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EXECUTIVE SUMMARY OF THE THESIS

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

TESI MAGISTRALE IN MANAGEMENT ENGINEERING – INGEGNERIA GESTIONALE

AUTHOR: Roberto Dusmet Farina, Federica Festa

ADVISOR: Massimo Fabrizio Mondazzi

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1. Introduction

In the context of the ongoing energy transition, the need for global decarbonization has never been so urgent. The world is at a crossroads, trying to balance the growing global demand for energy with the primary need to mitigate the detrimental consequences of climate change. In this moment, magnetic fusion emerges as a promising solution, offering the potential to transform our energy landscape and contribute to the unfolding energy transition. Nevertheless, at present, there are several technological challenges that must be addressed to realize magnetic fusion and render its electricity commercially viable. However, if these technological milestones are assumed to be achieved, and an ARC-like magnetic fusion power plant is assumed to be in operation, performing an analysis of the costs of magnetic fusion is fundamental for assessing its competitiveness in the energy market.

For this reason, this thesis delved into bridge the existing gap in the literature by presenting the first comprehensive and updated cost estimation of an ARC-like magnetic fusion power plant. Once performed the cost estimation and the LCOE, sensitivity analyses have proven indispensable to canalize the scientific research's effort in the right direction, with the purpose of reducing the magnetic fusion LCOE.

1.1. Role of fusion

Although magnetic fusion could be a promising solution in tackling the energy transition, this technology is not yet considered under frame of either the Net Zero Road Map published by the IEA in 2021, nor in the updated version published in 2023. Nevertheless, 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, beyond nuclear fission, a successful development of nuclear fusion has the potential to facilitate the attainment of this challenging target. Indeed, as stated by the MIT and PSFC, an ARC-like magnetic fusion power plant can play a fundamental role in electricity generation from

2030 and its capacity for expansion aligns with the NZE by 2050 (see Figure 1.1).

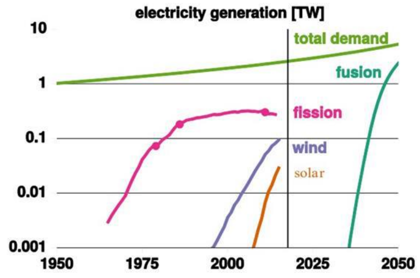

Figure 1.1: The role of an ARC-like magnetic fusion power plant in the electricity generation

2. Technology overview

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 (i.e., 14MeV). It is the fundamental process that powers the sun and other stars, as well as the potential future source of clean, abundant energy on Earth. To achieve fusion on Earth, the challenge is to create the same condition of the sun. It means to bring the two nuclei to temperatures of million degrees in order to have enough energy to make the reaction occur. To do that, several technologies have been proposed and the most promising is magnetic confinement with Deuterium-Tritium reaction. It means to confine a super-hot plasma (i.e., the fourth state of matter) long enough and provide sufficient heating to maintain the high temperatures needed for sustained fusion reactions. Magnetic confinement is the 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 most promising machine to create such conditions is the tokamak. 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 process starts cooling down the magnets that must be brought to -180 degrees Celsius (for High Temperature Superconductor (HTS) used in ARC configuration), then the fuel (Deuterium and Tritium) must be injected into the vessel (i.e., a vacuum chamber that can create a low-pressure environment by removing air and other gases from the containment area in order to prevent the plasma from coming into contact with particles or impurities). Once fuel has been injected, heating systems are employed to raise the temperature of the gases and form plasma. These systems consist of electromagnetic systems capable of releasing energy to the gas particles. After the plasma is heated to several million degrees, the reaction occurs. The fusion reaction consists in the fusion of Deuterium and Tritium releasing a Helium atom and a high energy neutron. The high energy neutron released after the reaction is obviously neutral to the magnetic field generated and can hit the walls of the vessel activating it. Indeed, the vacuum vessel is a component made of a resistant material that must withstand the high temperatures generated in the chamber and the high energy neutrons flux. For this reason, the vacuum vessel is the most critical component of the tokamak, even from a costs point of view, because must be substituted very often. It is important to underline that the impact of neutrons on the vessel is not the hoped-for result, indeed, most of the neutrons cross the vessel going forward to the Blanket. The Blanket is a component made of molten salts (FLiBe) surrounded by a tank, the salts are needed to absorb the high energy neutrons and generate heat from them. Indeed, very near to the blanket pass some water pipes to then generate vapor to power the turbine plant and generate electricity. Furthermore, the Blanket contains Lithium-6, that when hit by neutrons generates Tritium. This process is called Tritium breeding, and it is fundamental for the existence of fusion. Indeed, Tritium is rare in nature and can reach a cost of 30.000 €/g, for this reason, to make fusion electricity competitive, it is fundamental to produce Tritium internally. While the reactions inside the vessel occur, the plasma produces scraps that must be eliminated through a sort of ashtray that captures the waste without influencing the correct functioning of the process. This component is called divertor, it is typically situated at the bottom of the tokamak, and it is in charge of removing impurities and exhausted the heated particles from the plasma. Eventually the last component of the tokamak is the cryostat, that serves to maintain the right temperatures inside and outside the machine. Indeed, a tokamak is both the coldest and the warmest place on hearth with an internal temperature of hundreds of millions of degrees and a temperature for magnets operation of -180 degrees. Outside the tokamak can be found a complex net of auxiliary systems able to ensure the tokamak operation, safety, and control.

