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Assembling the Fusion Future: Technoscientific Promises and Justificatory Practices in ITER

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Abstract

English

This thesis examines how the ITER (International Thermonuclear Experimental Reactor) project is assembled through justificatory practices that satisfy technoscientific expectations and promises. Drawing on interviews, fieldwork, document and media analysis, and an approach to ITER through a new materialist lens, the thesis analyses the project as a mega-technoscientific assemblage composed of narratives, agendas, materials, institutions, and resources. Rather than treating ITER as a singular technical object, the research shows how its legitimacy is continuously produced through material-discursive practices that align future-oriented promises with past- and present-day institutional, technical, and geopolitical arrangements. In this sense, ITER is not merely supported by justification from the outside, but actively constituted through it.

The empirical analysis is organised around different dimensions of justificatory and promissory practices: planning, constructing, and reworking. With a particular focus on the European public fusion research and development (R&D), the empirical analysis shows how ITER's credibility and legitimacy are constructed and maintained through recurring acts of adjustment, rearticulation, and reconfiguration in response to delay, fragility, and controversy. Future-oriented documents such as the ITER Agreement, the ITER baseline, and the EUROfusion Roadmap do not merely describe the project's aims but actively perform legitimacy by translating uncertainty into managed progress through milestones, deliverables, and roadmaps. While the thesis does not systematically apply Boltanski and Thévenot's orders of worth (2021), it demonstrates that ITER is justified through multiple overlapping evaluative logics, especially appealing to common humanity, common dignity, common good, industrial progress, novelty, and scientific necessity, while embracing seemingly contradictory justification logics. Alignment and disalignment practices of negotiating the boundaries are essential for reinforcing legitimacy.

The thesis concludes with three interconnected themes of justification: embraced temporality and spatiality, ITER-fusion exceptionalism, and ITER-fusion optimism and imperative. First, ITER is shown to operate across expansive temporal and spatial horizons, connecting international cooperation, European fusion R&D, and the projected futures of commercial fusion energy. This long-term, widely distributed configuration is not merely ITER's neutral characteristic but is also actively used to keep the project legitimate. Second, ITER-fusion exceptionalism emerges through boundary work that differentiates fusion from nuclear fission, fossil fuels, renewables, and private fusion ventures, while simultaneously linking the project to both scientific credibility and radical novelty. Third, ITER is sustained by a strong promissory logic in which fusion is framed as a future necessity for humanity, thereby turning optimism into an imperative that criticises a potential challenge to the common good.

The thesis contributes to Science and Technology Studies scholarship by showing that technoscientific promises (van Lente, 2000) are not only discursive claims about the future, but are sustained through heterogeneous actors, infrastructures, and repair practices that make a long-term and uncertain project appear stable enough to continue. ITER thus offers a case of how futures are actively produced in the present through promise-making, milestone-setting, and continuous legitimisation. In ITER's case, the project's fragility and uncertainty do not necessarily undermine its legitimacy but instead serve as a reinforcing mechanism.

German

Diese Studie untersucht, wie das ITER-Projekt (International Thermonuclear Experimental Reactor) durch Rechtfertigungspraktiken konstruiert wird, die technowissenschaftlichen Erwartungen und Versprechungen gerecht werden. Auf der Grundlage von Interviews, Feldforschung, Dokumenten- und Medienanalysen sowie einer neu-materialistischen Betrachtungsweise analysiert die Studie das Projekt als eine megatechnowissenschaftliche Assemblage, die sich aus Narrativen, Agenden, Materialien, Institutionen und Ressourcen zusammensetzt. Anstatt ITER als ein singuläres technisches Objekt zu behandeln, zeigt die Untersuchung, wie seine Legitimität kontinuierlich durch materiell-diskursive Praktiken erzeugt wird, die zukunftsorientierte Versprechen mit vergangenen und gegenwärtigen institutionellen, technischen und geopolitischen Arrangements in Einklang bringen. In diesem Sinne wird ITER nicht lediglich durch Rechtfertigungen von außen gestützt, sondern aktiv durch diese konstituiert.

Die empirische Analyse gliedert sich in verschiedene Dimensionen legitimierender und versprechender Praktiken: Planung, Konstruktion und Überarbeitung. Mit besonderem Fokus auf die europäische öffentliche Fusionsforschung und -entwicklung (F&E) zeigt die empirische Analyse, wie die Glaubwürdigkeit und Legitimität von ITER durch wiederkehrende Akte der Anpassung, Neuformulierung und Neukonfiguration als Reaktion auf Verzögerungen, Fragilität und Kontroversen konstruiert und aufrechterhalten werden. Zukunftsorientierte Dokumente wie das ITER-Übereinkommen, die ITER-Baseline und die EUROfusion-Roadmap beschreiben nicht nur die Ziele des Projekts, sondern schaffen aktiv Legitimität, indem sie Unsicherheit durch Meilensteine, Teilergebnisse und Roadmaps in kontrollierten Fortschritt umwandeln. Zwar wendet die Studie die Wertordnungen von Boltanski und Thévenot (2021) nicht systematisch an, doch zeigt sie, dass ITER durch mehrere sich überschneidende Bewertungslogiken gerechtfertigt wird, insbesondere durch Appelle an die gemeinsame Menschlichkeit, die gemeinsame Würde, das Gemeinwohl, den industriellen Fortschritt, die Neuartigkeit und die wissenschaftliche Notwendigkeit, während es scheinbar widersprüchliche Rechtfertigungslogiken einbezieht. Praktiken der Angleichung und Abgrenzung bei der Aushandlung von Grenzen sind entscheidend für die Stärkung der Legitimität.

Die Studie schließt mit drei miteinander verknüpften Themenbereichen der Rechtfertigung: die integrierte Zeitlichkeit und Räumlichkeit, der „ITER-Fusions-Exzeptionalismus“ sowie der Optimismus und Imperativ der ITER-Fusion. Erstens wird gezeigt, dass ITER innerhalb eines weitreichenden zeitlichen und räumlichen Horizonts operiert und dabei internationale Zusammenarbeit, europäische Fusionsforschung und -entwicklung sowie die prognostizierten Zukunftsvisionen kommerzieller Fusionsenergie miteinander verbindet. Diese langfristige und weitreichende Konfiguration ist nicht bloß ein neutrales Merkmal von ITER, sondern wird aktiv genutzt und eingesetzt, um die Legitimität des Projekts aufrechtzuerhalten. Zweitens entsteht der „ITER-Fusions-Exzeptionalismus“ durch eine Abgrenzung, die die Fusion von Kernspaltung, fossilen Brennstoffen, erneuerbaren Energien und privaten Fusionsvorhaben unterscheidet und das Projekt gleichzeitig sowohl mit wissenschaftlicher Glaubwürdigkeit als auch mit radikaler Neuartigkeit verknüpft. Drittens wird ITER durch eine starke Versprechungslogik gestützt, in der die Fusion als zukünftige Notwendigkeit für die Menschheit dargestellt wird, wodurch Optimismus zu einem Imperativ wird, der eine potenzielle Herausforderung für das Gemeinwohl kritisiert.

Die Arbeit leistet einen Beitrag zur Wissenschafts- und Technikforschung, indem sie aufzeigt, dass technowissenschaftliche Versprechen (van Lente, 2000) nicht nur diskursive Aussagen über die Zukunft sind, sondern durch heterogene Akteure, Infrastrukturen und Reparaturpraktiken aufrechterhalten werden, die ein langfristiges und ungewisses Projekt stabil genug erscheinen lassen, um fortgeführt zu werden. ITER bietet somit ein Beispiel dafür, wie Zukünfte in der Gegenwart durch das Abgeben von Versprechen, das Setzen von Meilensteinen und kontinuierliche Legitimierung aktiv produziert werden. Im Fall von ITER untergraben die Fragilität und Unsicherheit des Projekts nicht unbedingt dessen Legitimität, sondern wirken vielmehr als verstärkender Mechanismus.

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Like my research subject, ITER — an ongoing and ever-expanding assemblage — this work is also an assemblage of the many entities on which I rely. I therefore extend my thanks not only to the people around me but also to the innumerable sociomaterial companions that sustain this work: computers, software, food, water, microbes, and the countless others with which I am entangled.

Declaration of Authorship

I hereby declare that this thesis is entirely my own and has been produced independently based on my own research and writing. All sources and materials used have been properly acknowledged.

In preparing this work, I made limited use of digital tools to support the writing process. Specifically, Grammarly was used for grammar correction and stylistic refinement; Perplexity and Microsoft Copilot were used for brainstorming ideas and for assisting with rephrasing certain passages; and DeepL was used to translate the English abstract into German.

These tools were used solely as aids for language improvement and clarification and did not contribute to the substantive content, research, analysis, or conclusions of this work. All intellectual content, arguments, and interpretations are entirely my own.

I take full responsibility for the content of this work.

Masafumi Nishi

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1. Introduction

"*This might be far in the future. But one thing is clear. The fusion reaction that powers the sun will be tamed on Earth. And in some form or other, our children will use it to power their world. So, let's give them an optimistic ending, fusion will win through, it may not be free, but it will certainly be there with power to spare.*" (WGBH (Television station : Boston, Mass.), British Broadcasting Corporation. Television Service., David Rose, 1976)

In March 2023, in Saint Paul-lez-Durance, southern France, I attended a guided tour of ITER – the International Thermonuclear Experimental Reactor, also known as "The Way" in Latin. Reflecting the sunlight of Provence, the assembly hall stood in the centre of the construction site, full of concrete, metal, cranes, trucks, and workers in yellow vests and helmets. The sign on the assembly hall reads "We have delivered" with flags of the ITER members (China, the European Union (Euratom), India, Japan, Korea,

Figure 1: The assembly hall in the ITER construction site (source: author)

Russia and the United States) and company logos. Construction began in 2007, and the machine was expected to achieve first plasma in 2025 and reach full-power operation in 2035, according to the 2016 baseline plan. However, it is expected to be delayed by several years due to the COVID-19 pandemic and component repairs (ITER Organization, n.d.-c, 2023). Under such circumstances, the sign "We have delivered" seems to have two meanings: first, it literally indicates that the ITER member states and companies have delivered components in the cooperation; second, it implies that they have achieved some of the milestones in the project – like the project language of "deliverables" that provide quantifiable goods or services in the process.

ITER has specific characteristics: a particular history of international collaboration, a long-term agenda, and a massive budget – some say, ITER is the most expensive scientific experiment ever, with the total cost of more than 20 billion euros (Seife, 2023). As elaborated later in this thesis (Chapter 4), the idea of creating an international collaboration for peaceful use of nuclear fusion energy was initially proposed at the Geneva Superpower Summit in November 1985 by General Secretary Gorbachev of the former Soviet Union to US President Ronald Reagan (ITER Organization, n.d.-g). After long negotiations on the design, financing, organisation and so on, the ITER Agreement was made between China, the European Union (Euratom), India, Japan, Korea, Russia and the United States – the so-called "ITER members" – in 2006 (ITER Organization, n.d.-g). Based on each ITER member's contribution for financing and components, ITER is expected to experiment the scientific and technological feasibility of nuclear fusion energy: "1) Achieve a deuterium-tritium plasma in which the fusion conditions are sustained mostly by internal fusion heating, 2) Generate 500 MW of fusion power in its plasma, 3) Contribute to the demonstration of the integrated operation of technologies for a fusion power plant, 4) Test tritium breeding, and 5) Demonstrate the safety characteristics of a fusion device" (ITER Organization, n.d.-h). ITER is an experimental machine that will not produce commercial electricity but is expected to demonstrate the production of net energy[1] ($Q \geq 10$, more than 10 times the energy gain out of the energy input). Moreover, ITER is designed to take a step toward a prototype of a commercial fusion reactor – a demonstration power plant, DEMO. DEMOs are currently in the very early stages of concept and design development in various countries, especially among ITER members. Alongside the ITER exploitation, DEMOs are projected to start being built in the 2030s at the earliest and to be operating by the 2050s (Chatzis & Barbarino, 2021a). The potential commercialisation of fusion energy would be followed by the performance of DEMOs, which would be achieved towards the end of the century.

In short, ITER is expected to play an important role in public fusion energy research and development (R&D), with long-term goals spanning 30 to 50 years from the present time, according to

[1] As a side note, journalist Steven Krivit criticises a confusing/misleading narrative on the expected net gain by mixing up terminologies of "fusion energy", "thermal power", and "power" in different meanings (Krivit, 2021).

ITER (n.d.-h) (Claessens, 2023) and EUROfusion (2018b), both of which represent the ITER members' politicians and scientists. Within the next 30-50 years, several steps are envisioned, from the first experiments and full plasma operation to the knowledge transfer to DEMOs (Chapter 4.3.3). However, the progress of ITER has not gone so smoothly as initially planned. The total budget has increased from the initial estimate of 5 billion euros for a 10-year completion plan to more than 20 billion euros, with a delay of at least several years for the first plasma (Seife, 2023) (Chapter 4.4.1). This situation does not help dispel scepticism about the technological feasibility of nuclear fusion, as the common saying goes: "nuclear fusion is ALWAYS 30 years away". Some may say nuclear fusion is simply an unreachable "dream"; a member of the European Parliament criticised the leaders of the ITER project and the director-general of the European Commission for the delays and organisational issues, saying "I'm not going to present the baseline which is based on dreams" (Zubașcu, 2023). In response to such criticisms, the European Parliament has decided to cut 120 million euros from the ITER nuclear fusion programme (Naujokaitytė, 2023).

So, is the dream of "ultimate energy" (Turrell, 2021) just a castle in the air? Or, is it true that "Fusion will be ready when society needs it", as fusion enthusiasts often quote Lev Artsimovich, a famous Soviet era physicist (e.g., Claessens, 2023, p. 216; IAEA, 2021, p. 1). Or, is fusion energy getting closer because at least people say 20 more years instead of 50 years[2]?

This research is not interested in whether either of those claims is more "correct" – maybe people in 50 years will judge the claims based on the trajectory of socio-technical development. As articulated in scholarship in Science and Technology Studies (STS), technology development carries uncertainties from agenda setting to outcomes, under complicated interactions with sociocultural factors (e.g., Jasanoff & Kim, 2009). This thesis explores how nuclear fusion R&D is situated within a particular socio-technical constellation and how promises, visions, and imaginaries have driven massive, long-term, and far-reaching technological development. To do so, this research focuses on the narratives and practices of ITER and EUROfusion (an EU-funded research consortium), as well as policy-related activities within the European Commission and Parliament. The research has been conducted through expert interviews, field research, and document and media analysis.

The main building where the tokamak machine (an acronym of "toroidal chamber with magnetic coils" in Russian, the core equipment of the thermonuclear fusion reactor) is assembled is called the assembly hall. Analogising the construction of the machine, ITER can be seen as an *assemblage* of heterogeneous actors (DeLanda, 2006). Within the assemblage – socio-material entanglement or phenomena as articulated below (see 2.7), organisations, people, materials, and concerns interact

[2] Jokingly mentioned by one of the speakers in an event "Fusion 24" on 18.06.2024. (https://fusioniscoming.com/) The recording of the event is available (UKAEA official, 2024). (accessed on 20.06.2024)

dynamically and performatively. As an assemblage, ITER has undergone constant changes throughout its history and even in the present. This research examines the assemblage of ITER with a certain regard for the justification theory (Boltanski & Thévenot, 2021) that enables the configuration of ITER's long-term, uncertain future-oriented R&D. Integrating the perspective of justification theory in the topic of long-term future-oriented technology, this thesis contributes to STS scholarship that assesses the dynamic roles of visions, promises, and imaginaries in shaping and reinforcing how a certain assemblage is (re)formulated and maintained amid constant change. In the case of ITER, visions, promises, and imaginaries take shape in specific formats that justify the mobilisation of actors. By looking at the biggest and most prominent example of nuclear fusion, ITER, this dynamic, relational approach also counters the problematic but prominent notion of fusion as "ultimate energy" within the fusion community (Turrell, 2021), which disregards the particular sociomateriality of technology. Critical reflection of notions resonates with new materialist approaches that encompass ethical and political dimensions in analysis.

To examine the complex assemblage of ITER, this thesis proceeds as follows. First, Chapter 2, "Situating ITER", explores the state-of-the-art of nuclear fusion energy. It starts with a critical discourse analysis of the energy transition and security as background to the claim that nuclear fission and fusion are strong candidates for alternative energy sources. As nuclear fission and fusion are often discussed in parallel in that type of argument, this follows from the distinction between nuclear realists and nuclear utopians. Both styles of arguments often co-exist in practice, as seen in the empirical chapters (Chapter 4). One of the nuclear utopians' arguments sees fusion as "dream energy" or "ultimate energy" that would solve energy problems as well as carbon emissions. Both technical and socioeconomic perspectives criticise this perspective by questioning technical feasibility, economic viability, and sustainability. To examine the "driving forces" or "catalyst" behind support for fusion, the chapter proceeds with a theoretical framework including sociotechnical imaginaries and visions that deal with uncertainties for the future of society and the trajectory of fusion energy R&D. The new materialism accounts are introduced to specify and clarify the interrelationships between actors/elements of fusion R&D. The theories and concepts, such as assemblage and sociology of translation, with a particular sensibility to materiality, enriches the discussion of sociotechnical imaginaries and visions. Technoscientific expectations and promises are articulated and translated from sociotechnical imaginaries and visions through material-discursive practices. Justifications align claims, values, and institutions by stabilising relations among elements with different logics through distinct mechanisms. Chapter 2 articulates the complex and sometimes almost mythical claims about the future of nuclear fusion energy, drawing on literature reviews.

Chapter 3 provides a scope for examining ITER. The overarching aim of this research is to disentangle the assemblage of ITER by tracing actors and relations. Research questions examine how the actors and relations are mobilised through material-discursive practices, how expectations and promises are created, reinforced, and modified, and how ITER is justified through different material-discursive practices. The research methodologies correspond to the research questions. Dynamic and diverse practices are analysed through interviews, field research, document and media analysis. The concept of assemblage resonates with the method of combining diverse sources, which provide different perspectives.

