amount of imported gas and increase the share of renewables.

Eventually, the *"GoHydrogen"* scenario includes all the action needed to be taken to achieve the Europe-wide climate neutrality by 2050. In this scenario, hydrogen will substitute the natural gas in Europe, becoming one of the main energy carries.

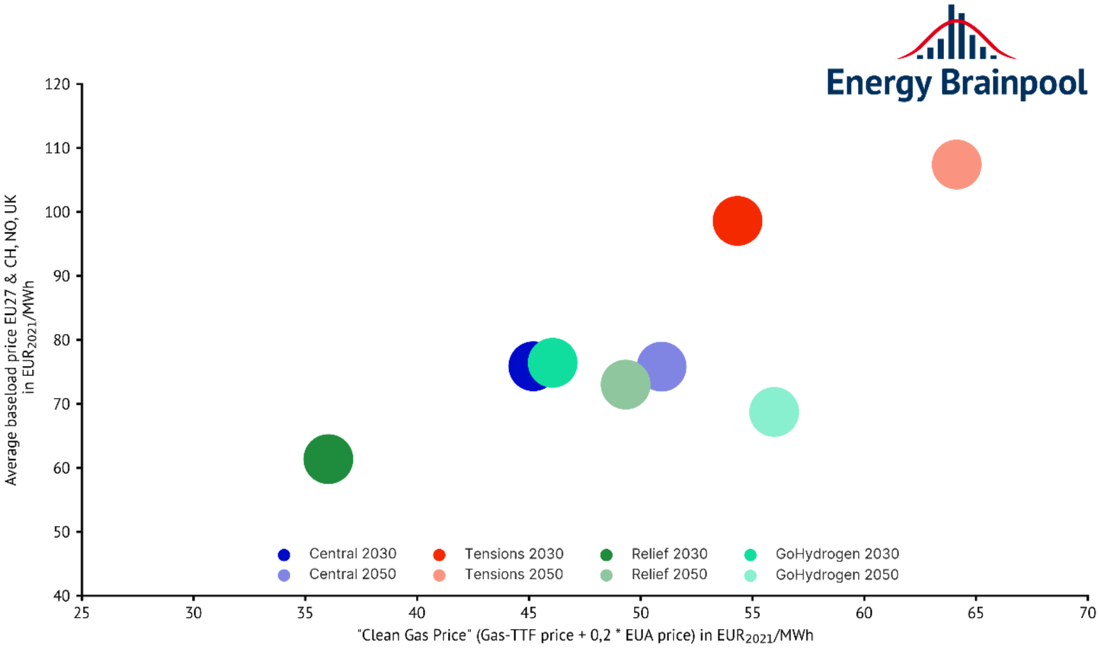


Figure 11.2: Average price of electricity in the four scenarios [80]

Figure 11.2 shows the average price of electricity in the four scenarios. For the purpose of study, only estimations by 2030 will be taken into account. 2030 have been taken as a reference, as the construction of ARC magnetic fusion power plant will start in 2030s.

To compute the 2030 and 2050 price for hard coal, oil, and EUA (i.e., Emission Unit Allowance), the Announced Pledges Scenario (APS) of the IEA's World Energy Outlook 2022 [81] was taken as reference. In defining, instead, the natural gas price in the scenarios that do not import from the Russian pipelines, US LNG price was taken as reference. These assumptions led to the commodity price shown in Figure 11.3.

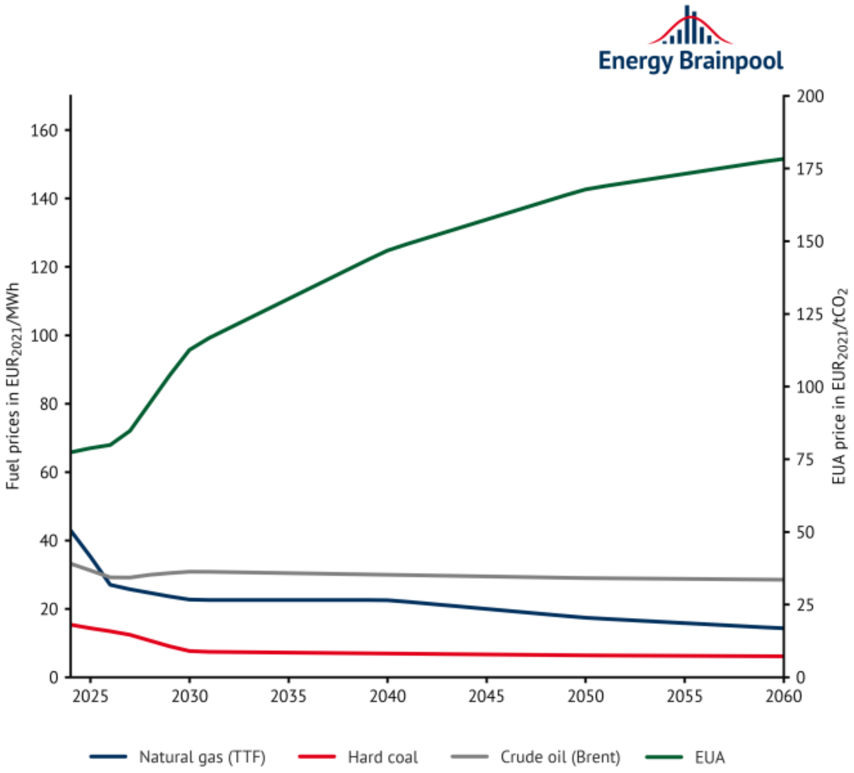


Figure 11.3: Commodities price [80]

Moreover, the European climate policy is a front runner in shaping the future energy mix. In the Central scenario the share of installed generation capacity from 2025 to 2060 is shown in Figure 11.4, assuming an increase of electricity demand by about 64% by 2050.

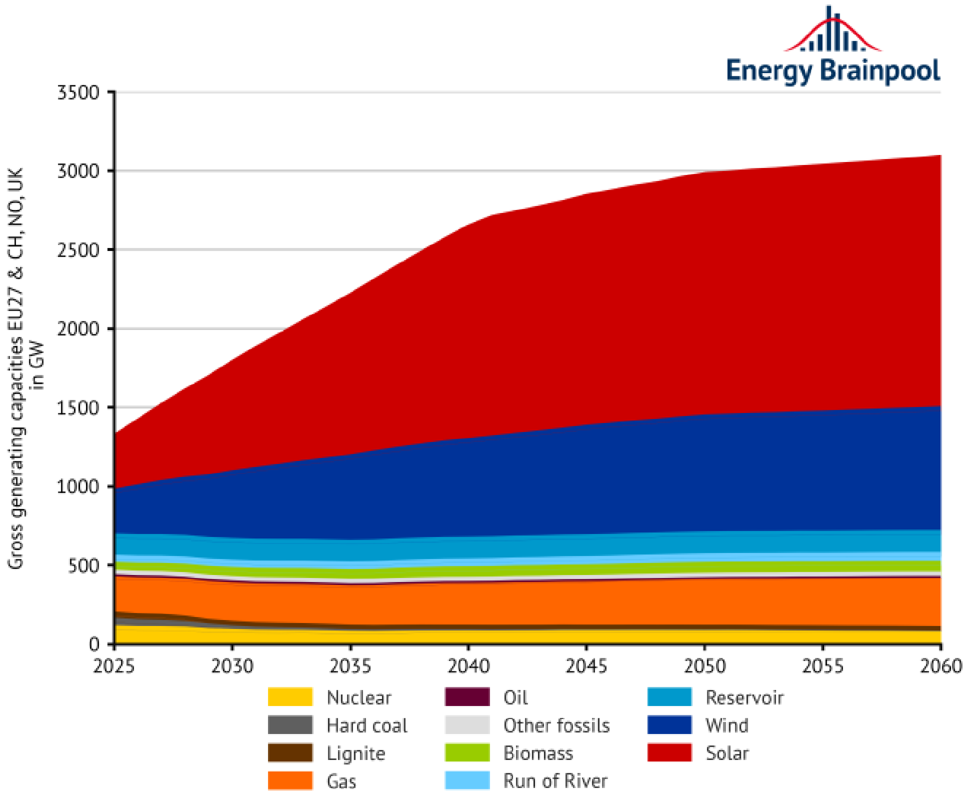


Figure 11.4: Gross generating capacities [80]

The forward baseload electricity price will be affected by both the price of commodity (i.e., hard coal, crude oil, natural gas), price of CO2 and the composition of the forward energy mix.