3. Thesis objective & research questions

It became evident that magnetic fusion holds the potential to revolutionize the energy mix in the future, positively tackling energy transition. Nevertheless, there are several technological challenges that must be achieved to realize magnetic fusion and make it commercially viable. Upon 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. For this reason, the main purpose of this thesis is to assess the economic viability of an ARC-like magnetic fusion power plant and to bridge the existing gap in the literature by providing an updated cost estimation of it and consequently conduct sensitivity analyses either on items performance or on items cost, in order to assess their potential impact on the LCOE. Having a complete cost estimate of an ARC-like magnetic fusion power plant is fundamental to understand the potential competitiveness of this technology on the electricity market. Moreover, sensitivity analyses can be conducted in order to understand where the scientific research has to canalize its effort, with the purpose of increasing the competitiveness of magnetic fusion. To achieve this goal the following research questions have been explored:

- ➢ RQ0: What is the current state of the art of magnetic fusion power plant 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?

After analyzing these research questions, the objective is to build an automated model to estimate the costs and LCOE of an ARC-like magnetic fusion power plant and conduct sensitivity analyses to canalize the scientific research in the right direction. This thesis offers a guiding paradigm for the organizations that wants to deepen their knowledge regarding the cost of an ARC-like magnetic fusion power plant, thereby facilitating further studies on the competitiveness of this design.

3.1. Methodology

The thesis has been divided into two major blocks: "Model conceptualization" and "Model development".

Model conceptualization

The model conceptualization section is devoted to answer RQ0, RQ1, and RQ2. For what concerns R0, Scopus and ResearchGate has been the two primary sources of documentation in identifying the potential role of fusion in the energy mix. The initial search yielded 210 articles. After narrowing the search criteria to a specific period and excluding non-English articles the database has been reduced to 97 articles. Subsequently, a screening process was carried out, firstly by screening the titles and secondly by reading the abstract of the remaining record. These two screenings resulted in the selection of 7 articles. Subsequently, the snowballing method was applied, resulting in the inclusion of 6 articles.
Concerning the state of the art of magnetic fusion power plants, from research primarily based on Google Scholar emerges 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 analysed. For sake of completeness, DTT state of the art has been analysed, as it will be fundamental for the model development.