Chapter 4 reveals different phases of ITER assembling practices. A relatively chronological order from planning to constructing and reworking does not mean that the practices are situated in linear order. Instead, most practices are continuously reintroduced and adopted. Chapter 4.1, "Planning ITER", focuses on the historical and political context of ITER, starting with the foundational document, "ITER Agreement". The document's characteristics of a legally binding reference and the materialisation of expectations strongly shape the formulation of ITER at the core. The strong emphasis on international collaboration highlights the project's communality. The project structure is carefully designed with this aspect in mind. At the same time, the research reveals that ITER is also embedded in a very European context. The historical account of the project planning trajectory shows the inseparable relationships between ITER and European fusion R&D. Therefore, the narratives and practices of "ITER as an international project" and "ITER as a European project" coexist and feed into mutually complementary justifications.

The construction phase of ITER proceeds with this double standard. Chapter 4.3 articulates the debates about the site setting and member contributions. While the international collaboration is delicately designed in the material contributions, financial structure, and governance structure, the physical presence of the ITER site also emphasises Europe's importance in the project. The machine's vast scale imposes material attraction as well as mythical notions about the project. The high-tech machine conceals both physical and metaphysical presuppositions in the construction practices. Not only the physical and spatial appeals of the project, but also the temporal speculation - from the past to the future -determine the legitimacy, as seen in the EUROfusion roadmaps. Construction in this chapter means both material and discursive practices, which are inseparable.

Chapter 4.4, "Reworking ITER," examines dynamics within repair and maintenance practices. It starts with the project's fragility. Against the material and discursive backlash that causes long-term delays, the project has been working on regaining legitimacy and credibility. Here, delicate and dynamic practices maintain material and discursive elements that have been addressed before. Strategic alignments and disalignments have taken place to sustain or reconfigure the project's legitimacy and credibility. This part contributes particularly to the discussion of technoscientific promises and their repair.

Chapter 5, “Discussion”, and Chapter 6, “Conclusion”, summarise the research findings and academic contributions. They emphasise that ITER encompasses vast temporality, from the past to the future, as well as spatiality, from Cadarache to the locations of ITER members. The fact that ITER is not a single machine but a vast assemblage lends legitimacy and credibility to its technoscientific promises. The solid, enfolded interrelationships (or interdependencies) create resilient and adaptable justifications for technical and social uncertainties. The specific characteristics of ITER equalise nuclear fusion energy R&D: ITER is “THE” fusion; fusion is ITER. This strong association also supports exceptionalism to the ITER-fusion assemblage. Distancing from other energy sources, particularly nuclear fission, provides the ITER fusion assembly with an exceptional project framework. That also leads to ITER-fusion optimism and an imperative. The middle- and long-term future-envisioning engenders optimism about the success of ITER-fusion. Thus, strong justificatory claims impose the obligation to continue the project. As the interviewees said, “So, we need nuclear fusion”, whatever it costs and “no matter how long it takes”.

Despite its limited scale, this research contributes to the discussion of technoscientific promises by providing an empirical study of one of the largest ongoing technoscientific projects on our planet. The sensibility towards materiality allows the research to see ITER as an assemblage. This research shows how the future of nuclear fusion energy has been promised and justified by the complex interrelationships within the assemblage, and how the project has continued despite uncertainties and fragilities.

2. Situating ITER: State-of-the-art and theories

2.1. Introduction

Nuclear fusion energy has been explored and developed since its discovery in the 1930s. However, until today (as of 2026), no one has achieved commercially viable fusion energy generation. Why is it so difficult to achieve it, and if so, why do people still keep trying it for decades? To understand the positionality of ITER, this section first briefly reviews the broader social context of the energy crisis and security, in which the "needs" for nuclear energy are often addressed. The section then addresses an important aspect of the discussions: nuclear energy – both fusion and fission – is associated with dreams, hopes, and expectations about its high energy intensity and low carbon emissions during electricity generation. Then it shifts to discussions of promise and expectation in technology development in STS and related fields. This section provides both empirical and theoretical background to map out ITER.

2.2. Energy Transition and Security in Europe

To map out the current state of nuclear energy, it is essential to begin with a discussion of energy transition and security in recent years, especially in Europe. Although pro-nuclear attitudes have long persisted in certain groups, advocacy for nuclear energy has grown recently due to the need for climate change mitigation and energy security.

One of the most prominent landmarks for climate action was that the 26th UN Climate Change Conference of the Parties (COP26) in 2021 set a goal to achieve net-zero CO2 emissions by the middle of the century, aligning with the accelerating phase-out of coal and encouraging investment in renewables (COP26, n.d.). To achieve this goal, the European Commission (EC) has set up a long-term agenda for research and innovation (Directorate-General for Research and Innovation (European Commission), 2009) and a roadmap for energy transition (European Commission, 2011). Based on these forward-looking agendas, the EC is working on the transition from coal to less carbon-intensive energy sources. Although renewable energies such as solar, hydro, and wind have been remarkably developed in the last few decades, the immediate transition to these renewables is considered difficult (European Commission, n.d.-c). After heated discussions and political negotiations, the EC labelled gas and nuclear as "green" transition energy (Limb, 2022). Also, the European Parliament approved gas and nuclear in the EU taxonomy to encourage investment in these energy sources under time limitations, certain conditions, and transparency requirements (European Parliament, 2022). These decisions are both symbolic and practical actions of the European Union (EU) that recognise the demands to reintroduce or expand nuclear energy in Europe.

Additionally, rising demand for energy security and independence is accelerating the adoption of nuclear energy. The energy crisis caused by the Ukraine war has revealed energy dependency on Russian oil and gas (Sandford, 2022). The EU partially banned the import of Russian oil (Kennedy, 2022) and declared a ban on Russian gas as a sanction for Russia (Casert & Petrequin, 2022). Accordingly, nuclear power came up again in the discussion as an alternative energy option: nuclear fission energy is often presented as "independent" energy, despite interdependencies among actors in resource access and in socio-technological requirements. For example, Germany, which previously decided to phase out nuclear power by 2022 after the Fukushima disaster, is reassessing the plan (Reuters, 2022). France, the traditionally pro-nuclear state, re-emphasised the importance of nuclear power for energy sovereignty and announced a plan to build 14 new reactors (Herd, 2022). The dynamics of nuclear energy are changing in the current energy-politics context. Moreover, new types of nuclear reactors, such as small modular reactors (SMRs) and nuclear fusion, have, to some extent, become a "hype" in Europe for future energy.

The EC's energy agenda today is to couple the green transition with energy security. In May 2022, the EC launched the REPowerEU plan with a mobilisation of almost 300 billion euros in budget, aiming at helping the EU to "save energy", "diversify energy supplies", and "produce clean energy" (European Commission, 2022). This also aligns with the European Green Deal, which aims to achieve climate neutrality while simultaneously driving economic growth. These agendas and plans reflect current problems while aligning with visions for the future. Kester articulates how the concept of energy security embraces forward-looking and imperative aspects: "Security is both a state of being (the end goal of 'feeling secure') and the means towards that end (either repairing threats or avoiding them)"; in other words, security can be "negative (negating threats and dangers) or positive (something to strive for)" (2018, p. 57). Hence, overall, visions and expectations for desired and undesired futures are enfolded in research and innovation (R&I) policies. Later in this chapter (2.7), the roles of visions and expectations in science and technology will be elaborated. Before that, the next section articulates an imaginary for nuclear energy in particular.

2.3. Nuclear Realists and Nuclear Utopians

In light of the current situation of climate change and international politics, the voice of nuclear proponents has risen in recent years. Despite the historical tendency towards anti-nuclear attitudes, even some environmentalist activists/groups advocate nuclear power to tackle the urgent need to tackle climate change (Lynas, 2014; van Munster & Sylvest, 2015). The support for nuclear energy is complex and diverse because nuclear energy – here, nuclear fission but not exclusively – is closely related to various sociotechnical issues such as military use (Peoples, 2016, 2019; Uchiyamada, 2019; van

Munster & Sylvest, 2014), (post-) colonialism (Hecht, 2012), and other socio-political themes. This section, however, focuses on analysing pro-nuclear discourse regarding energy and environmental aspects to understand the existing expectations, visions, and promises in “the second nuclear age”.

Abbott (2012) distinguishes nuclear proponents into two groups: nuclear realists and nuclear utopians. Nuclear realists support nuclear energy, claiming energy security, diversification of energy sources, and low-carbon emissions (Abbott, 2012, p. 23). This discourse is evident among officials and environmental scientists. As elaborated below (see 4.2.3), the EC considers nuclear fusion as one of the options for the energy mix. On the contrary, nuclear utopians, or what Peoples (2016) called "nutopians", argue that atomic energy is the ultimate energy solution for humanity and saves civilisation. This argument is prominent among scientific writers and physicists, particularly in Europe and the US, since the 2000s (Lynas, 2014; Turrell, 2021). American Physicist, Wallace Manheimer states that nuclear energy can “help civilisation survive” (Manheiemr, 2006, the name is as published). He examines the problem of current dependence on fossil fuels and renewable energies’ limited capacities and intermittence, and then concludes that fission and fusion breeding is “the only way our civilisation as we know it, can continue beyond the next half century or so” (Manheiemr, 2006, p. 121).

This type of nuclear utopian approach strongly resonates with ecomodernism. Ecomodernists understand energy as a key driver in improving the quality of life for humans, especially in the developing world. They emphasise the strong correlation between rising energy consumption and improving living standards (Asafu-Adjaye et al., 2015, p. 21). For them, an efficient energy source is energy-intensive because spatial efficiency can leave room for more natural environments. As a result, they profoundly present nuclear energy options – “closed uranium or thorium fuel cycle” or “hydrogen-deuterium fusion” – as “unlimited energy” that can flourish human civilisation for “centuries” and “millennia” alongside optimistic views on alternative options for other material inputs in case of exhaustion, given plentiful land and unlimited energy (Asafu-Adjaye et al., 2015, p. 10). This approach may be problematic because not only is the current socio-technical status far from realising the nuclear energy options that ecomodernists address, but it also raises ethical questions about the notion of continuous “growth”. It is also important to note that the nuclear utopian approach involves ambitious goals and almost sci-fi-like visions for the future, which sometimes strongly and controversially call for maximum technological development, e.g., the Breakthrough Institute.

This distinction between nuclear realist and nuclear utopian discourses is crucial to examining discourse, especially on fusion energy, because those two discourses take different forms in different contexts and serve different future visions. Those two do not seem to fit together, but in practice, they are intertwined and complementary. As articulated later, R&D in nuclear fusion is operationalised by the technology's practicality and desirability.

2.4. Nuclear Fusion: “Dream Energy”

This section briefly introduces technological aspects of fusion. Even though nuclear technology – fission and fusion – is un/intentionally considered as one technology, especially among the lay public (Prades López et al., 2008), technological differences are essential for discussing fusion. As examined below (see 5.2), making differentiation and relation with other forms of nuclear technology includes a political agenda and practice (Hecht, 2009; Peoples, 2019). However, articulating the technological features of fusion enables a more precise analysis of discourses and practices.

To begin a discussion about nuclear energy, it is crucial to distinguish between two nuclear power technologies: fission and fusion. All existing nuclear power reactors are based on nuclear fission technology. Nuclear fission is "a reaction where the nucleus of an atom splits into two or more smaller nuclei, while releasing energy" (Galindo, 2021). The widely used material is Uranium-235, which is enriched from mined uranium. Uranium mining has involved social and environmental problems. For example, uranium mining is often based on (neo-) colonial relations, which externalise the environmental and health problems from Western society (Hecht, 2012; Uchiyamada, 2021). A collision between a neutron and a uranium atom splits the atom, releasing large amounts of energy and heat, as well as neutrons to initiate further reactions. Controlling reactions, “chain reactions”, is vital to running the reactor safely. Otherwise, a fission reactor may cause fuel meltdown, leading to a catastrophic nuclear accident like Chernobyl or Fukushima. Additionally, fission reactions convert the fuel into highly radioactive waste. Whereas nuclear waste sustains high radioactivity for over 10,000 years, the solution is not yet established (Foley, 2021). Therefore, criticisms of nuclear fission technology raise preliminary concerns about contamination from mining, risk of a nuclear accident, and radioactive waste.

On the contrary, nuclear fusion is a different type of technology, which is often claimed to be less problematic (Turrell, 2021). The most common type of nuclear fusion reaction – including ITER – is fuelled with two isotopes of hydrogen, Deuterium and Tritium; therefore, this type of fusion is called deuterium-tritium fusion or D-T fusion. These isotopes exist virtually limitlessly on the planet (Turrell, 2021) although breeding of tritium is required. When the two nuclei are heated up under high pressure, they cause a fusion reaction that produces Helium and neutrons with energy (Amos, 2022). A fusion reaction has been experimented with in a doughnut-shaped reactor, called a tokamak (for the detailed structure, refer to Llewellyn Smith & Ward (2008)). Nuclear fusion was discovered in the 1930s and has been experimented with since the 1940s, with interest in its high-power generation (Chatzis & Barbarino, 2021b). Nuclear fusion is the same mechanism that the sun and stars use to produce energy. Therefore, there are many analogies between fusion R&D and the sun and stars; for example, Turrell calls the endeavour to reproduce nuclear fusion "star building" (2021), and Willmer introduces the analogy in Horizon Magazine by the EC (Willmer, 2022).

However, reproducing the reaction on Earth is technically challenging, as addressed in the section below (see 2.5). So far, net energy production – more energy output than input – has not been sufficient for commercial energy generation. Yet, nuclear fusion attracts its proponents because of its abundant resources, high-energy intensity, “safety” due to its technological features, and little radioactive waste (Turrell, 2021).

As nuclear fusion became a “hype” for its attractiveness, the public and private sectors have increasingly experimented with it (Funk, 2019). One of the main actors investing in fusion is the EU, which has hosted experimental reactors such as the Joint European Torus (JET) in the U.K. (until Brexit), contributed to ITER in France, and has been planning to construct a DEMO (see also 4.2.3). Under the H2020 Euratom programme (2014-2020), the EC sponsored 679 million euros to a fusion consortium, EUROfusion, to facilitate the collaboration for fusion research, aiming to achieve commercialisation around 2050 (European Commission, n.d.-a). Euratom research and training programme (2021-2025) allocates 583 million euros for actions in fusion research and development (European Commission & Directorate-General for Research and Innovation, 2021). Private sectors, such as Commonwealth Fusion in the U.S. and First Light Fusion in the U.K., also join the race for scientific achievement. The private start-up companies are sometimes funded by famous entrepreneurs like Bill Gates, Jeff Bezos, and Elon Musk (Turrell, 2021). While there is criticism about the feasibility of the technology, even by physicians (Jassby, 2019) (see also 2.5), fusion technology has seen heavy investment in R&D and is now in the race to achieve first commercialisation.

The arguments of fusion advocates can be summarised as follows. First, it does not produce high-level radioactive waste, which is one of the biggest problems with fission energy. Second, it has vertically unlimited fuel (Lithium in seawater would last 30 million years and Deuterium over a billion years), while the reserved uranium for fission lasts only 30 years (Turrell, 2021, p. 44). Third, fusion would be a base-load energy source, unlike existing renewable energy sources, which would not be sufficient or stable enough to meet demand. In this sense, plasma physicist Wayne and his colleague argue that "fusion energy is one of only a few truly long-term energy options." (Wayne et al., 2002, p. 647). Fourth, contrary to fission, fusion does not involve material and technology that can be used for developing a nuclear weapon, so it would not involve the proliferation risk of atomic weapons (Turrell, 2021, p. 40). Fourth, there is a very low risk of an accident since a fusion reaction occurs only under certain conditions and is easy to stop. Turrell emphasises fusion safety, referring to JET's exploitation manager's words, "The biggest risk” is ‘that you fall down’ in the reactor” (Turrell, 2021, p. 180). These points are often criticised by other scholars, which is reviewed below (see 2.5). Nevertheless, these positive potentialities of fusion energy explain the large-scale investment in fusion R&D and the race for the "dream technology".

2.5. Critiques on Fusion

As seen in the previous section, fusion is presented as "unlimited energy", whereas it raises several questions and concerns. In contrast to pro-fusion arguments, some argue that "the likelihood of seeing commercial fusion this century is virtually zero" (Abbott, 2012, p. 28). This section introduces some criticisms that provide a balanced view of the technology. It enables critical reflection on the promises and imaginaries that sometimes ignore or conceal the downsides among the hype.

One of the most prominent critiques of fusion lies in its feasibility. The technology has been researched and developed for over seven decades, but a commercial application still seems a long way from being realised – or it may never be. In February 2022, many fusion organisations and personnel celebrated JET's announcement that they generated 59 megajoules of energy for 5 seconds in the tokamak (Gibney, 2022) as a big "breakthrough" for the realisation. Also, today, many fusion start-ups promise commercialisation by 2030 (Turrell, 2021). Scientists at the National Ignition Facility (NIF) in the Lawrence Livermore National Laboratory in the U.S. achieved net energy gain for the second time in August 2023 (Reuters, 2023). The EUROfusion project more moderately set a roadmap for commercialisation starting from 2050 (EUROfusion, 2018b).

Despite big news and promises, no prospect of sustained and sufficient net energy gain for commercialisation has been identified yet. This is because of technical difficulties. For example, a reactor needs to withstand more than 100 million degrees Celsius, intense pressure to fuse deuterium and tritium, and plasma confinement. (Chatzis & Barbarino, 2021b). Some researchers argue that the second procedure to extract energy from the reactor is technically not realistic (Rhodes, 2012, p. 94). These technical difficulties with the machine remain unresolved through further experimentation. As a consequence, some might say, a realisation of the technology is endlessly postponed for "always next 50 years" (Rhodes, 2012, p. 91).