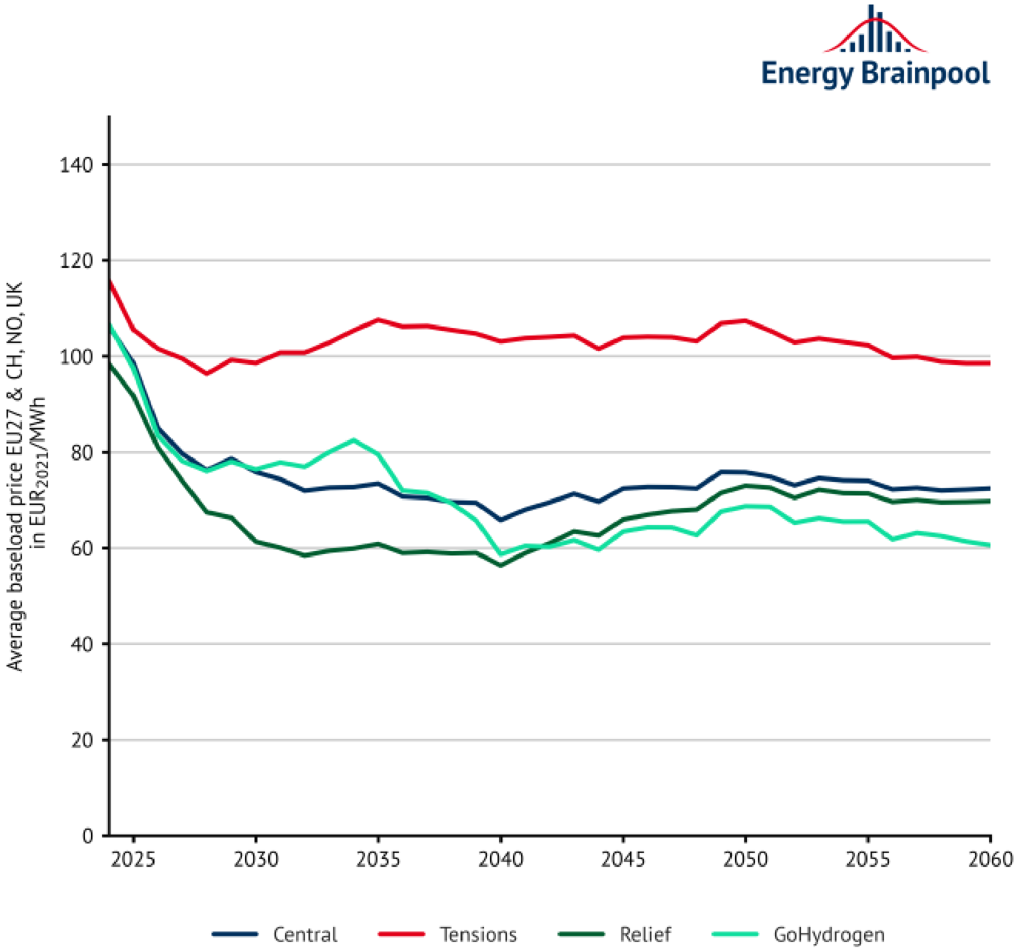


Figure 11.5: Average baseload electricity price 2025-2060 [80]

Figure 11.5 shows the path of the electricity price from 2025 to 2060 in the four different scenarios. The Central scenario is characterized by a decrease in the electricity price from 2025 to 2030. From 2030 onwards, the electricity price will slightly increase due to the increase of CO2 prices and demand for electricity. Fortunately, an increase in the share of wind and solar power in the energy mix will dampen this development because there will be an increasing number of hours in which the price of electricity is very low and even negative.

In order to assess the economic viability of an ARC-like magnetic fusion power plant in Europe, the forward electricity price by 2030 must be compared with the ARC LCOE. The Central scenario has been taken as reference. The forward electricity price in 2030 is around 70.91 €/MWh. This value has been adjusted for inflation[6].

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[6] Adjusted through the calculator CPI Inflation Calculator (bls.gov)

When comparing the forward electricity price with the ARC-like magnetic fusion baseline LCOE, fixed at 437.53 €/MWh, easily emerges that magnetic fusion is not already competitive in the European market. To make this technology competitive, 375.53 €/MWh should be reserved to incentive schemes.

11.3 Renewable energies incentives schemes

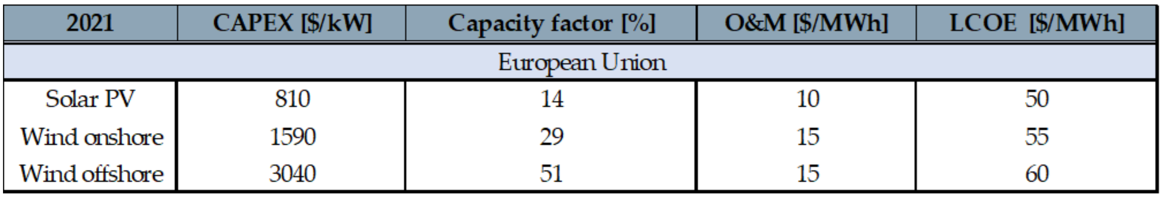
11.3.1 Nuclear fission incentives schemes

Since magnetic fusion is currently in the experimental phase and 7 technological milestones, described in the Chapter 5, must be achieved to make magnetic fusion commercially viable, there are not present already incentives schemes properly designed for this technology. If these 7 technological milestones are assumed to be achieved and ARC-like magnetic fusion is assumed to be commercially viable, a reasoning regarding the incentive for selling the electricity that comes from fusion can be made. For this reason, it has been deemed appropriate to align fusion' incentives with the incentive schemes associated with nuclear fission. The 2021 LCOE of nuclear fission, taken from the World Energy Outlook 2022, is fixed at 140 $/MWh [81]. To compare magnetic fusion incentives with fission incentives, Hinkley Point C plant was taken as a reference. Hinkley Point C has assured a 35-year contract for difference with a strike price of 92.50 £/MWh (i.e., 112.85 $/MWh = 148.95 $/MWh adjusted for inflation) (see Chapter 6). When turning the attention to fusion, which has a baseline LCOE of 437.53 €/MWh, it follows that the agreed contract for difference would have a strike price > 437.53 €/MWh.

11.3.2 RES incentives schemes

It is worth analyzing the incentive schemes associated also with renewable energy sources. Table 11.1 shows the 2021 CAPEX, capacity factor, O&M costs and LCOE of the Solar PV, wind onshore and wind offshore, in the European Union, taken from the World Energy Outlook 2022 [81]. Key components influencing the LCOE encompass various factors: capital costs incurred, the capacity factor, delineating the annual average output relative to the maximum rated capacity, expenses

Table 11.1: Solar PV, Wind onshore, and Wind offshore CAPEX, Capacity Factor, O&M and LCOE in 2021 [81]



2021	CAPEX [$/kW]	Capacity factor [%]	O&M [$/MWh]	LCOE [$/MWh]
European Union				
Solar PV	810	14	10	50
Wind onshore	1590	29	15	55
Wind offshore	3040	51	15	60

associated with fuel inputs, and ongoing operation and maintenance costs. Economic lifetime assumptions are 25 years for solar PV, and onshore and offshore wind [81].