To address RQ1 and RQ2, Scopus was the primary source of documentation. After defining 2 tailored search string, the research generated 251 documents. The same methodology employed for RQ0 was used, resulting in the selection of 16 documents. From this phase onwards, the bibliography of each document has been analysed to take all the information and data from the most original document with a consequent snowball effect in the research that brings 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 ARC-like magnetic fusion power plants. It will serve as a foundation for the model development and for the subsequent chapters of this thesis.

Model development

Once conceptualization of the model made by addressing research questions RQ0, RQ1, and RQ2 has been completed, the study's attention transitioned to the development of the model. 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 done, sensitivity analyses have been conducted to provide an answer to RQ2.2.

Research gap

At present, the 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. [1] (2015), which provides a cost estimation only for the tokamak components, without estimating the auxiliaries' components (i.e., balance of plant and buildings), the indirect and operational costs. Consequently, the LCOE cannot be computed. Moreover, the cost estimation provided by Sorbom was defined "rough" by himself, as for the computation of the fabricated costs it was used a coefficient which was multiplied by the components' weight. This coefficient was based on the cost per tonne of four different fusion plant in which the design and cost estimation was published between 1991 and 2002. For these reasons this dissertation 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 canalize their effort to lower the LCOE of the ARC-like magnetic fusion power plant.

4. Model description

In order to bridge the existing gap in the literature, a completely new and updated methodology has been used in the model to estimate the cost of an ARC-like plant and build up its LCOE.

Methodology

Starting from the design of ARC provided by Sorbom [1], which estimates the weight, volume, and material used of each reactor's components, an updated estimation of the fabricated cost has been computed. Through a formal interview with the Chief Engineer of ENEA DTT Gian Mario Polli, it has been decided to use the same breakdown used in the DTT project proposal [2] for the estimation of the fabricated costs. In this breakdown, the fabricated costs are divided in material costs (25%), engineering costs (15%), labor costs (40%), and risk margin (20%). This breakdown has been chosen, as the fabricated costs computation is based on real in-kind supply contracts incurred between ENEA and the Japanese magnetic fusion plant JT-60SA. For this reason, the ENEA breakdown has been considered reliable for its closeness to reality. Nevertheless, ARC construction phase is planned by 2030s while DTT is already in pre-construction phase. For this reason, the risk margin has been adjusted for each cost item (i.e., 30% risk for tokamak components, 20% for balance of plant, and 10% for buildings and indirect costs) in order

to comply with the level of uncertainty that characterize the ARC technology.
Regarding the balance of plant, buildings, and indirect costs, which can be considered technologically similar between DEMO2 and ARC, proportionalities between the two power plants have been made. The proportions are based on the plant dimensions, considering the major radius as a reference. On the other hand, the operational costs have been estimated applying the same breakdown of DEMO2 to ARC paying attention to the characteristics on which each operational expenditure is based.
Eventually, the LCOE is computed through a DCF unlevered method.

$$LCOE = \frac{\sum_s Replacement_s \sum_t ((Investment_t + Operational\ costs_t) * (1+r)^{-t})}{\sum_t ((Electricity\ production_t * (1+r)^{-t})}$$

Output data

The model revealed an ARC-like tokamak cost of 2983.28 M€ and a total investment cost of 5422.68 M€, the annual operational cost weight 112.97 M€/year. Once the annual electricity production and the discount rate (r) has been determined, the LCOE has been computed, revealing a baseline value of 437.53 €/MWh. The data showed are different to what the literature shows. Indeed, the study conducted by Sorbom, et al. [1] provides only a tokamak cost of about 5500 M€. It is justified by the difference in computation methodologies. Computing the LCOE with the Sorbom estimation, considering the operational costs, balance of plant and buildings costs equal to the new model, the total costs of the plant would be of about 8000 M€ and the LCOE of 718.17 €/MWh, a completely out of range LCOE. On the other hand, the LCOE provided by the model is higher than DEMO2 study LCOE [3]. It is justified by more optimistic assumptions considered in DEMO2 study referred to a lower contingency (i.e., 12%) and a much lower frequency of component replacement.