Second, fusion is not free from nuclear waste. Even though a fusion reaction itself does not produce radioactive waste from the resources as a fission reaction does, it activates the structural materials and generates explosive dust (Abbott, 2012, p. 28; Hancox, 1992). Activated structural materials would be nonrecyclable and would retain radioactivity for centuries. Routine replacement of the structural materials and decommissioning of the reactor would generate highly radioactive waste, which should be treated in the same way as the waste from fission reactors. Therefore, fusion is not "clean" as often claimed, and the environmental assessment should be considered throughout the reactor's lifespan (Rhodes, 2012, p. 92). Most energy-related discussions of nuclear power plants (and other energy plants) consider only the energy generation process. On the contrary, STS scholars have argued that an energy plant is embedded in a certain complex system of materials and socio-cultural practices (for example, Högselius, 2022). Barbara Adam also articulates the temporal aspects of neo/classical economics that often ignore the long-term consequences of economic activities, particularly in the case of nuclear energy and radioactive waste (1998). Therefore, the pro-fusion claim regarding radioactive waste should be revisited within a broader spatial and temporal context.

Third, contrary to pro-fusion arguments, the materials for fusion reactors might not be ensured indefinitely. Primarily, there is a question about the sustainable supply of tritium, one of the main fuels for fusion. The main source of tritium today is lithium, which is widely used for batteries. Since lithium is a rare metal that is expected to be used for many other means, especially for renewable energy storage and electric cars, the sustainable supply is questionable (Abbott, 2012; Rhodes, 2012). An alternative way of tritium production, extraction from seawater, is highly expensive and energy-intensive, with the current technology (Rhodes, 2012). Furthermore, a large power supply unit for fusion would contain many metals and rare-earth elements, which may impede the construction of large reactors. Therefore, the sustainability of reactor design should be reconsidered.

Fourth, it is difficult to completely rule out the possibility of military diversion of fusion technology. Rhodes (2012, p. 92) points out the possibility of replacing the lithium blanket with uranium to produce plutonium for a nuclear weapon. The expertise and infrastructure of nuclear research may contribute to weapon-making preparation (Abbott, 2012, p. 26). Indeed, fusion R&D is closely related to military and defence collectives. For example, NIF researches nuclear science for nuclear weapons and laser weapons (National Ignition Facility & Photon Science, n.d.; Potter, 2024). One of the EUROfusion partners is a plasma physics laboratory at the Royal Military Academy in Belgium. Fusion reactors are also in development for space rockets, which are often closely related to military applications. Although the IAEA clearly answers "No" to the FAQ, "Can fusion reactors be used to produce weapons?" (IAEA, n.d.), there are likely to be military applications, either directly or indirectly, from fusion R&D.

Fifth, many have pointed out that fusion energy would not be more economically viable than other renewable energies. Even fusion proponents admit that the price of fusion-generated electricity would not be lower than the current price of solar energy (Turrell, 2021). Furthermore, considering the entire process of massive R&D costs, site setup, decommissioning, and waste management, the cost of fusion energy over its lifespan increases more than the calculations suggest in pro-fusion arguments. Financial prospects are among the strongest incentives for investment. In particular, public research allocates limited resources to certain R&D under the pressure of legitimisation and justification for the allocations. If it is already clear that fusion energy would cost more than existing renewables, would that not run counter to neoliberal economic policy? While there is rich scholarship on non-financial initiatives of innovation policy (e.g., Diercks et al., 2019), the economic aspect of nuclear fusion energy reassures, say, the need for other "selling points" for the technology, particularly the public one, ITER.

Nuclear fusion is often touted as the ultimate solution to the energy crisis and to climate change mitigation. However, the criticisms above may lead to an environmentalist argument proposing to expand the capacities and efficiencies of renewables rather than to take on the risks and uncertainties of nuclear fusion, especially under conditions requiring responsive action. Abbott ironically concludes his article:

> *The sun is nature's nuclear fusion reactor, located at an arguably safe distance from Earth. It generously affords us 5,000 times our current world energy needs and will run reliably over the next billion years with zero downtime. It is uncertain whether man-made fusion reactors will ever become commercially viable. Even if they do, it makes no sense to take on uncertainty – in terms of resource and safety issues – when the sun already provides us with a virtually limitless nuclear resource delivered straight to our doorsteps.* (Abbott, 2012, p. 30)

The next section tackles the issue Abbott mentions – uncertainty. It is closely related to the strategies in science and technology development. There, expectations, visions, and promises play a key role in coping with uncertainties.

2.6. Uncertainties, Imaginaries, and Visions

The future embraces countless uncertainties. Beck famously argues that modern society involves significant risks due to technological developments, a globalised economy, geopolitical tensions, climate change, etc (1992). Interrelations among heterogeneous actors and factors impose far-reaching complexities on simulation or prediction. Technological developments would influence the form of society and vice versa. In particular, so-called "disruptive" technologies such as artificial intelligence or climate engineering might change the state of the art in social, political, economic, and environmental status. There are many works in the STS field working on the role of science and technology in an uncertain world (Callon et al., 2009; Nowotny et al., 2013). And, if one follows the proponents' arguments, nuclear fusion energy would probably be one of the most "disruptive" technologies. At the same time, technological developments are also influenced by resource allocations, coordination, and collaboration driven by short- and long-term visions and agendas. Technology itself embraces uncertainties in an uncertain situation.

Particularly for publicly funded R&D, visions and imaginaries in science, technology, and innovation are at the heart of agenda and goal setting, often in the form of policies. Jasanoff and Kim (2009) propose the concept of "socio-technical imaginaries" to describe the collective visions that encode the future of technoscience and the simultaneous development of society. By comparing the nuclear policies in the U.S. and South Korea, they show how national interests and visions have "the power to influence technological design, channel public expenditures, and justify the inclusion or exclusion of citizens with respect to the benefits of technological progress" (Jasanoff & Kim, 2009, p. 120). Also, socio-technical imaginaries embrace a future-oriented imperative to choose among socio-technological trajectories. For example, keeping some technologies out to re/confirm a national identity (Bayer & Felt, 2019; Felt, 2015). While STS research on socio-technical imaginaries often examines at the national level (e.g., Verschraegen et al., 2017), this approach is also useful at a supranational level, such as the EU (Völker et al., 2020).

Corresponding to works on imaginaries in STS, technology assessment scholarship has also analysed the constitutive role of visions in the ongoing R&D. According to Grin and Grunwald, visions – originated in the German term "Leitbild" – have two major features: "they are a mental image of an attainable future shared by a collection of actors" and they "guide the actions of interactions between those actors" (Grin & Grunwald, 2000, p. 11). Ferrari and Lösch see analysis of visions, namely, "vision assessment", as "socio-epistemic practices" that "simultaneously produce new knowledge and enable new social arrangements in different socio-technical constellations" and suggest integrating vision analysis into technology assessment (2017, p. 76). They identify some of the characteristic functions of visions as follows: 1) visions serve as an interface translating between present constellations and the future, 2) visions work as communication media, 3) visions enable coordination, and 4) visions develop a normative force (Ferrari & Lösch, 2017, pp. 78–79). One of the additional aspects of vision assessment is that, coming from a close relation to policymaking, it provides an ethical assessment of ongoing visionary practices (Lösch et al., 2017). The concluding chapters (5 and 6) examine the implications of ecomodernist visions for nuclear fusion R&D.

The concepts of imaginaries and visions are broad, overarching descriptions of the directionality of technoscientific society. Especially since the emergence of strategic science and technology at the end of the last century, it has been essential in science and technology policymaking to bridge the present and the future (van Lente & Rip, 1998). Then, the phenomena of those future-oriented science and technology development enclose specific performativity, agency, and representation (Michael, 2000). The following shows how imaginaries and visions are transformed into different forms, such as agendas, expectations, or promises and how these forms function within technology development.

The importance of the agenda can be seen in van Lente's conceptualisation of "the triangle of technological development", which consisted of artefacts, actors, and agenda (van Lente, 1993, p. 8). Agenda, often in the shape of a strategy, guideline, or priority, gives directions and priorities for both researchers and decision-makers by being commonly shared and reflected among the actors (van Lente, 1993). Agendas embrace temporality, corresponding to expectations about how science and technology will develop and achieve objectives over a given period.

In particular, promises render an obligatory chain of necessity for the technology (van Lente, 2000). Promises and expectations are often simplified and complexity-reduced master narratives (Dueten &

Rip, 2000). While activities of promises in science and technology are continuously driving specific technologies, strategic science entails expectations for a wider scope and generalised promises (van Lente & Rip, 1998, p. 223). As mentioned above (2.2), R&D in climate and energy science and technologies for climate mitigation often aligns with major agendas – net-zero carbon by 2050, for example. These kinds of long-term, generalised goals work as imperatives at diverse levels of society alongside techno-scientific development.

2.7. Forms and Agencies of Visions: New Materialism

The previous section has provided an overview of the roles and interrelationships of visions, imaginaries, expectations, and promises in technology development. Yet a question arises about the process by which the abstract metaphysics of visions emerges. Or, more precisely, the questions are: How is a vision constituted? How does a vision operate and perform within the dynamics of technology development? How do visions interact with the future and create a space where technology development takes place? In the constructivist perspective, visions are purely abstract or discursive constructs that are taken for granted as solid entities, which underplay the role of material things such as technical components, machines, infrastructure, and physical constraints. Therefore, this section adopts a new materialist perspective to analyse how visions emerge and act within socio-technical processes. Introducing new materialism into the discussion of visions, imaginaries, expectations, and promises sharpens the scope and approach to the dynamic and causal relationships/networks in technological development.

In particular, there are two reasons why the new materialist perspective helps us understand that. First, technologies, materials, and infrastructures have agency in configuring technological development. Particularly in a case like ITER, physical materials and infrastructure are essential parts of technological development. Unlike research that relies less on materials (e.g., theoretical physics, even though it still depends on things such as computers), nuclear fusion requires massive machines and vast infrastructure as prerequisites for the technology. Looking at the socio-cultural aspects of technology only allows us to examine (less than) half of the research objects and relations. Second, social and material aspects are inseparable, as many new materialist approaches argue. Especially in an ongoing project such as ITER, imaginaries, visions, expectations, and promises are intertwined with the physical existence of documents, machines, components, and other artefacts. If there is no "physical proof" in arguments, there is no credibility and legitimacy in such a context. In short, it is not possible to separate "ideas about technology" from "the material systems that make technology work".

According to Svensson, new materialism is an umbrella term that covers a constellation of thinking which has been "developed and influenced most notably by *actor-network theory* (Latour, Law, Callon), *assemblage theory* (DeLanda), *vital materialism* (Bennett), *agential realism* (Barad), and

Donna Haraway's theories of *hybrids* and *cyborgs*" (Svensson, 2021, pp. 2–3). The sensibility to new materialism has also increased in energy research in STS (Svensson, 2021). One of the important and common features of this approach is that "new materialists are rediscovering a materiality that materializes, evincing immanent modes of self-transformation that compel us to think of causation in far more complex terms; to recognize that phenomena are caught in a multitude of interlocking systems and forces and to consider anew the location and nature of capacities for agency" (Coole & Frost, 2010, p. 9).

The emergence of this rediscovery of materiality reflects on the criticism of too much emphasis on language in social science and humanities, e.g., social constructivism, linguistic turn, semiotic turn, interpretative turn, cultural turn (Barad, 2003, p. 801). In the case of STS, the social construction of technology (SCOT) (Bijker et al., 2012) is particularly subject to criticism. Excessive emphasis on cultural representations obscures the interrelationships between matters and cultural representations and ignores the agency of matters themselves, which is essential for techno-scientific practices. Revisiting materiality enables tracing "the complex and reversible causalities that run between different levels of the social system and especially between the microlevel or everyday, and the macrolevel or structural" (Coole & Frost, 2010, p. 32).

To understand new materialist approaches and their implications for this research, it is fruitful to provide a brief introduction to key concepts of materiality, assemblages, agencies, and other related notions here. First, definitions of matter, materialisation, and materiality are well elaborated in Kester (2018):

> *"*Matter *can be defined as something that occupies space and consists out of mass (atoms, particles, energy). The* material *is a term used to describe something made out of matter, when matter is reworked in different substances or elements. In turn,* materialization *describes the process of turning, shaping, enacting or creating material objects from social practices and ideas. Lastly, the concept of* materiality *stands for the theoretical and ontological position that claims that matter exists outside of human sensory observation."* (Kester, 2018, p. 127)

When applying these definitions to nuclear fusion, the following apply. Matter is physical stuff like atoms or energy. Material is shaped matter, such as steel or a reactor component. Materialisation is the process of making ideas into physical reality, like from design to construction. Materiality may be used to talk about the physical existence of machinery itself. Sensibility towards matters as constitutive and mediative elements diversifies potential agents in the analysis of techno-scientific practices, rather than a sole focus on discursive and social elements as seen in SCOT. Techno-scientific practices are carried out with a mix of heterogeneous actors, including matters. These mixtures/systems are often conceptualised as "assemblages" or "phenomena". One of the most commonly used concepts of assemblages can be defined by Manuel DeLanda's summary (2006, pp. 19–21):

1) *Assemblages have a fully contingent historical identity, and each of them is therefore an individual entity: an individual person, an individual community, an individual organisation, an individual city. ...*
2) *Assemblages are always composed of heterogeneous components. ...*
3) *Assemblages can become component parts of larger assemblages. ...*
4) *Assemblages emerge from the interactions between their parts, but once an assemblage is in place it immediately starts acting as a source of limitations and opportunities for its components (downward causality).*

In short, assemblages are constituted by heterogeneous components/elements, including humans (e.g., scientists, engineers, policymakers), nonhumans (e.g., components, machines, data), institutions (e.g., policies, regulations, funding structures), and other things. Assemblages are in continuous movement, sometimes through integrations to or separations from other assemblages within temporal and spatial dimensions/relations. While structuralist and constructivist thinking often sees human action as the centre or cause of every relation, assemblage theory broadens the scope beyond humans, examining detailed relationships among components/elements. In addition, the wider scope of assemblage theory allows us to redefine "agency". In the constructivist view, agency is something only humans possess via intentional actions. Instead, in the new materialist approaches, agency is distributed across humans and nonhumans. Agency is not something humans have by nature, but something that happens. For example, in nuclear fusion R&D, engineering constraints, funding rules, political goals, or material failures act, imposing certain directions or restraints.

While components of assemblages – or actor-networks (e.g., Latour, 2005) – have relatively common agreement among new materialists, relations between elements in assemblages are understood in different ways. Sociology of translation (Callon, 1984) sees relations of elements as sequences of translations: an actor's agency (re)formulates, transforms, or inscribes another actor. Translations sometimes pass through "obligatory passage points" (Callon, 1984) that exclusively shape the course of the sequence. While some works employ the sociology of translation to analyse expectations and promises (Joly, 2010; Joly & Le Renard, 2021), the agencies of materialities seem underrepresented. In the work of Joly and colleagues (Joly, 2010; Joly & Le Renard, 2021) visions are placed at the centre of causal relationships. From such perspectives, the agencies of materialities themselves appear only alongside inscriptions of visions. In many cases, however, it is difficult to examine contingent agencies and the sequences that have already been established and concealed – "black-boxed". Sometimes, it is impossible to trace the full sequence of translations, and it is not even helpful to do so when analysing ongoing, ever-changing phenomena, such as ITER.

Instead of tracing chains of translation, this research dives deeply into agency and materiality because the research object, ITER, is a constantly changing, dynamic assemblage that does not necessarily reveal such chains. For this reason, it is useful to employ the concepts of two new materialists: Karen Barad and Jane Bennet. Karen Barad's agential realism understands discursive practices with performativity. A performative understanding avoids too much focus on cultural and linguistic representation and shifts to discursive practices (Barad, 2003, p. 807). In phenomena – also, Barad calls it apparatus –, discursive practices are "*specific material (re)configurings of the world through which local determinations of boundaries, properties, and meanings are differentially enacted*" (Barad, 2003, p. 820). In this sense, Barad uses the phrase "material-discursive practices" to account for the inherent materiality of performative agencies. Agency is not attributed to the elements of assemblages, but it is rather "doing"/ "being" of material-discursive practices, which precludes "the possibilities and accountability entailed in reconfiguring material-discursive apparatuses of bodily production, including the boundary articulations and exclusions that are marked by those practices in the enactment of a causal structure" (Barad, 2003, p. 827). Material-discursive practice foregrounds how language, categories, representations, and material arrangements are entangled, so that discourse is not just talk but part of how realities are enacted. This research does not strictly focus on assessing reality in nuclear fusion R&D in an agential realist way. It still uses assemblage theory (DeLanda, 2006) as the core concept, addressing the existence of components/elements rather than seeing phenomena without them.

However, the use of the word "material-discursive practice" determines how to examine practices in ITER. Practices such as machine construction are not mere physical practices but rather entangled discursive and material practices; for example, machines are not just results/products of translation or a mixture of the social and the material, but they also perform and act. Machines can be visions at the same time. This research's focus on practices contributes to a sense of sensibility towards ongoing dynamics.

A focus on practice resonates with the way Jane Bennet clarifies the efficacy, trajectory, and causality of agency. In her work, efficacy is meant for the agency's creativity and capacity to make something new appear or occur; agency is bound to trajectory, directionality, or movement to shift from one to another or even create it; elements, including humans and nonhumans, entail partial, overlapping, and conflicting degrees of power and effectivity (Bennett, 2010, pp. 31–33). The notions of assemblages and distributed agencies, she argues, enable us to broaden the scope of analysis of responsibilities and accountabilities that are distributed and entangled within a complex system, for example, in the case of an accident such as a blackout (Bennett, 2010, p. 37). In case of an "event" (Kester, 2018) that interrupts relatively stable relationships, such as an accident or technical failure, agencies enact "rearrangements, rearticulations, and other reworkings" of phenomena/apparatus (Barad, 2003, p. 817). Bennett's perspective on distributed agencies and types of agencies is helpful when examining how elements act dynamically in cases involving events, such as failures and adaptations (especially Chapter 4.4). In short, a performative understanding of material-discursive practices enables the investigation of the dynamics of ongoing phenomena/assemblages.