To have an order of magnitude of the current price of electricity in Europe, the Italian market has been taken as a reference and 3 different case studies are chosen:

- Concerning offshore wind, thanks to the FER II Decree, Italy has the plan to bid auctions totaling 3.5 GW between 2022 and 2026. 20-year Cfds will be issued with an auction price cap of 165 €/MWh [82];
- Onshore wind project secured CfDs with a reference price of 66.5 €/MWh [83];
- Solar projects have secured a 20-year Contract for Difference (CfD) with a price of 65.17 €/MWh [84].

If the LCOE of fusion, that is 437.53 €/MWh and the consequent need of a Cfd >437.53 €/MWh is compared with the agreed Cfd for solar and wind seems that it is not feasible to have an agreed strike price > 437.53 €/MWh. Nevertheless, in 2010, when the solar PV LCOE was around 400 €/MWh [85] (see Figure 11.6), to increase the presence of renewables on the energy market, contracts for difference were signed, with an agreed strike price between 350 €/MWh and 430 €/MWh [86]. Although renewable energy had not achieved cost-competitiveness in 2010, the high strike price was agreed to encourage the adoption of relatively new and developing technologies. The same reasoning can be applied to fusion energy, which, in contrast to renewables, has the advantage of being a base-load source of green electricity, and consequently with the potential of attracting more interest from government.

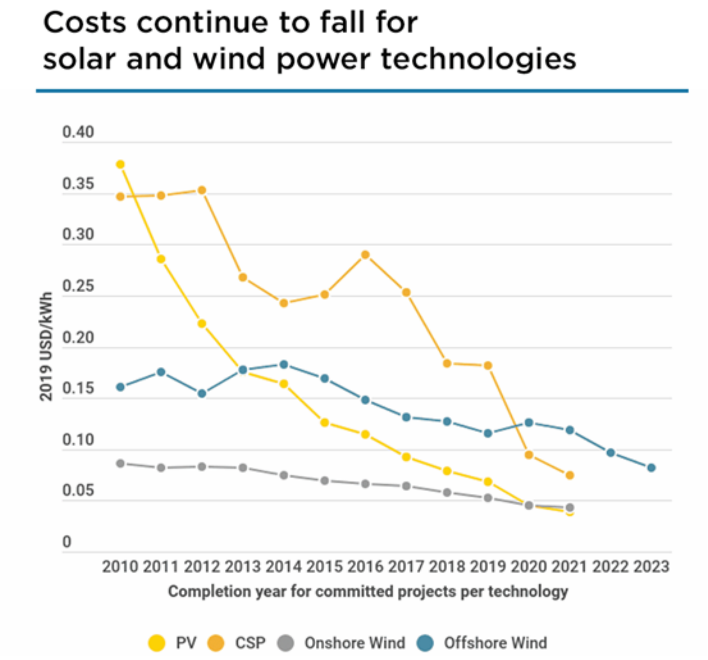


Figure 11.6: 2010 RES costs and their reduction up to 2023 [86]

11.3.3 RES drawbacks

Despite the substantial incentives provided by the government, particularly in the case of solar PV, aimed at increasing the proportion of these energy sources in the Italian energy mix, renewable sources encounter significant drawbacks. The most important disadvantage of renewable energy sources lies in their dependability on natural conditions, such as sunlight and wind speed, which can fluctuate significantly over short timeframes. As a result, consistent energy generation cannot be guaranteed, necessitating backup power sources of energy. Another drawback

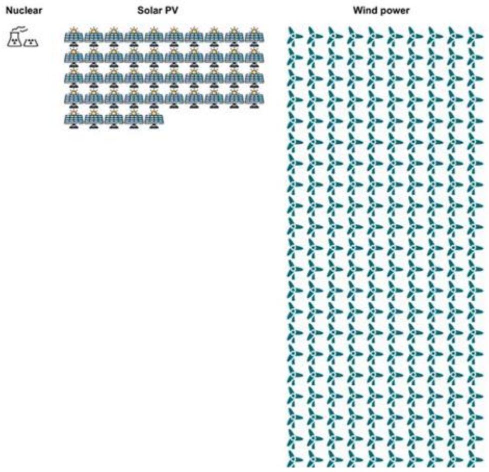


Figure 11.7: Land footprint of Nuclear, Solar PV and Wind power plants [87]

that cannot be underestimated is the land footprint of renewables. Assuming the average capacity factors of solar PV and wind of 27% and 37% respectively, and the capacity factor of nuclear power is 92%, it is easy to conclude that, if a typical 1 GW nuclear power plant requires 3.4 square kilometers of land, to generate the same amount of electricity, a solar farm would need an installed capacity of 3.3–5.4 GW, requiring between 116–200 km^2 and a wind farm would need to have an installed capacity of 1.9–2.8GW, requiring between 670–930 km^2 [87]. Figure 11.7 gives an idea of the land needed by each energy sources to produce 1GW of electricity.

Furthermore, renewable energy sources face significant challenges in terms of grid integration and stability. This stems from the limitations in the geographical placement of renewable facilities in proximity to the grid and the increased costs associated with balancing the grid due to the intermittent nature of these energy sources. Therefore, there is a notable rise in the expenditures related to grid balancing and integration. Conversely, a magnetic fusion power plant possesses the advantage of being situated near the grid, eliminating the need for grid integration measures and extensive grid balancing measures, owing to its inherent base-load nature.

Moreover, renewable energy sources, particularly solar (PV) and onshore wind, represent well-established technologies. Consequently, while their LCOE is expected to continue to decrease in the future, the rate of reduction will not match the rapid pace observed during their initial developmental stages. On the other hand, fusion energy is at its early stage of development, and consequently a relevant LCOE reduction, as for solar PV and wind, is expected, followed by technological advancement, learning rate and adoption of economies of scale or economies of multiples.

Taking into account the abovementioned limitations associated with renewable energy sources, namely the challenges of grid integration, intermittency, and the associated costs of grid balancing, and given the high amount of incentives given to such technologies to increase their share in the energy mix, it becomes evident that fusion energy emerges as a competitive and attractive alternative, and the same incentive scheme can be applied to magnetic fusion. Fusion Energy's inherent advantages, such as the ability to establish proximate power plants to the grid and its reliable base-load generation nature, position it as a compelling contender in the broader landscape of energy solutions. Furthermore, the viability and sustainability of fusion energy offers a promising pathway towards addressing the pressing global energy needs while mitigating the shortcomings that can hinder the widespread adoption of certain renewable energy technologies.

In light of these considerations, fusion energy presents itself as a relevant option with the potential to play a pivotal role in shaping the future of clean and efficient energy production.