5. Sensitivity analyses

Once having understood what the most impactful items on LCOE are, sensitivity analyses have been conducted to highlight what are the main technological improvements that would reduce the LCOE and make magnetic fusion competitive. Studies reveal that ARC magnetic fusion power plant can increase its fusion power capacity from the current 525 MW to 1001 MW without changing the plant configuration, but only increasing the plasma temperature. Obviously, this improvement requires investments in more robust materials and more complex auxiliary systems. The model shows that increasing fusion power capacity, after an increase in direct costs of even 40%, would still bring value to the project reducing the LCOE of about 41%. Moreover, due to the capital intensiveness nature of this project, an analysis of what are the key cost drivers that cause high capex has been conducted. It reveals that the magnets cost occupies 58.78% of direct costs and the main element that causes such a substantial cost is the REBCO tape. To date, the REBCO cost is high due to their meagre production and supply. For this reason, in the literature emerges that the cost of REBCO can be reduced by an order of magnitude from 90 €/m of today to 10 €/m, positively contributing to a reduction of the LCOE of about 36%. Furthermore, an analysis of the plant availability (or capacity factor) has been conducted. The plant availability is strictly correlated to the replacement rate of components, as during their replacement, fixed at once a year (with a plant shutdown of 3 months/year), all the scheduled maintenance occurs. If investments in more durable materials for the construction of the components that need to be substituted are made, the replacement rate can be reduced. The sensitivity analysis revealed that reducing the replacement rate from once a year to once every three or five years, net of substantial investments in more robust components (i.e., investments up to 474 M€ if the replacement rate is once every 3 years and up to 1043 M€ for the once every five-year case), create value in reducing the LCOE. Eventually, it is interesting to notice that the turbine plant efficiency is assumed at 40% by the design configuration. This item is underestimated by the literature, as auxiliaries' components are not the primary focus of scientists. Nevertheless, there are unproven technologies that could increase efficiency by up to 50%. With an efficiency of 50%, subsequent to investments in more sophisticated turbines of +40% of the turbine plant cost, the LCOE can be reduced by about 30%.

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. The fusion power capacity has been increased at 1001 MW and investments in a +20% of the direct costs have been taken into account. 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. Moreover, efficiency has been increased from 40% to 50%, net of an investment of +30% in the turbine costs. The resulting LCOE is 194.25 €/MWh. If it is included also the reduction in the REBCO tape cost from 90 €/m to 10 €/m, the LCOE arrives at its minimum value, 135.06 €/MWh.

6. Discussion

At present, 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. Indeed, in order to make magnetic fusion commercially viable, seven technological milestones must be achieved, including confining plasma at high temperatures, achieving the tritium self-sufficiency, and managing the heat exhaust system.

Behind these technological challenges, the sensitivity analyses show that the most impactful items are the fusion power capacity, the capex, the availability, and the turbine efficiency. From this thesis work emerges that magnetic fusion, with an ARC-like configuration, holds the potential to attain a considerable degree of competitiveness if all the abovementioned performance enhancements are achieved.

To assess the magnetic fusion competitiveness, its LCOE must be compared with a reference price of electricity. Nowadays, the electricity market is distorted by the geopolitical landscape. To make a fairer comparison, the forward price of electricity has been considered. Indeed, ARC power plant will start its operation after 2030. To compute the price of electricity several studies have been considered. From these studies emerge a market price of electricity adjusted for inflation of about 70.91 €/MWh. When comparing it with the baseline LCOE (i.e., 437.53 €/MWh) easily emerges that it is not already competitive in the European market and 375.53 €/MWh should be reserved to incentives. If contract for difference (CfD) is considered, magnetic fusion would need an agreed strike price > 437.53 €/MWh. This value is not far from reality, as in 2010 when the LCOE of Solar PV was around 400 €/MWh , CfD with a strike price between 350 €/MWh and 400 €/MWh [4] have been issued, showing opportunities to apply the same strategy for the future of magnetic fusion electricity.

7. Bibliography

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