The discussion of the new materialist approach of assemblages and agencies can sharpen the scope for investigating promises and expectations in technoscientific development. Earlier introduced van Lente's "the triangle of technological development" consisted of artefacts, actors, and agenda (van Lente, 1993, p. 8). Van Lente's analytical framework separates entities based on the epistemological assumptions of each element: agenda is discursive, actors are often humans, and artefacts are often nonhuman materials. However, following new materialist arguments on the inseparability of 'agentically intra-acting "components"' of phenomena (Barad, 2003, p. 815), it is rather useful to examine material-discursive practices at the centre of the assemblage. Practices enact different types of justifications for technoscientific promise and expectations. Joly articulates this dimension in "the economics of technoscientific promises":

> *"Speculative claims, expectations and promises are some of actions by which an entity attempts to impose and stabilize the identity of other actors. They guide activities and define roles, provide legitimization, and attract interest and credit. Hence, promises can be considered as an important part of the translation process. Techno-scientific promises are not only of a discursive nature; they also have a material dimension, for they foster new alliances and orientate entities (humans and non-humans) towards a given project, just as translation generally does."* (Joly, 2010, para. 8)

Rather than van Lente's demarcation of entities, effective technoscientific promises require not only rhetoric but also enrolments of non-humans (Joly, 2010). Only by doing so can promises be shaped to fulfil two main conditions: legitimacy and credibility (Joly & Le Renard, 2021, p. 900). According to Joly and Le Renard, "credibility builds on experience, while legitimacy rests on the claim of radical novelty—the idea that the solution proposed is very different from what is already available" (2021, p. 900). In practice, however, credibility and legitimacy are conferred simultaneously, intentionally or unintentionally. For this reason, this research again focuses on how practices work within/for promises, rather than categorising credibility and legitimacy. Rather, this research sees practices that act as justifications. The next section explores different types of justification that confer credibility and legitimacy, as well as the dimensions of inherent power.

2.8. Justification of Promises

Practices of technoscientific promises satisfy certain expectations and visions of the future. Credibility and legitimacy would justify future investment, resource allocation, participation, continuation, or rearrangement of R&I. The question now is how these dynamics are formulated, mobilised, and rearranged amid uncertainties and controversies. In other words, the question lies in the causalities and rationalities embedded in or inscribed within the relationships and agencies of elements within practices.

These questions correspond to one of the major criticisms of new materialism, which is that new materialists' mode of agency does not provide analytical resources to examine the interaction between different constitutive elements and thus cannot explain "why certain assemblages are put together, why some are more stable than others, and what social forces are at work within them" (Svensson, 2021, p. 5). Different qualities of elements and different types of relationships should be assessed with sensitivity in ideologies and hegemonies (Allhutter, 2019) as a complementary analysis to the new materialists' relational performativity.

In the case of analysis of technoscientific promises, it is essential to examine a) how and why expectations and promises are accepted as such in the first place, b) how expectations and promises mobilise constitutive elements in certain ways, and c) how expectations and promises overcome uncertainties and controversies and rearrange dynamics in assemblages. The theories of justification of actions by Boltanski and Thévenot (2021) support the investigation of the dynamics and relationships among these three dimensions. In alignment with the new materialist approach, they argue that justifications fall under six main logics: civic, market, industrial, domestic, inspiration, and fame. In the case of ITER, these logics cannot be clearly determined because public nuclear fusion R&D is not purely civic, market-oriented, industry-oriented, or domestically oriented, nor simply about inspiration or fame. As elaborated in Chapter 5, these logics should be considered together in this research.

Therefore, it is useful to refer to what Boltanski and Thévenot (2021) clarify justificatory mechanisms in common model of polity where all the logics above are abstracted: 1) the principle of common humanity: presumption that sharing the membership of humanity so that members are capable of reaching agreement, 2) the principle of differentiation: differentiating one state from another, justifying and reinforcing existing differences, 3) common dignity: all the members are designated to a certain dignity or future, 4) the order of worth: one is more worth than another, 5) the investment formula: sacrifice to achieve more worthful thing, and 6) common good: universal validity (Boltanski & Thévenot, 2021). It is also important to note that these justificatory principles are not mutually exclusive but are sometimes enacted simultaneously or in complementary ways within the regime. For example, common dignity might be led by the presumption of common humanity. Or differentiation from others might even occur within the course of common humanity and dignity. It is also important to note that these principles do not necessarily belong to any single person or institution, but they might be shared within the regime in which actors operate. Hence, it would not be misleading to argue that those principles share common ground with the notions of ideological practice and hegemony, thereby adding analytical perspectives to the new materialist approach to research on practices (Allhutter, 2019). Boltanski and Thévenot's theory of justification is used here as an interpretive sensitising concept to trace how actors justify ITER amid uncertainty. The research does not seek a full reconstruction of all orders of worth, but rather draws selectively on the framework to illuminate recurring justificatory patterns in the empirical material.

In addition, the notions of ideology and hegemony sharpen the scope of the ethical dimension in the research. New materialist notions about dynamic reality help reveal agencies and relations enfolded in assemblages. Throughout the works, new materialists have identified "ethical concerns about subjectivity, normative concerns about social justice, cultural concerns about the construction of gender and ethnicity", and social, material, and historical accounts in socio-economic orders (Coole & Frost, 2010, p. 27). Ethical dimensions are not external to the issue but rather part of broader relationships/phenomena in which we are only partially involved (Barad, 2007; Kester, 2018). Therefore, as we – or at least the author of this thesis – are part of the phenomena, it is inevitable to include ethical dimensions within the analysis.

2.9. Conclusion

This chapter is dedicated to situating ITER in wider sociotechnical contexts. It started with the most prominent context of energy transition and security in Europe, in which the imperative of "ultimate energy" emerges from the current geopolitical and environmental status, and then with the future-oriented account. Then, it has examined the positionality of nuclear energy, presented within the temporal dimension of energy alongside future visions. This chapter has shown that, among the different types of nuclear energy, nuclear fusion is particularly associated with the dream of "unlimited" energy and the notion of a "game changer". To balance such powerful arguments, the following section criticises pro-fusion arguments grounded in socio-material constraints. Then, the chapter broadens its scope to the scholarship in STS and related fields that provides conceptual frameworks for uncertainty, imaginaries, and visions. In particular, the ongoing R&D practices of nuclear fusion can be observed in the expectations and promises that shape and mobilise the R&D setting. This research argues that the forms and agencies of expectations and promises can be examined through a new materialist approach, providing a sensibility for the inseparability of the material and the discursive. Concepts of justification complement the rationale for the agencies and relations underlying the expectations and promises. Research in the new materialist perspective requires particular perspectives and approaches to the research practice. The next chapter provides a scope for approaching the case study.

3. Entering ITER: Research Questions and Methodology

3.1. Research Questions

The previous chapter explored the context and conceptual frameworks for investigating ITER. The analysis of assemblages requires detailed qualitative research. Following the current scholarship on nuclear energy and STS, this research explores the dynamics of fusion R&I with a focus on ITER. Concretely, it is dedicated to examining the following research question:

> *Main research question: How is the ITER project assembled through justificatory practices that satisfy technoscientific expectations and promises?*

This overarching question investigates the complex entanglement of the R&D project and opens the black box that often conceals the temporal and spatial correlations with other nuclear energy developments and with socio-political historicity, with a particular focus on justificatory practices. ITER is often presented as a "special" and "unique" machine. However, it is essential to critically engage with the notion of uniqueness and situate it within a broader context to reveal how ITER promises the future of nuclear fusion. Assemblage theory, as mentioned above, enables the identification of internal and external relationships with other entities. The research question explores practices embedded in relationships and agencies of elements throughout the hegemonic account of justification mechanisms. Consequently, the main research question is approached with the first sub-research question (SRQ) on the temporal and spatial embeddedness of ITER:

> *SRQ 1: How is ITER situated within the sociomaterial landscape of wider nuclear fusion energy R&D, particularly in the European context?*

This question is explored specifically through a genealogical analysis of ITER. To answer this question, this research focuses on the planning and construction dimensions of ITER. The foundational document, the "ITER Agreement", (IAEA, 2007) is the starting point to examine how ITER was formulated and how it has been acting in a certain way. A broader context for European fusion R&D also allows us to situate ITER. Additionally, socio-material analysis from the design setting to the site setting and construction will reveal the assembling practices of ITER. The analysis will be based on a mixed-methods approach that combines field research, interviews, and critical analysis of documents and media. The next SRQ closely asks about the mechanisms and dynamics of elements with a focus on future-making practices in the fundamental documents:

SRQ 2: How do the future-oriented documents in ITER situate promises and perform to justify the project?

One of the most prominent and influential elements for the justification in ITER is what Lösch and colleagues call “constructed futures”, such as visions, scenarios, and roadmaps (2017, p. 138). Those not only present technical depictions and predictions but also formulate certain presumptions and aims. This research carefully looks at the three most important documents of the “constructed future” of ITER: the ITER Agreement, the ITER baseline, and the EUROfusion roadmap. It studies how these documents are (re)formulated and, at the same time, influence other practices. The last SRQ tackles particularly the transformations of elements and relationships:

SRQ 3: How are ITER’s promissory and justificatory practices maintained, adjusted, or rearranged over time to preserve the project’s legitimacy amid sociotechnical uncertainties and controversies?

This SRQ specifically contributes to STS research on expectations and promises by looking at the ongoing dynamics of promissory and justificatory practices. Unlike much scholarly work that relies on retrospective analysis, examining the dynamic relations among ongoing technoscientific promises will provide real-time perspectives. This SRQ will be explored through comparisons of the EUROfusion roadmaps and updates to the ITER baseline over time, as well as discourse analysis of experts’ argumentation in response to sociotechnical uncertainties and controversies.

The questions above are not mutually exclusive. Rather, they shed light on diverse aspects of material-discursive practices that entail justificatory accounts. By doing so, this research will reveal the assembling practices of ITER, contributing to the STS scholarship on technoscientific expectations and promises in both theoretical and empirical ways. As mentioned above, nuclear fusion energy is one of the most hyped new and emerging technologies – it might not be a “new” technology, but it is conceived as such today. To the knowledge of the author, besides a few exceptions on the globalisation aspect of ITER (McCray, 2010) and scientific life (Hackett et al., 2004), nuclear fusion is underexamined in STS scholarship. This research will introduce a detailed analysis of technoscientific expectations and promises through the ongoing large technoscientific project.

3.2. Tracing Assemblages: Methodology

Following the notions of new materialism that insist on the inseparability of research subjects and objects, this section describes the research methodology in which the researcher – “I” – is an integral part of the research “object” ITER. All the methodologies used – field research and digital ethnography, interviews, and document analysis – are incorporated into one another, as Baker and McGuirk (2017) describe in an assemblage methodology. This chapter begins with an ethnographic introduction to my entry into the ITER site, including methodological notes and the researcher's sensibility. Throughout my research, I began to notice that ITER is not a single entity that can be completed at the construction site in southern France, but rather part of a larger assemblage (DeLanda, 2006). Those findings are presented alongside the methodological considerations of this research.

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On a sunny morning in March 2023, I was driving from the French port city of Marseille to Saint-Paul-lez-Durance to join a guided tour at ITER with my friends. After about 1.5 hours of driving along a highway and through a peaceful landscape, the French Alternative Energies and Atomic Energy Commission (CEA) buildings were first seen in an almost hidden corner near the highway exit. After 10 minutes, the ITER's entrance appeared. We switched to an arranged bus to enter the ITER construction site. The massive mirror-wall cube, the assembly building, was situated in the middle of the wide site with other facilities. I was astonished by the size of the site, the number of international people working, and the complexity of the facilities. ITER is described as the most expensive scientific research so far (Henley, 2011) and one of the most challenging endeavours, like the International Space Station.

The more I proceed with research, the more complexities emerge. Even though ITER is the largest existing nuclear fusion reactor, there are many other fusion reactors around the world, and their practices are often associated with ITER. Even though my focus lies on ITER in the context of European R&D in fusion, my research "object" cannot be situated only in the ITER complex in Saint-Paul-lez-Durance but needs to be extended to Culham in the UK (JET), Garching in Germany (JRC, EUROfusion), Rokkashomura in Japan (IFMIF), Vienna in Austria (IAEA), etc. Also, the research's temporal dimension needed to be extended. It is not possible to look only at the time span of ITER; it is necessary to dig into the past, present, and, of course, the future – a far future. The research perspective should cover the findings of nuclear fusion research in the 1920s, nuclear weapon development in the Second World War, the establishment of Euratom in 1958, the Reagan-Gorbachev meeting in 1985, the ITER agreement in 2007, and the aim of commercialisation after 2050 – or even later (or never…).

While I must be aware of the limitations of research, I must also somehow account for the vast spatial and temporal dimensions of my research. However, how can I do that? How can I see and analyse the giant, or "Chimaera"? Having researched the Fukushima Daiichi Nuclear Disaster, the Japanese anthropologist Uchiyamada (2019) depicts the giantness of the development of nuclear science and technology as a "nuclear machine", meaning the inevitable connections between nuclear weapons and energy, and the global network of materials, technoscience, politics, etc. Likewise, it is essential to analyse ITER as a heterogeneous mixture of entities, time, and space.

The scholarship of science and technology studies (STS) is committed to offering a perspective on science and technology in their internal and external relationships with sociocultural and political aspects. In other words, it does not separate science, technology, and society but rather sees the heterogeneity of the complex phenomena. Particularly, the concept of assemblage is helpful in fusion R&D as both a methodology and a theory, shedding light on the relations, alliances, and associations among things (DeLanda, 2006). Assemblage theory recalls ontological sensibilities towards technoscientific phenomena. Technology is "not material culture but rather a total social phenomenon in the sense argued by Marcel Mauss, a phenomenon that marries the material, the social and the symbolic in a complex web of associations" (Pfaffenberger, 1988, p. 249 in Bruun & Wahlberg, 2022). Particularly, this research draws considerable attention to policies with an epistemological commitment to "multiple determination, interactive processes, and labour" of policy making through "the relational and interactive configuration of actors, events, materials, and projects which display complex, relational spatialities" (Baker & McGuirk, 2017, p. 435). ITER is in a dynamic interplay of actors – scientists, politicians, publics, anyone and anything concerned – with materials, documents, practices, etc. With a focus on fusion R&D assemblages with a European focus, this research aims to depict the giant ITER within the context of assembly practices.

This notion of assemblage corresponds to methodology. Drawing attention to phenomena as complex dynamics, assemblage methodologies follow the actors and interrelationships within configurations. In a context of critical policy research, Baker and McGuirk argue that "assemblage thinking has become a valuable methodological tool, frequently used to disaggregate the phalanx of actors, materials, processes, and practices that help mobilize particular policy ideas" (2017, p. 429). Materials here also include not only technoscientific devices and the natural environment but also, for example, documents. Documents are often referred to justify and/or legitimise activities in the past, present, and future. Therefore, a document may act as an actor/actant (Latour, 1996) or constitutive elements (Barad, 2003) that create, maintain, disperse, or eliminate associations in assemblages. What is also noteworthy for assemblage methodologies is that the process of constituting assemblages is only provisional. "(R)elations may change, new elements may enter, alliances may be broken, new conjunctions may be fostered"; therefore, "assemblages are constantly opening up to new lines of flight, new becomings" (Anderson and McFarlane (2011, p. 126) in Baker & McGuirk, 2017, p. 432). This perspective is useful when examining a project that has been constantly reformulated over decades.

While Baker and McGuirk (2017) employ the word "assemblage methodology", Wahlberg suggests assemblage ethnography to "study and locate complex social phenomena within the discernible configurations that organise an assemblage, complex, or *dispositif*" (Wahlberg, 2022b, p. 139). Ethnographies, originating in anthropology, explore phenomena not limited to a single issue but as broader patterns, drawing attention to the details of practices, interactions, and discourses. The concept of ethnography is used to clarify the sensibility and detailed observation of phenomena, rather than to refer to classical anthropological fieldwork. Following this concept of "assemblage ethnography", this research employs multiple sources, methodologies, and sites to trace the actors and interrelationships in ITER within the wider context of nuclear fusion R&D. It uses a classic ethnographic sensibility for a guided tour of the ITER construction site, digital ethnography for an ITER virtual tour, expert interviews, and document analysis for legal and official documents, and media analysis on webpages and videos. Since assemblage methodologies aim to follow actors and interrelationships, this thesis takes a unique approach, not to curate the materials chronologically, but to follow the connections and associations among the themes emerging in the research. Additionally, in resonance with assemblage ethnography, this research particularly attends to the researcher's agency, which also shapes associations with the research "objects" through the researcher's background, senses, and thinking. Particularly, this sensibility is well noted during field research, interview practice, and document and media analysis.

Taking assemblage thinking into consideration, the documents are analysed with a scope of "document ethnography". Asdal and Reinertsen emphasise the performativity of documents, seeing documents as follows: 1) a document entails *action* that someone has recorded and preserved for a reason and that forces or prevents something; 2) a document is *relational*, which is attached to something outside of itself; and a document is *material* (2021, p. 3). An ethnographic exploration of documents suggests ways to examine situatedness, rhetoric, interactions, agency, and the performativity of documents. For example, a legal document signed by interested parties enforces actions and/or prevents the concerned from doing other actions. Strategy documents are based on high-level policies and principles to articulate a vision and share the future, allocate resources, and materialise the vision into actions. Therefore, in this research, document ethnography is considered as a part of assemblage methodologies.