12 Conclusions

The scope of this thesis is to assess the economic viability of an ARC-like magnetic fusion power plant and strategize method to render its electricity produced competitive on the market. To do so, a complete and updated cost estimation has been drafted through the development of an automated model. This model allowed to compute the Levelized Cost Of Electricity (LCOE) and carry out sensitivity analyses in order to assess where the scientific research has to focalize its effort to make magnetic fusion competitive on the energy market. To achieve this objective, collaborations with the main actors of magnetic fusion in Italy have been established. These engagements provide the authors the necessary technological knowledge to integrate an economic and managerial background with technical basis. Furthermore, with the help of these figures, it was possible to identify what the nuclear fusion industry needs. This thesis answered to five research questions, analysed below:

- **RQ0:** What is the current state of the art of magnetic fusion power plants and its potential role in the future?
  An accurate and comprehensive literature review revealed that magnetic fusion emerges in the energy landscape as a new green energy source, which can make a substantial contribution to lower the dependence from fossil fuels and achieving the Net zero emissions target by 2050. As a baseload source of green electricity, intrinsically safe, fusion does not suffer from the intermittent nature of renewable energy sources, effectively providing a reliable solution for maintaining a constant electricity supply. Nevertheless, nuclear fusion is not yet considered under the frame of either the Net Zero Roadmap published by the IEA in 2021 [10], nor in the updated version published in 2023 [14]. This decision is justified by the early stage of nuclear fusion technology. Indeed, the realization of fusion must face seven technological milestones:
  1. Plasma confinement at high-temperature;
  2. Management of the heat exhaust system;
  3. Exploration of neutron-tolerant materials that can resist the flux of neutrons (14 MeV);
  4. Achievement of the tritium self-sufficiency (tritium breeding ratio (TBR) >1);
  5. Safety features management;
  6. Inclusion of a Balance of Plant in order to generate electricity;
  7. Achievement of a competitive price of electricity

Upon successfully addressing these technological challenges, the construction of the first magnetic fusion power plant will commence, and the electricity generated from fusion will become available in the electricity market.

At present, there are only two project configurations of a magnetic fusion power plant: DEMO and ARC.

DEMO is the first of a kind plant, which represents the commercialization of the global ITER fusion experiment. Its design comprehends the usage of Low Temperature Superconductors (LTS), which, due to their weak magnetic field (Bo), require a higher major radius (Ro). The construction phase of DEMO will start in 2040.

On the other hand, ARC is the first of a kind plant, representing the commercialization of the SPARC fusion experiment. It uses High Temperature Superconductors (HTS), making its design compact and robust. The ARC construction phase will start in 2030s.

- **RQ1**: What is the cost estimation of a magnetic fusion power plant?
  - **RQ1.1:** What is the Levelized Cost of Electricity of an ARC-like magnetic fusion power plant?

At present there are only two papers related to cost estimation of magnetic fusion power plant. The cost estimation of the ARC plant cannot be considered complete as it provides only a bottom-up cost estimation of the tokamak components [38]. On the other hand, the DEMO2 cost estimation study provides a complete cost estimation of the plant and consequently building up the LCOE. Given the paucity of data of ARC-like plants, the thesis aims at bridging the existing gap in the literature by providing a complete and updated cost estimation of a magnetic fusion power plant consequently building up the LCOE of an ARC-like power plant.

The development of a model facilitated the estimation of the cost of ARC-like power plant, and the formulation of its Levelized Cost of Electricity (LCOE). The model confirmed the high capital requirements and the subsequent operational cost efficiency of these projects. In the baseline scenario, ARC-like plant's capital costs are estimated at about 5.42 B€ and the annual operational costs are estimated at 113 M€/year. Specifically, within this 5.42 B€, the key cost driver is represented by HTS magnets, which account for 49% of the total. This data strictly correlates the magnetic fusion competitiveness to the development of HTS magnets' industry. Concerning operational costs, the 55% is related to the replacement costs, due to the high frequency of replacement of component degraded by the neutrons flux. It has been analysed that, investing in more durable components would have a double impact on the LCOE, diminishing the annual replacement and increasing the plant's availability. Upon establishing the annual electricity production and the discount rate of the plant, the LCOE was formulated and estimated at 437.53 €/MWh. These findings were derived from a comprehensive analysis of existing literature, wherein the most dependable data were selected following a thorough examination of the methodologies employed to generate such information.

- **RQ2**: How a potential reduction of components' cost or an increase in the plant's performance can impact the LCOE?
  - **RQ2.2:** Where the scientific research has to canalize its effort to increase the competitiveness of magnetic fusion?

Given the early stage of development of magnetic fusion, sensitivity analyses are fundamental to understand where to undertake the next steps to make fusion electricity competitive. These sensitivities encompass the analysis of items that could face an enhancement of performances in the future. From these analyses emerge what are the most impactful cost drivers on LCOE. A potential reduction in costs or an increase in performance, compared to the baseline case, can have a relevant impact on the LCOE, bringing it up to market competitive values. Upon analyzing the impact of an enhanced item's performance (i.e., thermal power capacity, replacement rate of components, turbine efficiency) subsequent to its increase in the investment cost, it becomes apparent that investing in technologies and more robust materials, even with an increased CAPEX of over 40%, consistently yields a positive value in reducing the LCOE. Indeed, from the analyses conducted emerges that the LCOE can sharply decrease up to 135.06 €/MWh. This result encompasses a cumulative increase in thermal power capacity (i.e., from 708 MW (525 MW of fusion power capacity) to 1349.92 MW (1001MW of fusion power capacity)) and turbine plant efficiency (i.e., from 40% to 50%), after investments in materials and technologies (i.e., +20% in direct costs) that allow such an increase. Furthermore, market analysis in the literature allows to take in consideration a lower cost of REBCO tape (i.e., from 90 €/m to 10 €/m), the most relevant component of the HTS magnets, that allows to lead the LCOE to such value. All the above-mentioned enhancements in performance have been discussed with ENI team and are confirmed by the literature.

Once analyzing the LCOE and its potential reduction, an analysis of magnetic fusion competitiveness on the forward electricity market has been made. In the challenging context of uncertainties and volatilities that characterize the European electricity market, Energy Brainpool has estimated the forward price of electricity taking in consideration the current geopolitical conflicts. From the study emerges that the forward electricity price in 2030 has been estimated at 70.91 €/MWh. Comparing this value with the ARC-like magnetic fusion power plant LCOE (i.e., 437.53 €/MWh), it easily emerges that magnetic fusion electricity is not competitive in the market. Consequently, to make this technology competitive on the European market, 375.53 €/MWh should be reserved to incentives schemes.

Due the potential significance that contract for difference may attain in the future aimed at reducing the current volatility of the electricity market, this incentive scheme has been taken as reference. The magnetic fusion CfD would need to have an agreed strike price > 437.53 €/MWh, if this value is compared with the CfD currently issued for RES (i.e., between 65.17 €/MWh and 165 €/MWh), it seems to be unachievable. Nevertheless, in 2010, when the solar PV LCOE was around 400 €/MWh, Cfd with an agreed strike price between 350 €/MWh and 430 €/MWh have been issued in order to increase the adoption rate of this technology. The same strategy can be applied to magnetic fusion.

This thesis leaves to research and literature a management footprint in a high technical environment. It gives insights about technologies never been deepened from an economic point of view. Fusion technological pathway is developing faster and faster, hence, from now on, efforts must be dedicated to further analysis of its competitiveness on the energy market. This process would render the technological advancements economically sustainable. Future studies on technological development, which gives a look at economic perspective too, would bring the highest value on the commercialization of magnetic fusion.

13 Bibliography

[1] OurWorldInData, "CO2 emissions".

[2] U.S. Energy Information Administration, "International Energy Outlook," 2021.

[3] bp, "Statistical Review of World Energy 2021 - Full Report," 2021.

[4] OurWordlInData, "Future population growth".

[5] UNFCCC, "Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 11 December 2015," 2015.

[6] Carbon Brief, "Which countries met the UN's 2020 deadline to raise climate amition," 2021.

[7] UNFCCC, "COP 27 Sharm el-Sheikh Implementation Plan," 2022. [Online]. Available: https://public.wmo.int/en/our-

[8] OurWorldInData, "Emissions by sector".