This research also relies heavily on visual materials, including presentations, website images, virtual tours, and roadmaps. As seen in McCray's work "The Visioneers" (2012), which uses visuals to conduct a detailed analysis of the historical account of future-oriented technoscientific visions, visuals and other non-verbal representations may provide imaginaries and visions much more strongly than written texts. Spencer argues that visual methods are valuable in social science research because they operate quickly and powerfully on the senses, eliciting an immediate, pre-reflective response and enhancing the authenticity and detail of the research (2022). In a methodological book aimed at social science students, Freedman and Siegesmund introduce a conceptual research framework that a research image can be understood as data, investigation, theorising, report, and record within the embedded and influencing context (2023). A single image may contain multiple modes. Also, visual cultural forms and contexts are essential for situating the image: what medium is used (e.g., fine art, design, etc.) and in what contexts (e.g., popular culture, media, etc.) (Freedman & Siegesmund, 2023). With such considerations in mind, this research analyses visual content, semiotics (composition, layout, signs, etc.), and discourse within the context. For example, the slides from the ITER visit are contextualised in science communication and promotion of ITER. Screenshots of virtual tours are interpreted in light of the format's immersive nature. The visual elements of the EUROfusion roadmap and the ITER baseline are interpreted as the construction of visions, particularly designed for stakeholders. Contextualisation and the researcher’s sensory inputs add layers to the analysis of images, which resonates with the approach of assemblage ethnography.

To sum up, this research employs assemblage ethnography as an overarching approach to examine ITER. Various data sources are combined in a complementary manner to explore a range of issues across the planning, construction, and rework dimensions of ITER. The primary data sources are 1) the ITER visit[3] in March 2023, 2) two online expert interviews with a EUROfusion researcher/officer and an ITER Communication officer in summer 2023, 3) the ITER virtual tour and website, 5) official and legal documents of ITER, EU, IAEA, etc., and 6) secondary sources such as news media and academic literature. For the secondary source, this thesis largely refers to a book, “ITER: The Giant Fusion Reactor: Bringing a Sun to Earth” (second edition) (2023) by Michael Claessens, who was the head of Communication of ITER until 2015 and has worked for F4E and the Director-General for Energy in the EC (ITER Organization, 2024a). His deep insider’s perspective and a critical point of view, as a whistleblower of ITER (Claessens, 2022; Matthews, 2024) are valuable as data sources for validation and discourse analysis. The online interviews were recorded, transcribed, and then analysed through open coding based on grounded theory (Glaser & Strauss, 1967). The documents and media are examined by discourse analysis (Gill, 2000). All the data sources contribute to examining the promissory and justificatory practices across the various aspects of the giant, ITER.

[3] Individual visit in English (https://www.iter.org/about/visiting-iter/individual-visits) (accessed on 16th of March, 2025)

4. Assembling ITER: Empirical Findings

4.1. Introduction

Earlier chapters elaborated on the state of the art in which ITER is situated and then on conceptual frameworks for seeing and analysing ITER. Also, it argues that the methodology aligns with the conceptual frameworks and analytical approaches: assemblage theory and assemblage methodology. In light of these considerations, this empirical chapter analyses the research findings. As mentioned above, it is hardly possible to expand the scope of this research into an endless assemblage of issues across vast temporal and spatial dimensions. Yet this chapter seeks to trace the connections and interrelationships and, at the same time, to sort out the findings in a graspable way.

For that reason, this chapter is divided into three parts, corresponding to the dynamic mechanisms in the ITER assemblages: "planning", "constructing", and "reworking". These dimensions do not necessarily correspond to the chronology of the project. Rather, these dimensions provide different aspects of practices that promise and justify the project. Therefore, the aspects and practices articulated across the different dimensions correspond and coincide with one another. For example, issues and practices in planning dimensions are always relevant in the entire project cycle. Construction refers to the planning and, at the same time, includes constant reworking. Reworking addresses the planning practices to ensure legitimacy.

Having these interrelationships of different dimensions in mind, "Planning ITER" mainly focuses on the initial formulation of ITER. It considers the official launch of ITER under the ITER Agreement and the associated expectations in the project's early stage. The formation of assemblages is powerfully coordinated by their unique setting and the strategies of the ITER members. "Constructing ITER" particularly examines the practices of the congregation of materials and information throughout the project. "Reworking ITER" investigates practices that often cope with uncertainties and controversies emerging from the processes. These three dimensions are, to some extent, aligned with the ITER timeline. Yet, they are not necessarily situated in a linear progression. Plans and construction are in constant motion, adapting, adjusting, and rearranging. Still, it is helpful to think through these dimensions to create focal points in analysis. Also, the analysis uses the method of following the actors when examining influential elements, such as key documents. The following shows the promissory and justificatory practices of ITER.

4.2. Planning ITER

4.2.1. ITER Agreement

This section examines the official narrative of ITER's establishment by analysing the foundational document, "ITER Agreement". As seen in the later sections (in 4.2.2, 4.2.3, and particularly 4.3.1), ITER has a complicated and highly political prehistory of negotiation, both in front channels and back channels. Yet, it is helpful to start with the official narratives carefully crafted and published as legal documents and official websites, in order to critically engage with materials afterwards. The official narratives have certain characteristics for (re) constructing history that may be agreed upon and endorsed by the ITER members.

The official story starts with the agreement. After the long negotiations among interested parties, "the Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project" (hereafter, ITER Agreement), for which the Director General of the IAEA was the depositary, was signed at the Elysée Palace in Paris on 21 November 2006 (IAEA, 2007). This agreement was signed by the delegates of the People's Republic of China, EURATOM, the Republic of India, Japan, the Republic of Korea, the Russian Federation, and the United States of America. The agreement confirmed the establishment of the ITER Organization as an intergovernmental organisation, meaning that the ITER Organization enjoys privileges and immunities on the territories of the seven ITER members, like other intergovernmental organisations such as the United Nations (ITER Organization, n.d.-f). This special status of the project highlights its highly political nature. Under this legal status, the ITER Organization is taking a neutral stance, not belonging to any specific member, even though the machine would be located at a specific site. By doing so, ITER stands as an international institution that researches and develops nuclear fusion energy in cooperation with the ITER members.

In the ITER Agreement, every page is hand-signed by the seven delegates of the ITER members, confirming the document's legitimacy and credibility. The agreement's depositary is the IAEA, which is responsible for the document's validity, and the document is officially published on the IAEA website[4]. The treaty-style agreement outlines "the ITER Organization's purpose and functions and establishes its mandate to ensure the widest possible cooperation between ITER members for the success of the ITER Project" and defines "the governance, structure, and roles of the Organization" as well as the budget and

[4] IAEA "Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project" (https://www.iaea.org/publications/documents/infcircs/agreement-establishment-iter-international-fusion-energy-organization-joint-implementation-iter-project) (accessed on 22.08.2024)

the relations of the Organization with external bodies (ITER Organization, n.d.-f). Since the construction site is legally restricted, visiting requires a security check with passports/IDs.

The agreement confirms that the headquarters of the ITER Organization is located in St Paul-lez-Durance, Bouches-du-Rhéne, France. Even though the neutrality of ITER is emphasised via the legal status, the roles of France and Europe are regarded as central: the Agreement refers to EURATOM as "the Host Party" and to France as "the Host State". Although the ITER Organization's legal entity is an intergovernmental organisation, its physical presence in France lends it a local dimension. The Organization has a legal status of "nuclear operator" under French nuclear law because the activities carried out by the Organization concern nuclear safety and protection (ITER Organization, n.d.-f). Although research activities on nuclear fusion differ in some respects from those on nuclear fission, the existing laws impose the same measures on the Organization.

As the ITER Agreement establishes the project's framework, the ITER Organization serves as the main body for management and procurement. The purpose of the ITER Organization is "to provide for and to promote cooperation among the ITER members … on the ITER Project, **an international project that aims to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes, an essential feature of which would be achieving sustained fusion power generation**" (IAEA, 2007 Article 1, emphasis added). In particular, the following analyses the preamble of the ITER Agreement because the one-page statements capture the essence of the document. The symbolic and abstract statements construct stability and legitimacy of the long-term high-risk project. Here are quotes from the entire preamble section that illustrate both practical and symbolic actions in the document. It states that the ITER members confirm:

- *"RECALLING that the successful completion of the ITER Engineering Design Activities under the auspices of the International Atomic Energy Agency (hereinafter "the IAEA") has placed at the disposal of the Parties a detailed, complete and fully integrated engineering design of a research facility aimed to demonstrate the feasibility of fusion as an energy source;*
- *EMPHASIZING the long term potential of fusion energy as a virtually limitless, environmentally acceptable and economically competitive source of energy;*
- *CONVINCED that ITER is the next important step on the path to develop fusion energy and that now is the appropriate time to initiate the implementation of the ITER Project on the basis of progress of research and development in the field of fusion energy;*
- *HAVING REGARD to the joint declaration by the Representatives of the Parties to the ITER negotiations, on the occasion of the ministerial meeting for ITER on 28 June 2005 in Moscow;*
- *RECOGNIZING that the World Summit on Sustainable Development of 2002 called upon governments to promote increased research and development in the field of various energy*

technologies, including renewable energy, energy efficiency and advanced energy technologies;

- *EMPHASIZING the importance of the joint implementation of the ITER Project to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes and to stimulate the interest of young generations in fusion;*
- *DETERMINED that the ITER Project's overall programmatic objective will be pursued by the ITER International Fusion Energy Organization through a common international research programme organized around scientific and technological goals, developed and executed with participation of leading researchers from all Parties;*
- *EMPHASIZING the importance of safe and reliable implementation of construction, operation, exploitation, de-activation and decommissioning of the ITER facilities with a view to demonstrating safety and promoting social acceptability of fusion as an energy source;*
- *AFFIRMING the importance of genuine partnership in implementing this long term and large scale project for the purpose of fusion energy research and development.*
- *RECOGNIZING that while scientific and technological benefits will be shared equally among the Parties for fusion energy research purposes, other benefits associated with the implementation of the Project will be shared on an equitable basis;*
- *DESIRING to continue the fruitful cooperation with the IAEA in this endeavour;*
- *HAVE AGREED AS FOLLOWS:…"* (IAEA, 2007, Section Preamble)

This declaration-style preamble highlights several aspects of ITER, claiming and enforcing legitimacy, stability, and cooperative commitment. First, the preamble, starting with the confirmation of the ITER members on the capitalised verbs, creates a unified set of statements. The members are not individual states pursuing nuclear fusion energy, but are "members" who support international cooperation from the pre-agreement phase through to the future of ITER. The preamble reaffirms international cooperation in the design and development of IAEA activities, and in the construction, operation, exploitation, deactivation, and decommissioning of the ITER facilities. Using terms like "joint implementation" stabilises the status of the members, thereby confirming the importance of nuclear fusion energy R&D. By confirming that "scientific and technical benefits will be shared equally among the members", it ensures equal status for all members. In addition, the explicit mention of the peaceful purpose of fusion technology provides the basis for global cooperation. Second, relating to the first point, the preamble contextualises ITER within the international community. It includes the reaffirmation of "the importance of genuine partnership" within and beyond the ITER members. Reassurance for cooperation with the IAEA, the international nuclear organisation, lies from the design phase to future activities. Also, mentioning the 2002 World Summit on Sustainable Development situates ITER as a response to global challenges. The response is fusion energy, which is considered a potential "virtually limitless, environmentally acceptable and economically competitive source of energy". ITER's response to global challenges is addressed by the note on equitable distributions of benefits other than scientific and technological ones. All of the notions above are based on the assumption that nuclear fusion energy is technologically mature and necessary. To sum up, the preamble aims to achieve institutional stability by ensuring the management structure and the distribution of benefits, normative stability by associating global issues with the peaceful use norm, and epistemological stability by establishing the technological feasibility and necessity of the technology for addressing global challenges and benefiting future generations. The stability established by the preamble provides a solid basis for the project.

After the preamble, the detailed descriptions of the project's structures, organisations, budget, and time span are consolidated in the following acts (see 4.2.2 for details). The reasons the ITER members join the project may vary by their strategic directions – for example, McCray (2010) argues that European research integration is one of the priorities of the ITER project for EURATOM. However, the preamble forcefully affirms that the ITER members are on the same footing in recognising the importance of fusion energy and the endeavour to pursue technological feasibility in light of global necessity. That can be understood as what Butler argues with the term "performativity", which is based on the linguist Austin's speech act theory (1993). The verbs not only reflect the agenda of the ITER members but also specify actions for nuclear fusion R&D under a given ITER setting. The ITER Agreement's validity and legitimacy were affirmed through the official ceremony with IAEA delegates, witnesses, and other officials, which established the framework for project actions and the collective epistemic framing of nuclear fusion's potential and ITER's positionality in fusion energy R&D.

4.2.2. ITER as an International Project

Nuclear fusion energy often appears alongside the narrative of "international cooperation/collaboration". One claim is that the technical complexities and resource intensity exceed a state's capacity. However, as seen later, there are a number of national and private projects that sometimes seem to be progressing more rapidly than ITER, and international cooperation/collaboration appears to be somewhat burdensome to ITER's progress (see also 4.3.1 and 4.4.1). Yet, the narrative of international cooperation/collaboration, in my view, is one of the key justificatory discourses/practices. This section focuses on the "internationality" aspect within the planning dimension and on the retrospective understanding of ITER planning.

As seen in the previous section (4.2.1), the ITER Agreement has shaped international collaborative agendas and actions. In ITER, this "international" characteristic is emphasised as an essential part of the project. To examine the organisational structure of ITER and its emphasis on internationality, it is necessary to return to the construction of the ITER concept and official narratives (for unofficial narratives, see 4.3.1). The section primarily draws on the ITER Organization's website, presentations from the ITER visit, and Claessens' work (2023). The process of reaching the agreement has been a long technopolitical trajectory of assembling different interests and actors into a form of an international project.

In the official ITER narrative, the origins of ITER are traced back to the Geneva Superpower Summit in November 1985. That was the year Mikhail Gorbachev was elected General Secretary of the Soviet Union, and signs emerged that Cold War tensions were melting. At the summit, when the two superpowers' top leaders met for the first time, Gorbachev and US President Reagan proposed a collaborative international project to develop fusion energy for peaceful purposes (Claessens, 2023; ITER Organization, n.d.-g). Instead of accelerating the nuclear weapon development race, they proposed to use their technologies for nuclear fusion energy development for "the benefit of all mankind" (Delmotte, 2022, p. 13). One year after the Summit, the EU (as EURATOM) and Japan joined the group to pursue the design development. ITER conceptual design was made in 1990 (Tomabechi et al., 1991), the interim design in 1995, and the detailed design in 1996 (Stacey, 1997). Finally, detailed engineering design was approved by the ITER members in 2001, followed by the joining of China and Korea in 2003 and India in 2005 (ITER Organization, n.d.-g). As a result, the ITER Agreement was signed in 2006, as mentioned above (4.2.1).

The official narrative retrospectively presents the course of ITER as a linear trajectory. The linear narrative presents the project's consistent aim of developing the peaceful use of nuclear technology to address the global challenge, even though the historical account of complex strategic technopolitical formulations reveals different aspects of this narrative, as also seen in the interviews (see 4.2.3). The linear trajectory starting from the Superpower Summit is constructed through the narrative creation of ITER's essence: international cooperation for the peaceful use of nuclear technology.

The peaceful use of nuclear technology, but for what purposes? Like in the talk between Superpowers, it is claimed for humankind. The motif of ITER as an international endeavour for common humanity is ubiquitous, from the official websites and the ITER guided tour to the narratives of the people involved in the project.

Figure 2: "Global challenge, global response" Presentation for ITER guided tour (Delmotte, 2022, p. 14)

In the ITER guided tour I attended, this point was particularly emphasised. At the beginning of the presentation, the presenter asked the participants where they were coming from. The participants were from different countries, including France, Italy, India, and Japan (me). After this interaction, the guide started the presentation of ITER as an international project. The presentation titled "ITER: Energy for our future" started with a picture of the ITER members' flags in the background, saying "ITER: A multinational scientific collaboration without equivalent in history; A large-scale experiment to demonstrate the feasibility of fusion energy" (Delmotte, 2022, pp. 1–2). International cooperation is grounded in a problematisation of the current energy status: "One of the biggest challenges for our civilization" regards energy consumption and production (Delmotte, 2022, p. 3). The increasing energy demand for the future was emphasised with a note that "access to electricity is the main vector of development of human societies" (Delmotte, 2022, p. 3).

The establishment of prerequisites for humanity provides a compelling argument for developing "carbon-free energy on a massive scale" (Delmotte, 2022, p. 4), which here means nuclear fusion. The argument for common humanity and dignity in a justificatory regime (Boltanski & Thévenot, 2021) is smoothly translated into ITER's characteristics. As the presentation on page 16 (Figure 2) shows, ITER is presented as a "global response" to the "global challenge". The ITER members' population size and GDP are shown as representative of the entire humanity: the ITER members account for more than 50% of the population and more than 85% of global GDP. In addition to the memberships, the ITER Organization has signed cooperation agreements with various international entities, including the Principality of Monaco, CERN, IAEA, the Australian Nuclear Science and Technology Organisation, Kazakhstan, Canada, and Memoranda of Understanding on Academic and Scientific Cooperation with universities and research institutions in the ITER members (ITER Organization, n.d.-f). These international collaborations are designed to facilitate the exchange of technical knowledge, administrative experience, and educational activities. Abstraction of the global population, GDP, and project participation by members and associated partners enables the narrative construction of ITER as an international project addressing all of humanity.

In line with the narrative of ITER as a common humanity project, the organisational structure is designed to distribute responsibility and represent the ITER members' interests (see 4.3.1). The technoscientific knowledge produced within the project is to be shared strictly among the ITER members. The decision-making body of the ITER Organization is the Council, consisting of up to four representatives from each ITER member. The Council meets twice a year in the headquarters of the ITER Organization to hold inter-member meetings. The ITER Agreement decides the responsibilities of the Council as "the promotion, overall direction and supervision of the ITER Organization in pursuit of its purpose", and it takes decisions and makes recommendations on any questions, matters, or issues (IAEA, 2007, Article 6). Importantly, the Council is the assembly where the ITER Research Plan – the so-called "project baseline" or simply "ITER baseline" – is discussed based on submissions from the ITER Organization and domestic agencies. The project baseline is the document for (re)scheduling the timeline, (re)calculating the budget, and technical (re)adjustments, which has been updated throughout the project process (see 4.4.2). The ITER Organization is an intergovernmental organisation comprising the ITER members that manages and implements the project. Each ITER member has a domestic correspondence ("domestic agency") of the ITER Organization in the country, e.g., ITER Japan. On the other hand, the Council comprises the political delegates of the members who govern the project with a high-level decision-making authority.

The ITER Organization was created as a single entity to both represent the members and conduct the activities of the international project. The Organization's structure is designed to ensure that international cooperation processes are carried out consistently. The contribution to the Organization can be divided into two categories: in-kind resources and cash resources. In-kind contributions are contributions in the form of components, equipment, materials, goods, services, and staff. It is based on the agreement on which ITER members contribute to which components, as specified in the document that estimates component values. In-cash contributions are financial contributions to the ITER Organization's budget. The contributions of the ITER members are made through their domestic agencies. In fact, in-cash contributions are limited to one-tenth of the contributions overall, while in-kind contributions are the rest of the contributions (ITER Organization, n.d.-d). This specific form of contribution symbolically and practically represents the meaning of international collaboration – this aspect is examined in more detail in the later section (4.3.1).

The project's international collaboration is also reflected in a unique style of knowledge management. One of the most emphasised aspects of the ITER guided tour was also the sharing of intellectual property in the project. The ITER Agreement, Article 10 and the Annex on Information and Intellectual Property stipulate the sharing of intellectual property. According to Article 10, "the ITER Organization and the Members shall support the widest appropriate dissemination of information and intellectual property they generate in the execution of this Agreement" (IAEA, 2007). The Annex strictly defines the types of information and intellectual property, as well as their dissemination and protection. It ensures that the ITER Organization and its members are required to share information and intellectual property with one another. The sharing of information and intellectual property is one of the most fundamental reasons the members join the project. In the official agendas, at least at the beginning of the project, ITER's activities and generated information are considered a necessary pathway, or, what Callon calls, "obligatory passage point" (1984) to proceed with constructing DEMOs for each member. Classens also argues that this approach of sharing contributions and knowledge "derives from the very essence of ITER, which is as much an educational programme as a technological one; thanks to ITER all its members have acquired the experience and knowledge that will enable them to move to the next step", and therefore, "In short, DEMO could not exist without ITER" (2023, pp. 175–176) (for temporal aspects, see also 4.3.2). Therefore, the agreement and obligation to share information indicate the long-term trajectory of fusion R&D activities. That aligns with each member's strategy on fusion R&D, at least in the official narrative.

In practice, this sequence is not as straightforward as the plan (see 4.4.2 and 4.4.3). However, the formulation of the plan is inscribed for the purpose of the ITER project: the common humanity goal that should be achieved through international cooperation. IAEA often endorses this discourse: the Director General of IAEA, Rafael Mariano Grossi, mentions ITER as a prime example of international cooperation and emphasises "The current level of international commitment is bringing us closer to a fusion future than ever before" (IAEA, 2021, p. 1). Classen, who was a communicator for the ITER Organization, emphasises "technological diplomacy" of ITER; technology to overcome political tension, as well as diplomacy as a catalyst for technological development (Claessens, 2023, p. 211). Particularly in the case of ITER, political and diplomatic aspects are inseparable from the outset. He shares his opinion on this:

> "*In my opinion,* ***ITER's most important innovation is not technological****. There are over 100 tokamaks around the world of which ITER is just one more—albeit the biggest to date. ITER would never have been possible without long-term international collaboration;* ***what makes it unique is the very fact that 35 (currently 33) countries are working together to build a complicated and sophisticated project****. If ITER had been just a construction programme, it would certainly have been organised differently*." (Claessens, 2023, p. 217) (emphasis added)

On the one hand, technoscientific practices always collaborate with other research activities and actors to some extent. However, the formulation of a project – the management structure, decision-making processes, information and intellectual property management – is defined by specific interests within the technopolitical dynamics. In the case of ITER, the project's origin is presented as the peaceful use of nuclear technology for energy development. And this project's ultimate goal has been continuously ensured through the specific formulation of agreements and representations. Yet, from a member's perspective, various formulations and dynamics justify the project. The next section reveals the European account of the project.

4.2.3. ITER in Europe

While international collaboration constitutes the foundation of ITER, as highlighted in the preceding section, the physical establishment of the substantial reactor necessitates a specific geographical location. While the latter section (4.3.1) provides a detailed analysis of the site setting, this section prepares the ground for the European acquisition of ITER by examining the historical context of European fusion research. This addresses the implications of the physical entity, specifically the materiality, of hosting the machine in Europe by investigating the technopolitical dimension of ITER from the European perspective. This section draws on academic literature on the European fusion programmes, as well as official documents, to examine European perspectives on ITER. It elucidates the strategic decisions regarding the integration of European fusion energy R&D into ITER.

To begin the section on the European account in ITER planning, it is important to note that most ITER members have been developing their own R&D projects in addition to their contributions to ITER. The individual programmes do not necessarily align with ITER's technical specifications and timeline, contrary to the master narrative of ITER as a necessary step in nuclear fusion energy development, as seen in the previous section (4.2.2). For example, the recent "breakthrough" at the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (Reuters, 2023) is part of a US national programme that develops a laser-based fusion facility. NIF has been developed, contrary to ITER's peaceful aim, partially in order to develop new types of weapons without nuclear weapon explosions and a stewardship programme for stockpiles (National Ignition Facility & Photon Science, n.d.). Chinese R&D in fusion is being conducted under an "aggressive programme[5]" aiming for a fast-track to DEMO design and construction (Conroy, 2024), and thus, fusion-related patent rankings are beating those of the U.S. (Inomata, 2023; Stanway, 2019). The U.K. is joining the EUROfusion consortium while developing its own programme at the Culham Centre for Fusion Energy under the UK Atomic Energy

[5] Interview with the EUROfusion officer/researcher.

Authority (Culham Centre for Fusion Energy, n.d.). At the same time, it hosts the Joint European Torus (JET), which is a key facility for the EUROfusion consortium, the research body for EURATOM. Japan has a close relationship with the EU and operates the largest existing tokamak reactor, JT-60SA, as well as a stellarator and a laser-type facility[6]. Korea and India are also developing their own domestic projects.

In contrast to the domestic programmes of the other members, EURATOM, the host party, places ITER development at the centre of its fusion R&D activities in Europe. Whereas the official narrative of ITER began with a conversation between the US and the USSR in the 1980s, excluding Europe (see 4.2.2), ITER has a different story for Europe. To begin with, let us travel back to the time of EURATOM's formation, the pan-European nuclear community that has endured the evolution of the EU and serves as the legal entity that hosts ITER.

The EURATOM treaty was signed alongside the Treaty establishing the European Economic Community (EEC) on 25th March 1957 in Rome. The two treaties, collectively referred to as the Treaty of Rome, are widely regarded as pivotal in establishing the foundation for European cooperation. The initial countries involved were Belgium, France, Germany, Italy, Luxembourg, and the Netherlands. Whereas the Treaty of EEC aimed to foster closer links and advance economic growth through increased trade via the creation of a common market (European Parliament, n.d.), the EURATOM Treaty aimed "to promote research, to achieve security of supply, to establish a system for supervising the peaceful use of nuclear materials intended for civilian use and ensuring high common standards for health and safety" (European Union, n.d.). In the establishment of EURATOM, there was an optimistic hope that nuclear energy would be the leverage for economic and political stability (Krige, 2008; Treaty Establishing the European Atomic Energy Community, 1957). At the time, nuclear energy mostly meant fission energy, which was rapidly developed and implemented after Eisenhower's famous "Atoms for Peace" speech in 1953. Yet, there was only one line dedicated to fusion for the research and training programme in the 176 pages of the EURATOM Treaty: "study of fusion, with particular reference to the behaviour of an ionised plasma under the action of electromagnetic forces and to the thermodynamics of extremely high temperatures." (Claessens, 2023, p. 43; Treaty Establishing the European Atomic Energy Community, 1957). The EURATOM Treaty prioritised the industrial development of fission, allocating less than 5% of the total budget to fusion research. (Palumbo 1987 in McCray, 2010).

The focus on fission in Europe during the 1950s was accompanied by a gradual international shift toward recognising the potential of nuclear fusion. This transition occurred in parallel with the development of the tokamak concept by Soviet scientists, marking a significant milestone in the field. During the 1950s, European scientists conducted research on nuclear fusion energy within each

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[6] Ministry of Education, Culture, Sports, Science and Technology Japan "Fusion, Energy: connect to the Future" https://www.mext.go.jp/a_menu/shinkou/fusion/ accessed 23.12.2024.

country's national programme, as well as through the EURATOM research and training programme. As fusion research required a huge budget and information exchange that exceeded the capacity of national programmes, the initiative to cooperate at the pan-European level was launched. The European Commission assigned an Italian scientist, Donato Palumbo, to manage EURATOM's fusion programme in 1958 (McCray, 2010, p. 287). Despite this initiative, fusion research in Europe was relatively small during the 1960s, without clear research strategies and goals for fusion (Claessens, 2023). However, in 1968, the situation shifted when Soviet scientists made a breakthrough with a tokamak device — a doughnut-shaped chamber that uses magnetic confinement and remains a staple in most fusion experiments, including ITER (McCray, 2010). This discovery significantly boosted the enthusiasm for fusion energy among both scientists and politicians.

As a consequence of the news of the tokamak and following optimism, the 1970s can be seen as a "new age for fusion" with many "breakthroughs" presented in the national laboratories inside and outside of Europe, alongside the European integration that started also in research areas (Claessens, 2023). In 1971, the EEC decided to enlarge the European fusion programme and launch a large multinational experiment (Stefanini, 2017). Following this decision, the design work on the Joint European Torus (JET) started in 1973, as the first attempt to create pan-European fusion research (EUROfusion, n.d.-c). During this period, the oil crisis also served as a warning to Europe regarding the long-term unreliability of petroleum as a resource. Alongside the economic and political change after the Second World War, the UK joined the EEC and EURATOM in 1973. Because the UK had been strongly engaged in fusion research at the national level before joining EURATOM, it had first hesitated to create a pan-European cooperation (McCray, 2010). JET, which was decided to be located in Culham in the UK, was a particularly large and expensive machine at that time, estimated at US$210 million and then ended up doubling in the completion (McCray, 2010). The complexity of research and the high cost of developing machines enforced consolidated and coordinated actions for fusion R&D. Following the approval of the funding in 1978, JET created the first plasma in 1983 and the first D-T experiment in 1991 (Claessens, 2023). JET had been considered the largest and most advanced fusion reactor in the world until its closure in December 2023. As the JET machine was built to exploit scientific data in the large tokamak setting, scientists needed to develop a larger, more advanced fusion machine.

Alongside JET, there was already an idea to build a bigger and more powerful machine in Europe. The scientists already knew that JET would not be sufficient to test the feasibility of nuclear fusion energy and that it would be tremendously expensive. An initiative to build an international machine, called INTOR – which was similar to ITER in concept –, as a next step of JET for Europe, Tokamak Fusion Test Reactor (TFTR) for the US, JT-60 for Japan, and T-15 for the USSR, was initiated in 1973 by Richard Nixon and Leonid Brezhnev and discussed over the years (ITER Organization, 2008). As the INTOR option did never reach to the design phase, the option exclusive to Europe, known as the Next European Torus (NET), was envisioned as a collaborative transnational project across Europe, intended to serve as a stepping stone towards a future commercial fusion reactor; In 1978, a small team of scientists and engineers began developing potential design concepts for NET (McCray, 2010, p. 291). During the 1980s, the fusion research community in Europe carefully weighed whether to build its next major fusion machine as a purely European project or to pursue a broader international partnership (McCray, 2010, p. 295).

In parallel with the discussion on NET in Europe, the Geneva talk on an international nuclear fusion reactor took place in 1985. As seen in the previous section (4.2.2), it took more than 15 years to obtain approval of the final design for ITER. While the conceptual design activity was launched in 1988 by the EU, Japan, USA, and USSR, the Europe-only option of NET was still reserved in the first long-

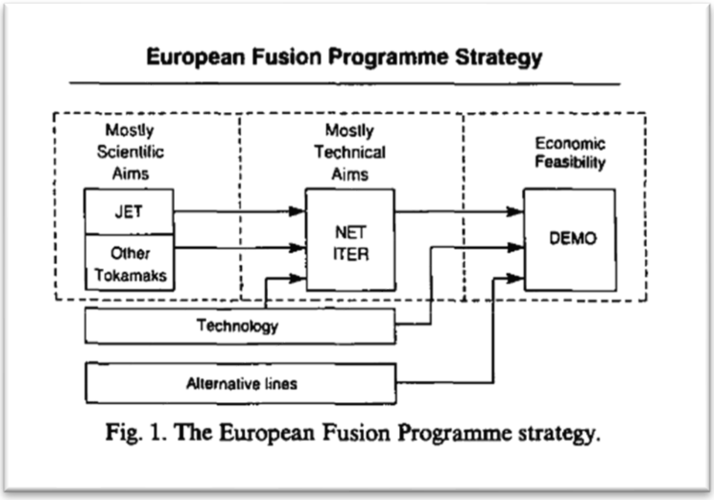

Figure 3: European Fusion Programme Strategy (Maisonnier & Toschi, 1989, p. 4)

term strategy of the European Fusion Programme Strategy, which was established in 1983 (Maisonnier & Toschi, 1989; Vandenplas & Wolf, 2008, p. 25) (Figure 3). This shows that ITER was positioned as an equivalent of NET – or rather, as an additional/alternative option – within the R&D trajectory of the European fusion strategy. Indeed, as the technical features of NET resemble those of ITER, some European scientists have argued that the NET machine would have been operating by 2008, and thus the fusion research would have been more advanced if NET were chosen instead of ITER (Vandenplas & Wolf, 2008, p. 27).

On the other hand, during the development of the ITER design, the pan-European NET initiative aligned the ITER design with NET's so that they could contribute to ITER without diverting technical staff and resources from NET (McCray, 2010, p. 294). In this sense, ITER has already been inscribed by the European fusion community's technological and organisational characteristics from the very early stage of the project.

From a European perspective, it is no wonder that Europe was so eager to secure the largest share of the project. In fact, as elaborated in the later section (4.3.1), the EU has invested most of the fusion-related budget and a large share of the overall nuclear-related budget in ITER.

Alongside the time JET had been operating and the ITER design had been developed, European fusion research began to be strongly coordinated. The European Fusion Development Agreement (EFDA), the first framework contract under the EC's EURATOM Framework Programme, was established in 1999. Led by Max-Planck Institut für Plasmaphysik in Garching, Germany, EFDA included three activities: "technology activities carried out by the Associations and by European industry; the collective use of the JET facilities; the European contributions to international collaborations such as ITER" (IAEA, 2001). With EFDA, laboratories and research institutes in 29 European countries, including Switzerland, were coordinated by the EC and tasked with research on materials development, diagnostics, modelling, etc (EFDA, 2014). EFDA was succeeded by EUROfusion, which still operates as a research consortium contributing to ITER (for details, see later in this section and 4.3.3).

In 2007, following the ITER Agreement, the EC established Fusion for Energy (F4E), the Joint Undertaking, the EU's domestic agency for ITER (2007/198/Euratom, 2007). Obliged by the ITER Agreement, the domestic agency aimed to contribute to the ITER construction as a legal entity; the European contribution should pass through F4E. Planned for 35 years, F4E is aimed to provide contributions to ITER particularly, "(a) oversee preparation of the ITER project site; (b) provide components, equipment, materials and other resources to the ITER Organisation; (c) manage procurement arrangements vis-à-vis the ITER Organisation and, in particular, associated quality assurance procedures; (d) prepare and coordinate Euratom's participation in the scientific and technical exploitation of the ITER Project; (e) coordinate scientific and technological research and development activities in support of Euratom's contribution to the ITER Organisation; (f) provide Euratom's financial contribution to the ITER Organisation; (g) arrange to make human resources available for the ITER Organisation; (h) interface with the ITER Organisation and carry out any other activities in furtherance of the ITER Agreement" (2007/198/Euratom, 2007, Article 3 in Annex). F4E is financed by EURATOM, the ITER host state (i.e., France), and additional resources, with a planned budget of more than 9.6

(EUR million)

2007-2016		2017-2041		2007-2041
	of which 2007-2011		Constant values	Total
4 127	1 717	5 526	3 544	9 653

Figure 4: Total budget planned for F4E (2007/198/EURATOM)

billion euros (in 2007 value) (Figure 4). The table shows the presumption that a large proportion of the budget would be spent on construction at the beginning.

Compared to other Joint Undertakings of the EU (e.g., Clean Hydrogen Partnership), F4E has unique features; it is aimed at contributing to a single project rather than a broad agenda with multiple projects; it is financed mainly by public (mostly by EURATOM, complemented by France) (cf. Fusion for Energy, 2024) rather than other Joint Undertakings' public-private partnership financing structures. This large European public institution has been playing a key role in ITER by providing resources.

While F4E is the main actor for the European contribution to ITER, EUROfusion has conducted the research activities in succession to EFDA since 2014. My interviewee jokingly told me that "F4E converts European money into stainless steel and concrete. […] What we [EUROfusion] are doing is research, and we try to do research which is helping ITER and to basically optimise the ITER research plan"[7]. Since the ITER Agreement, the EU has been focusing its fusion-related R&D within the framework of ITER. Accordingly, the EUROfusion consortium is conducting research that makes a significant contribution to ITER. EUROfusion is a research consortium that consists of 28 institutes and 3 associated partners (UK, Norway, and Switzerland) and 4800 researchers, staff, and students (EUROfusion, n.d.-b). EUROfusion has been funded by the EURATOM Research and Training Programme and member countries – for example, €549.4 million from EURATOM and approximately €450 million matching funding from member states, from 2021 to 2025 (EUROfusion, n.d.-a). Under EUROfusion, research and training activities of the member institutes and laboratories are coordinated for ITER, DEMO, and ultimately for fusion energy. One of the notable activities that materialise this vision is the creation of the EUROfusion Roadmap (EUROfusion, 2018b). The later section (4.3.3) will take a closer look at this roadmap as part of the temporal practices that justify ITER.