[9] OurWorldInData, "Sources global energy".

[10] IEA, "Net Zero by 2050 - A Roadmap for the Global Energy Sector," 2021. [Online]. Available: www.iea.org/t&c/

[11] M. Rooney *et al.*, "Improving the world through engineering FUSION ENERGY: A GLOBAL EFFORT-A UK OPPORTUNITY," 2021. [Online]. Available: https://imeche.org/policy-and-press/reports

[12] ENEA, *Divertor Tokamak Test facility - Interim Design Report - A milestone along the roadmap to the realisation of fusion energy*. 2019.

[13] S. Banacloche, A. R. Gamarra, Y. Lechon, and C. Bustreo, "Socioeconomic and environmental impacts of bringing the sun to earth: A sustainability analysis of a fusion power plant deployment," *Energy*, vol. 209, Oct. 2020, doi: 10.1016/j.energy.2020.118460.

[14] IEA, "Net Zero Roadmap A Global Pathway to Keep the 1.5 °C Goal in Reach," 2023. [Online]. Available: www.iea.org/t&c/

[15] J. V. Minervini, "A PATHWAY TO FUSION ENERGY BASED ON HIGH-FELD REBCO SUPERCONDUCTING MAGNETS," 2019.

[16] H. Cabal *et al.*, "Fusion power in a future low carbon global electricity system," *Energy Strategy Reviews*, vol. 15, pp. 1–8, Mar. 2017, doi: 10.1016/j.esr.2016.11.002.

[17] S. Entler, J. Horacek, T. Dlouhy, and V. Dostal, "Approximation of the economy of fusion energy," *Energy*, vol. 152, pp. 489–497, Jun. 2018, doi: 10.1016/j.energy.2018.03.130.

[18] C. Bustreo, U. Giuliani, D. Maggio, and G. Zollino, "How fusion power can contribute to a fully decarbonized European power mix after 2050," *Fusion Engineering and Design*, vol. 146, pp. 2189–2193, Sep. 2019, doi: 10.1016/j.fusengdes.2019.03.150.

[19] Fusion Industry Association, "The global fusion industry in 2022 -Fusion Companies Survey," 2022.

[20] L. Longo, "Atomi e Forze Fondamentali".

[21] IEA, "What is Deuterium?," 2023.

[22] R. V. Krishnamurthy, "Hydrogen isotopes".

[23] "ITER", Accessed: Dec. 21, 2022. [Online]. Available: https://www.iter.org/

[24] X. Wang *et al.*, "REBCO -- a silver bullet for our next high-field magnet and collider budget?," Mar. 2022, [Online]. Available: http://arxiv.org/abs/2203.08736

[25] EUROfusion, "History of Fusion".

[26] T. Rothman, "Was Einstein the First to Invent E = mc2?," 2015.

[27] O. Ali, "How Do Astronomers Use the Hertzsprung-Russell Diagram to Study the Evolutionary Stages of Stars?," 2023.

[28] J. Dineley, "How to Weigh an Atom: Francis W. Aston's Mass Spectrograph," 2019.

[29] European Space Agency, "Studying the stars, testing relativity: Sir Arthur Eddington".

[30] The Nobel Prize, "Hans Bethe Facts".

[31] K. Alexander and S. Padma Kant, "Joint ITER-IAEA-ICTP Advanced Workshop on Fusion and Plasma Physics."

[32] Princeton Plasma Physics Laboratory, "Tokamak Fusion Test Reactor".

[33] G. da Landriano, “Il progetto europeo di fusione ITER è in ritardo. Un fallimento che pone la UE al terzo posto mondiale, se va bene,” 2023.

[34] U.S. Fusion Energy, “The Science of Fusion Where the triple product reigns supreme,” 2019.

[35] A. J. Creely *et al.*, “Overview of the SPARC tokamak,” *J Plasma Phys*, vol. 86, no. 5, 2020, doi: 10.1017/S0022377820001257.

[36] I. E. IAEA, “ITER Technical Basis,” Jan. 2002.

[37] IAEA, “Technical basis for the ITER-FEAT outline design,” Nov. 2000.

[38] B. N. Sorbom *et al.*, “ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets,” *Fusion Engineering and Design*, vol. 100, pp. 378–405, Nov. 2015, doi: 10.1016/j.fusengdes.2015.07.008.

[39] EUROfusion, “European Research Roadmap to the Realisation of Fusion Energy,” 2018.

[40] EUROfusion, “European Research Roadmap to the Realisation of Fusion Energy,” 2018.

[41] EUROfusion, “The state of the art for DEMO,” 2022.

[42] G. Federici *et al.*, “Overview of the DEMO Staged Design Approach in Europe.”

[43] Commonwealth Fusion Systems (CFS), “Designing and building fusion energy systems to power the world,” 2023.

[44] ENEA, *DTT Divertor Tokamak Test facility Interim Design Report A milestone along the roadmap to the realisation of fusion energy*. 2019.

[45] IAEA, “Fusion device information system,” 2023.

[46] European Commission, “Researchers to receive €132 million through the new Euratom Research and Training Work Programme 2023-2025 for investments in nuclear innovation and technology,” 2023.

[47] IAEA Nuclear Energy Series, “Financing of New Nuclear Power Plants,” 2008. [Online]. Available: http://www.iaea.org/Publications/index.html

[48] One Hundred Seventeenth Congress of the United States of America, “COMMITTEE ON FINANCE,” 2022.

[49] IAEA, “Feed-in tariff”.

[50] “November 2022 Guidance on development costs and the nuclear Regulated Asset Base model,” 2022.

[51] Australian Energy Regulator, “Why do we index the regulatory asset base?”

[52] E. &Industrial S. Department for Business, “Revenue stream for the Nuclear RAB model Consultation in respect of revenue regulations relating to the implementation of the nuclear RAB model revenue stream,” 2022.

[53] D. Dalton, “European Investment Bank To Finance Nuclear Energy Projects,” 2007.

[54] NEXT-KRAFTWERKE, “What is a contract for difference?”.

[55] New Civili Engineer, “Future of Energy | Hinkley Point C progresses towards final stages of undersea work,” 2023.

[56] A. Cossins-Smith, “Cost of EDF’s Hinkley Point C nuclear project rises to $40bn,” 2023.

[57] World Nuclear News, “Three-year extension agreed to Hinkley Point C contract,” 2022.

[58] T. Committee, “Delivering nuclear power Eighth Report of Session 2022-23 HC 626.”

[59] ENEA, *Dtt : divertor tokamak test facility project proposal : an opportunity for facing one of the major challenges along the roadmap to the realisation of fusion energy*. ENEA, 2015.

[60] “FIRE Lighting the Way to Fusion A Comparison of Unit Costs for FIRE and ITER,” 2002. [Online]. Available: http://fire.pppl.gov

[61] D. M. Meade, “Lighting the Way to Fusion A Comparison of Unit Costs for FIRE and ITER,” 2002. [Online]. Available: http://fire.pppl.gov

[62] FIRE, “FIRE at Snowmass,” 2002.

[63] E. Rocco, “An overview of the Burning Plasma Experiment BPX vacuum vessel system,” 1991.

[64] PCAST study group, “Technical and Cost Assessment of the PCAST Machine Final Report PCAST ITER Volume II,” 1995.

[65] F. Najmabadi *et al.*, “Overview of the ARIES-RS reversed-shear tokamak power plant study,” 1997.

[66] T. I. Economic Modeling Working Group of the Generation International Forum, “Cost estimating guidelines for generation IV nuclear energy systems (Revision 4.2),” 2007.