So far, this section has shown the European context for ITER, by reviewing from the early history of European fusion research until the current political and scientific setting of fusion R&D. The European fusion R&D has gone through different eras: the 1950s and 60s for the foundational setting, 1970s for the first wider attentions and collaboration for JET, the 1980s and 90s for planning of NET and ITER, and from the 2000s for the focus on the ITER contribution. A historian, McCray, concludes that the goal of creating ITER contributed to the unification of national fusion programmes and the acceleration of European integration and cooperation overall (2010, p. 299). The strong connection between JET and ITER is also evident in the change in JET's wall materials, which align with those of the ITER reactor (Politico, 2017). The EUROfusion website writes explicitly: "JET serves as the 'test-bed' for ITER and is often referred to as 'Little ITER'" (n.d.-d). While this section has provided the context for ITER in Europe, the next section (4.3.1) examines one of the core issues: site selection and

[7] Interview with the EUROfusion researcher/officer.

budget allocation. Overall, it is not incorrect to say that ITER is both an international project and a European project.

4.2.4. Conclusion

So far, this chapter, “Planning ITER,” has investigated the genealogy of ITER, focusing on the pre-construction phase. It began the discussion with a close examination of the ITER Agreement, particularly the preamble, which revealed the materialisation of the international project’s technopolitical history and, at the same time, symbolically and practically constrained the project's trajectory. The Agreement and the official narrative emphasise internationality as the core of the project through the story unfolding from the Geneva Superpower Summit, as well as the utterly unique types of ITER members’ contributions. This reinforces the master narrative of ITER: international cooperation to address humanity’s challenges. Simultaneously, Europe’s account on ITER is undeniable. The history of European fusion research shows the intertwined relationship between ITER and the integrated European fusion community itself. The project’s both internationality and Europeanness – peculiarly, not in contradiction – have been constantly reproduced and reinforced through the material-discursive practice of construction and maintenance, which will be explained in the following chapters.

4.3. Constructing ITER

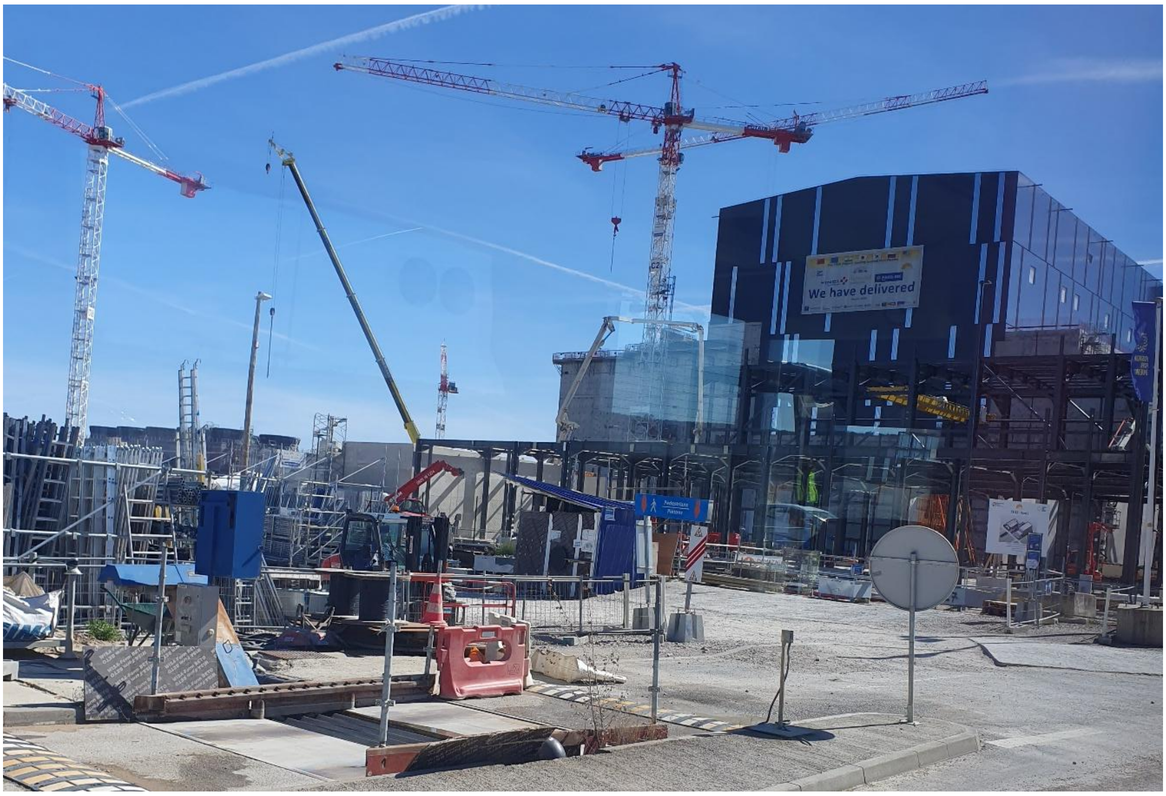

Figure 5: Construction in the ITER site (Photo: Author)

When I visited the ITER construction site, I was overwhelmed by the size of the whole site: the assembly hall was confidently standing in the middle of the site; trucks were running around to bring materials in; rough and wide roads were connecting different spaces and facilities; massive cranes were occupying the sky; workers were busily walking around in their safety uniforms. The physicality and materiality of this massive machine cannot be fully explained in texts and numbers. The previous chapter provided an overview of ITER planning, covering the project's origins, political discussions, and the machine's legal and technical basis, often drawing on documents such as the ITER Agreement and EU official records.

While practices seen in the previous chapter often involve materiality (e.g., physical importance of documents), as scoped in the earlier section (2.7), the construction of the site pushes substantive materiality to the forefront. While technology is sometimes debated in public discussions without reference to materials, STS scholarship has emphasised the importance of materiality, which is inseparable from discursive aspects such as sociality (Law & Mol, 1995). This chapter examines the construction of the ITER, with a particular focus on materiality. In discourses and practices, or simply, material-discursive practices relating to the ITER construction, materiality plays a key role in various promissory and justificatory practices, involving decision-making processes and outcomes. Yet materiality is intentionally or unintentionally emphasised or obscured in representations or narratives. And sometimes materiality returns to the topic like a "flashback" (see also 4.4.1).

This section broadly explores the construction of ITER, including both material and discursive – more precisely, these two aspects are inseparable in the form of material-discursive practices in the new materialist account. Hence, this chapter intentionally examines various entities, leaping from concrete and metal to rhetoric and argumentation. The first part begins with the process and negotiations in one of the most important matters in construction, namely, the ITER site setting. Physical existence has a significant impact on the overall project and on each member's contributions. The second part compares futuristic representations and physical/material issues. Those two themes, which seem contradictory, sometimes transition smoothly from one to the other, or else confront each other. The third part focuses on roadmap-making within the European fusion research agenda as part of constructing a justificatory narrative.

4.3.1. Site Setting and Member Contributions

The previous chapter (4.2.3) addressed the European context for ITER, highlighting the specificities of European ambitions and aspirations. In other words, it clarified why the EU wanted to have ITER within Europe. Although ITER is an international collaboration and its international nature is emphasised, the machine should be physically located in one place. In theory, "ITER could have been built in any one of the 35 countries that are participating in the project" (Claessens, 2023, p. 37). Then, what is the story behind its presence in the small town of Cadarache, Saint-Paul-lez-Durance, France? Why is ITER not in Japan or in Spain? Indeed, there was extensive technopolitical discussion and negotiation behind the decision on site selection among the ITER members and even within Europe. The ITER Agreement (IAEA, 2007) was the result of long technopolitical negotiations over where to locate the machine and who would pay for what (4.2.1). This section focuses on the material-discursive account of the ITER machine itself; the historical account of site-setting and negotiations over member contributions reveals controversies and alignments with the "global" dream.

After the Reagan-Gorbachev talks, a group of experts conducted extensive preparation for the design. As seen above (4.2.3), the technical features of the ITER design resembled those of the NET plan to preserve the continuity of European fusion R&D. The technical design was not separate from political discussions. One of the reasons for this highly technopolitical account is that, simply, the machine and related budget were massive: thousands of tonnes of machine with at least a couple of billion euros. The members' budgetary limitations forced the machine to be smaller than initially proposed (Claessens, 2023, p. 34). Once the final design was completed, the next question was who would host the machine and, consequently, who would contribute what. Unlike the common brief for technology in theory, which overlooks the physical and material aspects of technology, having a massive technoscientific device in the area would bring significant benefits to the host. A large "empty" – inevitably rural – area should be developed to accommodate not only the 30-meter-tall reactor but also the massive facility site and countless infrastructure and related facilities surrounding the reactor. It also includes accommodations for international and local employees, schools, shops, etc. And of course, the technological benefits of hosting the machine include technology transfer to the participating companies, capacity building for partners, and training and education for future scientists and technicians. Simply put, if the members were serious about fusion R&D, every member would want to host the machine. And if not hosting the machine, every member would want to contribute to developing essential components so that technological development and capacity building thrive in their own territory. An interviewee clarified the dynamics of the acquisition of the machine:

> "*So as that [engineering design] came to fruition in the late 90s, everybody wanted to be the host. Of course. Everybody. Why? Because whoever is the host, you think your [country's] companies will probably get the best value*."[8]

To address issues of the division of contributions and the sharing of benefits, ITER took a unique approach by creating a single currency, the "ITER Unit of Account (IUA)," and systematising in-kind contributions. The IUA system, sort of "fusion euro", incorporates variations in exchange rates and fluctuations in the cost of living to ensure an equitable allocation of the value associated with each procurement arrangement among the project participants (Claessens, 2023, p. 121). Based on the IUA calculation, ITER's components were divided into the host's contribution and 85 packages, including "the superconducting coils, the plasma heating system, vacuum pumps, cryogenics, and diagnostic devices" (Normile, 2003, p. 1299). Only about 10% of the total financial cost would be paid by the members to the ITER Organization in cash for the installation, while the remaining 90% of the cost would be contributed "in-kind" in the form of completed components, systems, or buildings (ITER Organization, n.d.-d). Normile clarifies this point by quoting Yasuo Shimomura, deputy ITER team leader at that time: "everybody wants to supply the fusion-related high-technology packages, and no one is interested in the conventional components", because development and production of fusion-related high-technology could lead to spinoffs in other high-tech areas (Normile, 2003, p. 1299). In the end, some essential fusion-related and most desired packages were split up so that every member "receives enough chips to stay in the game" (Normile, 2003, p. 1299). This gives only a glimpse of the great struggle in negotiations on the host and division of contributions. According to my interviewee, it was "the first compromise step"[9] to create an in-kind contribution system instead of an in-cash contribution.

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[8] Interview with an ITER Communication officer
[9] Interview with an ITER Communication officer

Indeed, it was one of the main reasons that the ITER Agreement was signed almost 20 years after the initial proposal. There are several works (Claessens, 2023; McCray, 2010; Normile, 2003) that provide detailed analysis of the site selection processes, which are highly political negotiations rather than technical rationality/need. These political discussions and negotiations often lack clear records, relying instead on fragmented information and rumours, which the following attempts to consolidate using the available sources. As mentioned earlier (4.2.2), in the early stages of the ITER concept, Japan and the EU joined the US and the USSR in the plan. Within the EU, the big political players competed over the acquisition of ITER: Germany, the UK (at the time), France, and Italy, to name a few. Germany and the UK left the race as Germany had held a large stellarator project, "Wendelstein", and the UK had JET. In the meantime, Canada briefly joined the project in hopes of hosting the machine in the early 2000s, but withdrew soon after losing the site-selection race. The US's ambition to acquire the site did not materialise, as the country had briefly dropped out of the project under Bill Clinton and rejoined only under George W. Bush. The European partners struggled to harmonise the opinions between France (Cadarache) and Spain (Vandellós). The interviewee shared a "legend" about the site-setting negotiations between France and Spain in the 2000s. The story is relatively long, but it is worth quoting as it was told:

> "*So, at that stage, it looked like there was a pretty good chance that it would either go to France or Spain. Now, what I'm going to tell you is a legend. I cannot verify the accuracy, but I've heard this story from several people that Jacques Chirac, who was the French President, said to his foreign minister, "Go to the Spanish Foreign Minister". And let's look at three things that are coming up. The FIFA World Cup, the America's Cup – the yachting race, the sailing race – and* ***this thing called ITER****.* ***And can we agree that these are all coming to either France or Spain? But nobody should get all three. It should only be two out of three at max.*** *So, they agreed on that. And then they said, okay, you're pretty good at football, so probably you want to host the FIFA World Cup. And because of your location, probably you want to be the host of the sailing competition.* ***So, we'll take this thing called ITER****. Well, what was funny was that at the time, it wasn't clear that Europe would be the host. But Jacques Chirac loved Japan. Had a very good relationship with the Japanese and the Japanese Prime Minister.*"[10] (emphasis added)

Contrary to the official EC statement on "'intense efforts' made by the Italian Presidency and the Commission to find a consensus" and consequent "unanimous decision by European research ministers in the Competitiveness Council" on November 26, 2003 (European Commission, 2003), this "legend"

[10] Interview with the ITER Communication officer. This story was also shared in an interview for a science newspaper (Pomeroy, 2025).

tells us about a purely and clichédly diplomatic – not even technological at all – character of site setting negotiation in Europe.

Now, the final options were France's Cadarache and Japan's Rokkashomura. Located in the north of the main island of Japan, Rokkashomura is famous for being the "nuclear village" where the Japanese government has introduced nuclear-related facilities, such as uranium enrichment and plutonium reprocessing plants, MOX fuel fabrication facilities, and low-level nuclear storage facilities (Uchiyamada, 2019). This rural village has been subjected to the government's nuclear agenda in return for the economic benefits. In the meantime, Cadarache has also been one of the centres of nuclear R&D. The French Alternative Energies and Atomic Energy Commission (CEA) has one of the largest nuclear energy research sites, hosting nuclear fusion and fission reactors, and reprocessing facilities (CEA, n.d.). Negotiating over these two nuclear sites, the "legend" continues between Jacques Chirac and the Japanese Prime Minister:

> "*So, legend says he [Jacques Chirac] went to the Japanese Prime Minister and said, do you really think that anybody wants to live in Rokkashomura? It's very, very remote. We have to bring all of these international people. It's going to be very hard to do the project there. So, I'm sorry, but you are going to destroy the project if you insist on it being in Japan. It really needs to come to France, and* ***we'll give you some advantages there****. So, the Japanese Prime Minister said, okay, we agree that it will come to Europe, to France, but* ***you can't announce it because George Bush hates you****, because this was like 2005 by this time or so. And* ***remember that France did not join the coalition that went to the war in Iraq****. So, the Japanese prime minister said, let me talk to George Bush. And that happened. And George Bush said, OK, we could have it in France. So, this is how it ended up in Provence. This is the legend. The last part is the legend. But what did that mean? Well, Japan said, we want to have certain advantages. So, Europe actually agreed that certain procurements that they would do would go through Japan*."[11] (emphasis added)

The story shows the high sensitivity of the mega-technoscientific project amid international tensions and the political compromises that occurred during the negotiation. Claessen also underlines that personal networks of high-level scientists and politicians influenced the decision-making on the site setting in Cadarache (Claessens, 2023, Chapter 4). While on the front, ITER is a peaceful international collaboration project (see chapter 4.2.2), behind the scenes, the project's financial scale and potential technological benefits enforced purely political logic.

Another story about site negotiations shows the strong European desire to host the fusion reactor aggressively. Faced with a deadlock in negotiations over Cadarache or Rokkashomura, the European

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[11] Interview with ITER Communication officer. This story was also shared in an interview for a science newspaper (Pomeroy, 2025).

Union – under France's leadership – warned that it might proceed to construct ITER as a solely European initiative. The EU stated that, if ITER had been located in Japan, its financial contribution to the construction would have been limited to just over 5% of the total cost (Claessens, 2023, p. 34). The French Prime Minister (at the time) Jean-Pierre Raffarin emphasised the project's importance, stating, "We must have ITER […] even if we undertake it alone" (Claessens, 2023, p. 34). To reinforce this stance, France pledged to double its financial support, offering an additional 20% (approximately US$1.1 billion) on top of the EU's existing 40% commitment to the total projected cost (McCray, 2010, p. 298). The series of assertive European political initiatives to secure the ITER project succeeded. A science historian, McCray, analyses the securing of the Cadarache site as the result of "strong-arm European diplomacy" under Chirac's ambition for European leadership, French prestige, and Provençal economic development, and as fostering European integration and cooperation on national programmes (McCray, 2010, pp. 299–300).

As a "compensation" of choosing ITER site in Cadarache, the EU and Japan agreed on so-called "The Broader Approach" that introduced three fusion-related projects and facilities (the JT-60SA, the International Fusion Material Irradiation Facility (IFMIF), and the International Fusion Energy Research Centre (IFERC)) to complement ITER and accelerating the development of fusion power towards DEMOs, with the EU's in-kind contribution of 340 MEUR, initially planned for ten years with extension (European Union, 2008). This bilateral agreement was seen as the result of a compromise in political negotiations, which became obvious in the interview:

Interviewer: *"JT 60 is like a collaboration of Japan and Europe?"*

Interviewee: *"**It was set up when Japan and Europe were battling** [over] **which country would get ITER, and then when ITER was decided to be in Europe**. Then, **as a kind of exchange money**, we decided to then help JT 60 to build a satellite tokamak in Japan."* (emphasis added)[12]

This person from EUROfusion sees the EU-Japan bilateral agreement rather as a political result than a scientific necessity. The interview focused on the agreement and the imbalance between the two entities. The interviewee's general impression towards the Japanese team is positive. However, the agreement resulting from the political return does not necessarily ensure balanced scientific exchange. As the Japanese fusion programme has a similar schedule, Japan seems to have more to gain from the European fusion programme and ITER, while the interviewee emphasised that it was a good collaboration, especially in material research.