[67] INNOVITALIA, “Fusione nucleare a Joint European Torus ‘JET,’” 2022.

[68] X. Wang *et al.*, “REBCO - a silver bullet for our next high-field magnet and collider budget?,” Mar. 2022, [Online]. Available: http://arxiv.org/abs/2203.08736

[69] B. Lindley, T. Roulstone, G. Locatelli, and M. Rooney, “Can fusion energy be cost-competitive and commercially viable? An analysis of magnetically confined reactors,” *Energy Policy*, vol. 177, Jun. 2023, doi: 10.1016/j.enpol.2023.113511.

[70] D. Maisonnier *et al.*, “Power plant conceptual studies in Europe,” *Nuclear Fusion*, vol. 47, no. 11, pp. 1524–1532, 2007, doi: 10.1088/0029-5515/47/11/014.

[71] I. Cook, N. Taylor, and D. Ward, “The Role of DEMO in a Fast-Track Development of Fusion Power.”

[72] G. Federici *et al.*, “Overview of the DEMO Staged Design Approach in Europe,” 2019.

[73] “SuperOx”, Accessed: Sep. 21, 2023. [Online]. Available: https://eng.superox.ru/

[74] “SuperPower”, Accessed: Sep. 21, 2023. [Online]. Available: https://www.superpower-inc.com/

[75] X. Wang *et al.*, “Electromagnetic Design of 1.5 T No-Insulation REBCO Coil System Charged by Multiflux Pumps for Dedicated MRI,” *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, Aug. 2019, doi: 10.1109/TASC.2019.2901917.

[76] T. Benkel, Y. Miyoshi, X. Chaud, A. Badel, and P. Tixador, “REBCO tape performance under high magnetic field,” *EPJ Applied Physics*, vol. 79, no. 3, Sep. 2017, doi: 10.1051/epjap/2017160430.

[77] J. Cicéron, A. Badel, and P. Tixador, “Superconducting magnetic energy storage and superconducting self-supplied electromagnetic launcherï¿½,”

European Physical Journal: Applied Physics, vol. 80, no. 2, pp. 20901–20911, 2017, doi: 10.1051/epjap/2017160452ï.

[78] ITER, “Tritium: Changing lead into gold,” 2016.

[79] McKinsey, “Four themes shaping the future of the stormy European power market,” 2023, Accessed: Sep. 21, 2023. [Online]. Available: https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/four-themes-shaping-the-future-of-the-stormy-european-power-market

[80] EnergyBrainpool, “EU Energy Outlook 2060,” 2023.

[81] IEA, “World Energy Outlook 2022,” 2022. [Online]. Available: www.iea.org/t&c/

[82] AEGIR, “With the FER II Decree on its way, Italy is gearing up for take-off as an offshore wind market,” 2022.

[83] H. O’Brian, “Italy assigns CfDs to 296MW of onshore wind in latest tender,” 2021.

[84] Statkraft, “Mytilineos and Statkraft sign a 10 year PPA in Italy,” 2023.

[85] C. Arndt, F. Hartley, G. Ireland, K. Mahrt, B. Merven, and J. Wright, “Developments in Variable Renewable Energy and Implications for Developing Countries,” *Current Sustainable/Renewable Energy Reports*, vol. 5, no. 4. Springer Nature, pp. 240–246, Dec. 01, 2018. doi: 10.1007/s40518-018-0121-9.

[86] InfoBuildEnergia, “Conto Energia per impianti fotovoltaici: le tariffe 2009,” 2008.

[87] A. Delichatsios, “The Land Footprint of PV Solar (and Nuclear and Wind Power),” 2022.

[88] European Commission Directorate-General, “ExternE Externalities of Energy : Vol. 2 METHODOLOGY”.

[89] “JT-60SA”, Accessed: May 25, 2023. [Online]. Available: https://www.jt60sa.org/wp/

[90] K. Calvin *et al.*, “IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland.,” Jul. 2023. doi: 10.59327/IPCC/AR6-9789291691647.

[91] “Fusione nucleare: potrebbe essere il momento di svolta,” 2022.

[92] “NASA”.

[93] S. B. Krivit, “#97 Lithium, Lithium, Everywhere, and None to Use for Fusion Reactors,” 2022.

[94] “T-1”.

[95] “The T-3 A tokamak at the Kurchatov Institute of Atomic Energy Photograph taken around”.

[96] “Joint European Torus (JET)”.

[97] “Tokamak Fusion Test Reactor”.

[98] FRAMATOME, “Hinkley Point C: supply low-carbon energy to 6 million households in the United Kingdom”.

[99] Google Finanza, “Da Euro a Dollaro Statunitense,” 2023.

14 Appendix A

14.1 Formal interview with the Chief Engineer of ENEA DTT Gian Mario Polli

0:0:0.0 --> 0:0:1.120

Gian Mario Polli

Ci sono, ditemi pure.

0:0:1.770 --> 0:1:0.760

Federica Festa

Ok, dalle mail è emerso che più o meno la percentuale di divisioni dei costi tra ingegnerizzazione e materiali, costo del personale e il rischio era materiali il 25%, ingegnerizzazione 15%, costo del personale 40% e il rischio 20%. Quindi se potessimo approfondire un po' di più, come sono state calcolate queste percentuali, noi dalle mail sappiamo che sono state calcolate sui precedenti contratti fatti con JT-60 SA, poiché ENEA fa parte di EUROfusion. Lei ci ha detto che, ad esempio, il costo del personale è stato assunto leggermente inferiore. Poi si è preso il costo del personale italiano ed è stato stimato come rule of thumb. Cose di questo tipo, quindi vogliamo approfondire da questo punto di vista, un po' ogni percentuale come è stata calcolata?

0:1:2.940 --> 0:1:31.860

Gian Mario Polli

Eh beh, più di quello che già avete, di quello che ha ribadito, non è che saprei indicarvi nel senso, sono state fatte queste valutazioni sulla base di esperienze di contratti precedenti. Allora la domanda sarebbe più giusta, come abbiamo fatto a fare la valutazione iniziale dei contratti JT-60SA? In quel caso ci siamo riferiti a precedenti contratti di fornitura.

0:1:33.260 --> 0:4:51.630

Gian Mario Polli

Nel caso in esame di DTT abbiamo adottato questo criterio fondamentalmente da applicare a seconda dei casi, ovviamente con qualche correzione. In funzione delle forniture, insomma, è un dato a consuntivo, quello che noi avevamo per JT-60SA, quindi il dato era noto. Potevamo stimarlo in maniera molto, molto adeguata, molto decisa. Dipende, ripeto, dipende molto dalle forniture. Adesso credo di aver fatto l'esempio dei magneti TF che si compongono fondamentalmente di diversi sotto contratti, c'è il contratto di fornitura dell'avvolgimento, in cui l'impresa deve sostanzialmente fare manodopera, non acquista materiali se non in minima parte attrezzature di avvolgimento e però riceve tipicamente questo come processo tipico che è avvenuto in passato. Sta venendo anche adesso riceverà dal committente il conduttore e lo trasforma, lo piega. Fa la lavorazione. Quindi è chiaro che lì è preponderante la quota di personale rispetto alla quota di materiali. Se poi il contratto sempre facendo riferimento ai magneti toroidali c'è il contratto di fornitura delle casse che sono i componenti in cui l'avvolgimento deve essere inserito per conferirgli quella rigidità strutturale che altrimenti renderebbe il magnete stesso non sufficientemente portante. In questo caso è vero, viceversa si parte da una spesa per materiali molto significativa che devono essere poi trasformate con un apporto di personale piuttosto limitato. Perché? Le lavorazioni meccaniche sono lavorazioni in macchina, quindi richiedono attrezzature per i quali, insomma, si possono considerare dei costi di ammortamento, ma poi un costo orario dell'attrezzatura stessa e i costi di personale. Ripeto, si concentrano tutti alla fine, nelle fasi di verifica dimensionale e packaging. Quindi è per questo che poi, a seconda dei casi, siamo stati spinti a ritenere che una percentuale fosse adeguata e quindi quelle descrizioni che lei faceva riferimento fossero adeguate oppure no, dovessero essere modificate. E l'esperienza e la tipologia di contratto o la tipologia di fornitura che ci aiutano nello stabilire con maggiore precisione. Quale percentuale utilizzare e quale comunque tipicamente non sapendo né leggere e scrivere quelle forniture su cui avevamo una esperienza limitata? Le percentuali che lei ha riportato erano quelle, diciamo di standard di riferimento, ecco.

0:4:53.430 --> 0:4:53.690

Federica Festa

Ok.

0:4:53.150 --> 0:4:54.840

Gian Mario Polli

Non so se ho risposto alla domanda.

0:4:53.760 --> 0:5:23.640

Federica Festa

Si sì, quindi al variare del componente sono state scelte percentuali più o meno adatte, però in linea generale, le percentuali scelte sono state queste. E approfondendo leggermente ogni percentuale, sapendo che ovviamente si è basati sui contratti di fornitura di JT-60SA, che è un impianto che sta in operazione in questo momento o è già stato costruito?

0:5:24.380 --> 0:5:28.130

Gian Mario Polli

È in costruzione, è stato costruito e in fase di Commissioning finale.

0:5:28.810 --> 0:5:47.910

Federica Festa

Ok. In base a quei contratti si è aggiustato ad esempio il costo di manodopera, assumendo che ci sia questa supply chain europea e quindi il costo di manodopera inferiore. E lei ha detto che anche il costo di trasporto è leggermente inferiore perché si è presa appunto una supply chain europea.

0:5:48.980 --> 0:8:34.950

Gian Mario Polli

Allora JT-60SA è stata un'impresa in cui l'Europa ha contribuito per un investimento complessivo di circa 400 milioni in-kind alla fornitura di componenti di apparecchiature per queste forniture, di cui l'Italia ne ha contribuito, in particolare per circa 90 milioni di queste forniture. Noi abbiamo praticamente il dettaglio, perché per quelle italiane sicuramente le abbiamo fatte noi; quindi, sappiamo i costi da cosa sono stati i prodotti. Conosciamo tutto l'iter, il processo di assegnazione contrattuale eccetera, e la supply chain era italiana, totalmente italiana, perché tutte le gare sono state assegnate a tutte imprese italiane. Per le altre gare europee vale un discorso simile, seppure non abbiamo avuto un ruolo operativo noi come ENEA, tuttavia, avevamo rapporti, contatti diretti con i nostri alter ego del Seat spagnolo, del Kit, il tedesco e così via che hanno contribuito in maniera analoga, sempre riferendosi a fornitori italiani, scusate europei. E poi ci sta la parte invece di componentistica che ha costruito direttamente il Giappone, che è circa restante metà che in altri 400 milioni. E sulla quale, invece le informazioni sono più vaghe e per le quali abbiamo dovuto operare uno sforzo maggiore di rivalutazione del peso del costo del personale, dei costi di trasporti, eccetera eccetera. Quindi tenderei a distinguere. Insomma, caso per caso. Noi a questo esercizio l'abbiamo fatto caso per caso. Il mio editoriale e io abbiamo preso i dati noti a noi perché noi abbiamo fatto quei contratti e avevamo quindi un'informazione completa ed esaustiva. Nel caso dei magneti PF coloidali e viceversa, questo era una fornitura direttamente gestita dal Giappone. E allora ho dovuto, abbiamo dovuto fare delle deduzioni, peraltro con anche delle complicazioni in più che adesso non so. Se volete entrare in merito, ma legate al fatto che nel caso giapponese i magneti F che li si chiamano EF però vabbè poco sono stati costruiti direttamente on site.

0:8:36.270 --> 0:8:36.790

Federica Festa

OK.

0:8:35.740 --> 0:9:7.500

Gian Mario Polli

Viceversa, Eh, nella strategia di DTT, i magneti verranno costruiti presso il fornitore e poi spediti. Questo cambia notevolmente i costi e cambia anche la tempistica di manifattura e la disponibilità del personale. Però abbiamo cercato di tenerne conto. In questo senso abbiamo cercato di quindi rimodulare, laddove era necessario e mettere dei coefficienti correttivi. Insomma, per qualche modo ecco, questo era la ragione.

0:9:10.330 --> 0:9:32.270

Federica Festa

E OK invece per quanto riguarda il costo dei materiali, ovviamente vi siete, se è stato fatto affidamento, ad esempio, mi viene da dire nella fornitura dei magneti TF da quello che lei ha detto si è valutato quanto occupava il costo dei materiali. E si è fatto un, diciamo un breakdown dei costi rispetto a tutto il resto?

0:9:33.210 --> 0:11:29.400

Gian Mario Polli

Sì, ah, anche lì bisogna distinguere molto come ho fatto l'esempio prima dell'avvolgimento del TF, i costi di materiali abbiamo detto costituiscono una voce molto piccola perché riguardano soltanto le attrezzature e alcuni componenti che l'impresa è chiamata aggiungere al costo complessivo. Il costo vero del materiale è intrinseco nella fornitura dei conduttori e degli strand. Lì c'è veramente un costo di materiale molto importante per quello, ovviamente si conoscono. Bisogna conoscere il mercato, bisogna sapere qual è il costo al chilo, per esempio del materiale superconduttore o dell'acciaio. E si fa una valutazione tenendo conto dei margini, ovviamente di applicazione, cioè nel senso non prendo esattamente il complessivo finito che mi serve, ma devo considerare un opportuno margine nel caso dei superconduttori e gli strand, si può. Strand del 20 al 30% nel caso dell'acciaio, per fare le casse, per esempio, tipicamente il 50% in più. Bisogna considerare perché si parte da faccio un esempio da 500 tonnellate. Era questo il caso JT-60 se partiti da 500 tonnellate di acciaio grezzo che poi sono state lavorate per arrivare a 360 tonnellate di acciaio. E quindi il costo, il costo del materiale per quella fornitura si fa sulla base del grezzo, considerando i valori del mercato che quindi si conoscono dell'acciaio.

0:11:24.710 --> 0:11:45.540

Federica Festa

Ok ottimo e ritornando ai costi di trasporto, ci chiedevamo all'interno di quale di questo breakdown sono inclusi i costi di trasporto oppure se sono calcolati al di fuori del breakdown che ci ha fornito lei, cioè di ingegnerizzazione, materiali, rischio e costo del personale.

0:11:46.660 --> 0:12:2.550

Gian Mario Polli

Eh ci stanno vabbè, questa è una molto sintetico. Poi di fatto c'è una voce a parte dei costi di trasporto che non incidono tipicamente non incidono per maniera significativa sul valore complessivo delle forniture.

0:12:3.220 --> 0:12:5.210

Federica Festa

Ok.

0:12:4.90 --> 0:13:37.700

Gian Mario Polli

Ma, tranne alcuni casi particolari, anche lì bisognerebbe analizzarli. Prima ho fatto l'esempio del PF, il tipo per cui i giapponesi hanno deciso di costruire in casa EF era proprio per risparmiare sui costi di trasporto, cosa che noi sulla quale non potremmo beneficiare. Quindi avremo dei costi di trasporto che saranno significativi in quel caso, perché si tratta di componenti molto grandi e per i quali, insomma, bisogna attuare tutta una serie di procedure di interruzione traffico stradale, rimozione di ostacoli che hanno dei costi significativi e quindi alla fine incidono sul valore complessivo della fornitura. Però lì era una questione di scelte, di strategie, di disponibilità anche in sito ITER per fare un esempio che è molto più grande di DTT. E anche JT-60 probabilmente non avrebbe neanche potuto farli trasportare i magneti PF perché avrebbe, non lo so. Avrebbero dovuto inventarsi delle strade nuove, cioè sono talmente grandi che veramente un'ipotesi fortissima che non hanno preso in considerazione, immagino e hanno dovuto però realizzare un edificio ad hoc e ospitare avere un problema di interferenza di personale di ditte che lavoravano contemporaneamente per poter realizzare allo stesso modo, in maniera in sito.

0:13:43.780 --> 0:13:46.850

Federica Festa

Ok e non so se Roberto ha qualche domanda.

0:13:47.760 --> 0:14:11.20

Roberto Dusmet Farina

Ah, per me è tutto molto chiaro, cioè abbiamo chiarito che quindi le motivazioni di tutto questo breakdown sono arrivate soprattutto grazie all'esperienza maturata da JT-60 e quindi questo secondo me è abbastanza significativo anche per la tesi. E quindi per me è ottimo.

0:14:34.930 --> 0:14:35.600

Federica Festa

Certo.

0:14:12.260 --> 0:15:48.460

Gian Mario Polli

Eh, giusto per vostra informazione laddove non avevamo informazioni dirette per JT-60 e abbiamo raccolto anche da altri impianti che sono in costruzione, a parte anche ITER ha fornito dei riferimenti vista la macchina, molto più grande e quindi la scalatura già sul peso è uno strumento se volete utile, con cui uno può valutare. E fare qualche considerazione, però c'è anche lì, c'è un'altra complicazione. ITER è una macchina nucleare e viceversa DTT no e così come non è neanche JT-60 e questo è un fatto che introduce dei fattori di scala ulteriori; quindi, anche di questo bisogna tenere conto. Altro esperimento da cui abbiamo estratto informazioni utili per la valutazione dei costi di DTT è stato W7-X che non è un tokamak, che è uno stellarator, un'altra macchina a fusione che è stata costruita nei primi anni 2000 in Germania e con la quale avevamo dei rapporti diretti; quindi, abbiamo potuto beneficiare di uno scambio di informazioni per il costo di specifici componenti, attrezzature particolari per tutti i sistemi ausiliari. Abbiamo ricavato le Loro breakdown di spesa dei costi proprio sostenuti e lo abbiamo utilizzato.

0:15:49.280 --> 0:16:23.700

Federica Festa

Ok, OK, ottimo, quindi ne approfitterei per parlare un po' anche del dello State of art di DTT. In questo momento, cioè noi, quello che sappiamo è che DTT come anche JT-60, sono impianti sperimentali DTT in particolare volto a testare diverse configurazioni di divertore, per poi aumentare le performance. Penso anche per il futuro DEMO e volevamo sapere un ppo'a che livello si è arrivati alla costruzione oppure se è solamente in fase di pre-costruzione.

0:16:26.590 --> 0:17:14.20

Gian Mario Polli

Siamo per costruire, non so se intendete costruzione infrastrutturale edifici, ecco, se è quello il tema siamo in fase di pre-costruzione, nel senso stiamo facendo. Abbiamo completato le indagini e stiamo finalizzando il progetto definitivo per poi uscire in gara con l'appalto per gli edifici. Però ci sono tanti altri appalti che sono stati lanciati e sono in fase esecutiva. Relativa alle forniture dei componenti che dovranno essere assemblati in loco non appena la macchina la Hall, sperimentale sarà resa disponibile. Complessivamente abbiamo lanciato gare per circa 200 milioni di euro su un budget complessivo di 600 milioni.

0:17:14.910 --> 0:18:19.130

Gian Mario Polli

E quindi 1/3. Tra la fine di quest'anno e il prossimo anno contiamo di lanciare altrettanto valore di gare e poi a seguire, nel 2025 praticamente a conclusione e questo dovrebbe completare il quadro delle gare, poi le forniture continueranno. Ovviamente sono forniture pluriennali e quindi anche se verranno lanciate nel 2025 si completeranno fino al 2027-2028-2029 quando è previsto l'accensione del primo plasma nel 2029 che appunto verrà avviato, speriamo senza problemi, senza i problemi che ha vissuto al momento JT-60 che sono due anni che non è riuscito ancora a partire.

0:18:23.790 --> 0:18:29.20

Federica Festa

E quindi in breve anche JT60-SA e si trova sullo stesso, cioè si trova anch'esso in precostruzione

0:18:30.70 --> 0:18:38.710

Gian Mario Polli

No no JT-60 in fase avanzata di commissioning che significa che la macchina c'è.

0:18:38.380 --> 0:18:39.0

Federica Festa

Ok.

0:18:39.370 --> 0:21:20.310

Gian Mario Polli

JT-60SA è un po' diverso perché, eh, allora, mentre DTT parte su un Brown Field, come si dice, cioè su un campo già in cui è presente già altro, altre infrastrutture, ma devono essere integrate nuove infrastrutture. In particolare, la Hall sperimentale deve essere costruita, nel caso di JT-60SA, è stata riutilizzata la Hall sperimentale del precedente esperimento, che si chiama JT-60. Quindi, una volta hanno liberato la Hall, hanno potuto cominciare subito l'assemblaggio. Oltretutto hanno riutilizzato tantissime attrezzature di riscaldamento della macchina che erano già presenti, sono stati riutilizzati quindi da questo punto di vista l'investimento era minore e se volete anche più facilitato. Ecco rispetto al nostro. E quindi lo stato dell'arte attualmente è che è stata completato l'assemblaggio della macchina a meno dei componenti in vessel, nel senso all'interno della macchina praticamente non c'è nulla, ci sono, c'è soltanto un limite che limita appunto le superfici magnetiche del plasma. Ma invece l'inserimento e l'integrazione del divertore, dei componenti del plasma è previsto soltanto nella fase successiva dopo il primo plasma, quindi una fase che dovrebbe tipicamente essere una fase di assemblaggio successiva che dovrebbe verificarsi a partire dal prossimo anno. Questo è fatto, questo è lo stesso approccio, se volete che stia utilizzando anche ITER non parte subito con la macchina già completamente integrata, ma parte prima con un primo plasma chiamato politico, diciamo così, eh, che serve soltanto a qualificare, diciamo una parte dei sistemi. Poi si interromperà subito l'esercizio di ITER e si riprenderà l'assemblaggio dei componenti interni e quindi poi dopo ci sarà un

primo plasma ufficiale, più significativo. Per quanto riguarda DTT, invece, abbiamo deciso di procedere direttamente con l'inserimento di componenti in vessel, la sin da subito; quindi, il primo plasma sarà un plasma, già un plasma operativo strumentale.

0:21:22.320 --> 0:21:27.860

Federica Festa

Ok perfetto per me è tutto chiaro, non so se Roberto vuole aggiungere qualcosa.

0:21:29.510 --> 0:21:32.90

Roberto Dusmet Farina

No, no, per me è tutto chiaro, perfetto.

0:21:31.820 --> 0:21:32.510

Federica Festa

Ok.

15 Appendix B

1.1. Excel model

The following link is directed to the open source of the Excel model used for the development of the analyses in the thesis.

Excel model of the thesis: Assessing the economic viability of an ARC-like magnetic fusion power plant: Cost Estimation, LCOE, and Sensitivity Analyses

16 List of Figures

17 List of Tables

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