"*[Addressing that the interviewer was Japanese] Well, to be very honest with you, and I like to be honest, I think JT 60 is a great device. Fantastic. And I really think that's going well. There's also in talking near Nagoya NIFS, the National Institute for Fusion Studies, which is working*

[12] Interview with the EUROfusion researcher/officer

*on an accelerator; it's a great team, it's really doing fantastic work. I will visit them in two weeks. Really very good. I think the Japanese DEMO activities**, I'm not really impressed because the team is relatively small**. We have, within the so-called broader approach activities, we have annually two meetings with Japan. So usually one meeting in spring is here and the full meeting is in Japan, where we exchange ideas and **it's usually one directional that it's a lot of information going from Europe to Japan, but we don't get much back, which probably comes because of the fact that our activity is much larger, we have much more people, and things move faster here than Japan**. Still, Japan has a time schedule which is similar to Europe. **But I really would like to see that there's more balance that we are working.** In some areas it works very nice. Like in the area of materials, we're testing materials in Japan, **but in some other areas I have the impression that Japan is leaning very much on Europe and that would be good to get that more balanced**."*[13] (emphasis added)

The interview highlights the imbalance of efforts between the EU and Japan. After the site was decided to be in Cadarache, Japan does not show the same enthusiasm for ITER-related activities as the EU. The EU and Japan are the two leading contributors, but hosting the machine creates an EU-centred approach in ITER.

After all the political negotiations, including the EU-Japan agreement, the ITER Agreement was finalised, with financial contributions allocated among members. During the construction phase, the EU is responsible for approximately 45.5% of construction costs, while the other members contribute approximately 9.1% each (ITER Organization, n.d.-a). The ITER members' in-kind contributions have been organised into around 140 Procurement Arrangements, each outlining the technical and managerial

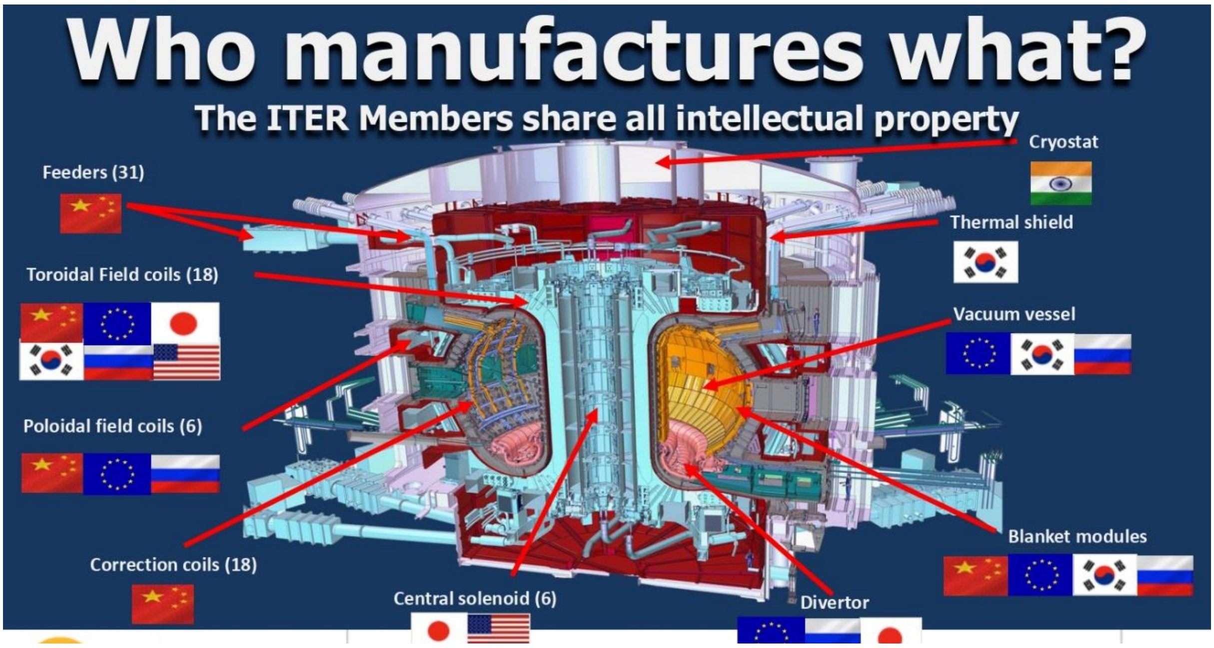

Figure 6: Who manufactures what? (Delmotte,2022)

[13] Interview with the EUROfusion researcher/officer

requirements for acquiring plant systems, components, or site infrastructure. During the operational phase, the cost-sharing among members will be distributed as follows: the EU will cover 34%, Japan and the US 13% each, and China, India, Korea, and Russia 10% each (ITER Organization, n.d.-a). France pays 20% of European contributions, which is equivalent to that of another ITER member (Claessens, 2023, p. 121). In short, ITER is heavily funded by the EU and France.

As mentioned earlier, the procurement distribution was a major struggle. Before the ITER Agreement was signed, the negotiations over "who manufactures what" were decided by the ITER Council, consisting of the members. However, Claessen argues that this logic to meet each member's expectations and technical and industrial capabilities was pushed "to its extremes" (Claessens, 2023, p. 87). As seen in Figure 6, many essential components in the reactors were distributed among several members. For example, 18 of the toroidal field coils are distributed among six members, i.e., each member manufactures identical parts in its territory and brings them to Cadarache by plane or boat, etc. This complex structure, of course, brings issues to the project. The interviewee from the ITER Communication Office told me that around 2015, when this person joined the organisation, the project was "doing quite poorly":

> "*A lot of the complexity of the project was showing up, and* ***the complexity both of building the machine and also the arrangement of doing that by making components from 35 countries on three continents and putting them into one machine****. It's just* ***probably the most complex science project in history****. And that complexity was not being mastered, I would say*."[14] (emphasis added)

ITER's complexity was "built-in" as an "integral part of the programme's structure as decided by its founders" (Claessens, 2023, p. 120). The distribution of about one million components was, according to Rossi, "not optimised for cost or technical success, but for political 'return' to each member state of ITER" (2020). Political return here includes a mix of technoscientific development across industries, capacity building, and spinoffs, as well as competitiveness in the race for fusion energy realisation. Claessens calls this "return" the "secondary aim" in addition to (or on the other side of the coin of) the publicly funded international collaboration to learn and develop the most advanced fusion technologies (Claessens, 2023, p. 86). To satisfy this "return" or "secondary aim" to all the members, all the intellectual properties generated from ITER's activities, including in-kind contributions, are shared among the members (see section 4.2.2). This approach of in-kind contributions and a share of intellectual property helps balance the unequal distribution of the project's outcome caused by the single site.

Nevertheless, the EU, the winner of the site, is largely responsible for the machine's construction. The budget allocation for ITER within the European budget is subsequently large. The European budget

[14] Interview with the ITER Communication officer

for ITER was initially allocated from the EURATOM Framework Programme (FP) following the ITER Agreement in 2006. Under "Council Decision on the 18th of December 2006 Concerning the Seventh Framework Programme of European Atomic Energy Community (Euratom) or nuclear research and training activities", the EU decided to allocate 1,947 M EUR for fusion research, and more than half of it was dedicated to the construction of ITER (Council of the European Union, 2021). It accounted for more than 70% of the total budget of the EURATOM Framework Programme (FP) for 2007 to 2011 (see Figure 7). The budget for thermonuclear fusion in this FP increased dramatically due to ITER construction over the history of FPs (see Table 1). The first phase of FP7 was largely dedicated to the construction of ITER, which was more than twice as large as FP6. The ratio of fusion within EURATOM has been tremendously larger than in previous FPs since the independence of the EURATOM FP in FP4. This means that EURATOM is prioritising fusion energy over other nuclear-related R&D, such as nuclear fission safety and decommissioning.

Maximum overall amount and shares assigned to each programme

1. The maximum overall amount for the implementation of the Seventh Framework Programme for the period 2007 to 2011 shall be EUR 2 751 million. That amount shall be distributed as follows (in EUR million):

Fusion energy research (1)	1 947
Nuclear fission and radiation protection	287
Nuclear activities of the JRC	517

(1) Within the amount foreseen for fusion energy research, at least EUR 900 million will be reserved to activities other than the construction of ITER, listed in Annex I.

Figure 7: Budget Allocation in EURATOM FP7[15]

[15] EURATOM FP7 (Council of the European Union, 2021)

FP	Year	Thermonuclear fusion (MEUR)	Total budget for FP (MEUR)
1	1984 - 1987	480	
2	1987 - 1991	611	
3	1990 - 1994	458	
4	1994 - 1998	840	1254
5	1998 - 2002	788	1260
6	2002 - 2006	750	1230
7.1	2007 - 2011	1947	2751

Table 1: The EU Budget for fusion energy throughout FP before and after the start of ITER construction (adapted by the authors based on EURATOM FP documents[16])

[16] The sources include (2002/668/Euratom, 2002; 2006/970/Euratom, 2006; 2012/94/Euratom, 2011; 1999/64/Euratom, 1998; 90/221/Euratom, EEC, 1990; 94/268/Euratom, 1994; 87/516/Euratom, EEC, 1987; Council Resolution of 25 July 1983 on Framework Programmes for Community Research, Development and Demonstration Activities and a First Framework Programme 1984 to 1987, 1983)

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ANNEX I

SCIENTIFIC AND TECHNOLOGICAL OBJECTIVES, THEMES AND ACTIVITIES

INTRODUCTION

The Seventh Framework Programme of the European Atomic Energy Community (Euratom) for nuclear research and training activities is organised in two parts corresponding to the 'indirect' actions on fusion energy research and nuclear fission and radiation protection, and the 'direct' research activities of the JRC.

I.A. FUSION ENERGY RESEARCH

Objective

Developing the knowledge base for, and realising ITER as the major step towards, the creation of prototype reactors for power stations which are safe, sustainable, environmentally responsible, and economically viable.

Rationale

There are serious shortcomings in Europe's energy supply with respect to short, medium, and long-term considerations. In particular, measures are needed to address the issues of security of supply, climate change, and sustainable development, while ensuring that future economic growth is not threatened.

In addition to the efforts which the EU is making in the field of research into renewable energies, fusion has the potential to make a major contribution to the realisation of a sustainable and secure energy supply for the EU a few decades from now after the market penetration of commercial fusion reactors. Its successful development would provide energy which is safe, sustainable and environmentally friendly. The long-term goal of European fusion research, embracing all the fusion activities in the Member States and associated third countries, is the joint creation, in approximately thirty or thirty-five years and subject to technological and scientific progress, of prototype reactors for power stations which meet these requirements, and are economically viable.

The strategy to achieve the long-term goal entails, as its first priority, the construction of ITER (a major experimental facility which will demonstrate the scientific and technical feasibility of fusion power), followed by the construction of DEMO, a 'demonstration' fusion power station. This will be accompanied by a dynamic programme of supporting R&D for ITER and for the developments in fusion materials, technologies and physics required for DEMO. This would involve European industry, the fusion associations and third countries, in particular parties to the ITER Agreement.

Activities

1. *The realisation of ITER*

   This includes activities for the joint realisation of ITER (as an international research infrastructure), in particular for site preparation, establishing the ITER Organisation and the European Joint Undertaking for ITER, management and staffing, general technical and administrative support, construction of equipment and installations and support for the project during construction.

2. *R&D in preparation of ITER operation*

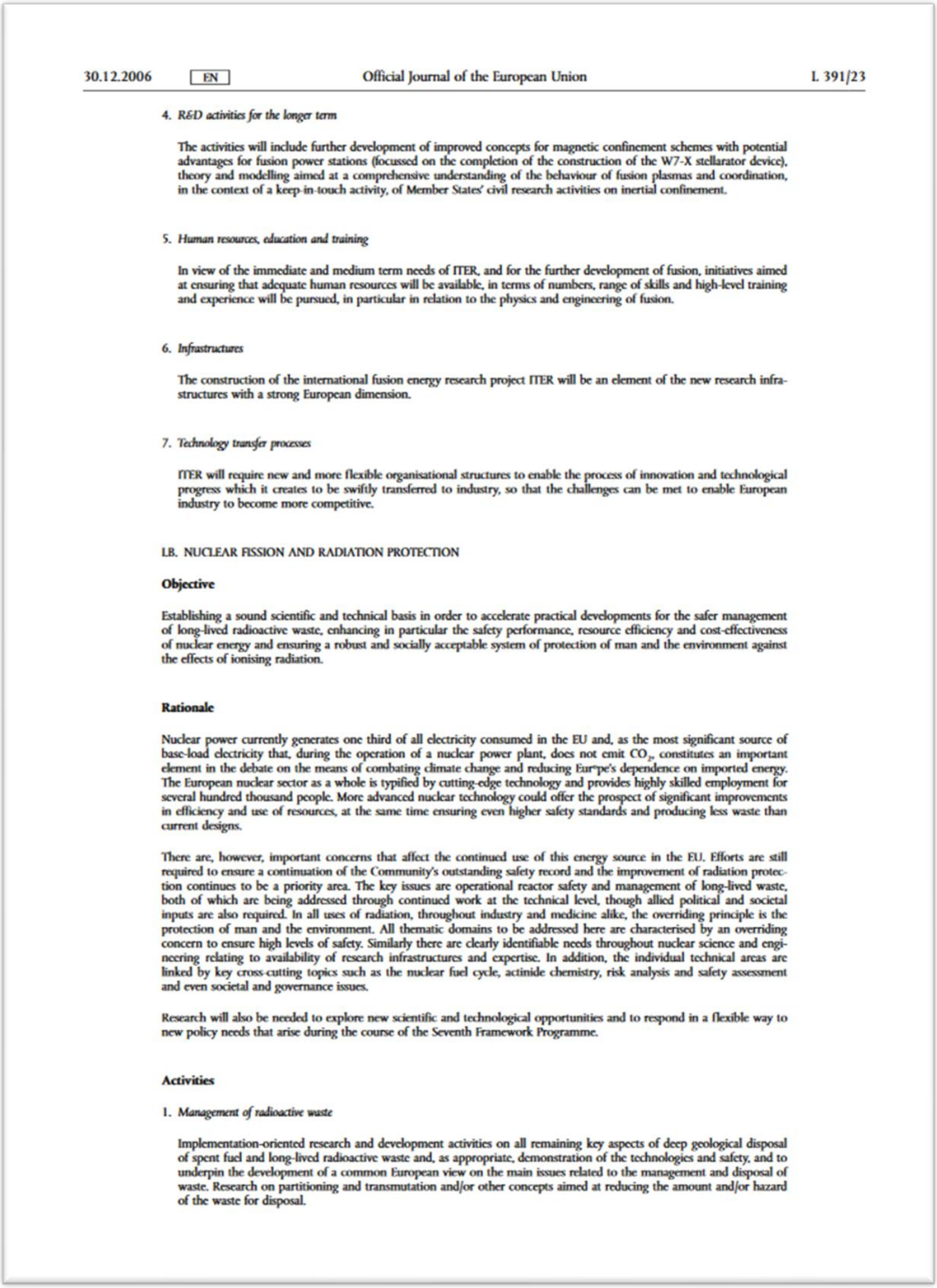
   A focused physics and technology programme will exploit the relevant facilities and resources in the fusion programme, i.e. JET and other magnetic confinement devices, existing, future or those under construction (Tokamaks, Stellarators, RFPs). It will assess specific key ITER technologies, consolidate ITER project choices, and prepare for ITER operation through experimental and theoretical activities.

3. *Technology activities in preparation of DEMO*

   This entails the vigorous development of fusion materials and key technologies for fusion, including blankets, and the establishment of a dedicated project team to prepare for the construction of the International Fusion Materials Irradiation Facility (IFMIF) to qualify materials for DEMO. It will include irradiation testing and modelling of materials, studies of the DEMO conceptual design, and studies of the safety, environmental and socio-economic aspects of fusion energy.

Figure 8: EURATOM FP7: Annex 1-1[17]

[17] EURATOM FP7 (Council of the European Union, 2021)



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4. *R&D activities for the longer term*

The activities will include further development of improved concepts for magnetic confinement schemes with potential advantages for fusion power stations (focussed on the completion of the construction of the W7-X stellarator device), theory and modelling aimed at a comprehensive understanding of the behaviour of fusion plasmas and coordination, in the context of a keep-in-touch activity, of Member States' civil research activities on inertial confinement.

5. *Human resources, education and training*

In view of the immediate and medium term needs of ITER, and for the further development of fusion, initiatives aimed at ensuring that adequate human resources will be available, in terms of numbers, range of skills and high-level training and experience will be pursued, in particular in relation to the physics and engineering of fusion.

6. *Infrastructures*

The construction of the international fusion energy research project ITER will be an element of the new research infrastructures with a strong European dimension.

7. *Technology transfer processes*

ITER will require new and more flexible organisational structures to enable the process of innovation and technological progress which it creates to be swiftly transferred to industry, so that the challenges can be met to enable European industry to become more competitive.

I.B. NUCLEAR FISSION AND RADIATION PROTECTION

Objective

Establishing a sound scientific and technical basis in order to accelerate practical developments for the safer management of long-lived radioactive waste, enhancing in particular the safety performance, resource efficiency and cost-effectiveness of nuclear energy and ensuring a robust and socially acceptable system of protection of man and the environment against the effects of ionising radiation.

Rationale

Nuclear power currently generates one third of all electricity consumed in the EU and, as the most significant source of base-load electricity that, during the operation of a nuclear power plant, does not emit CO_2, constitutes an important element in the debate on the means of combating climate change and reducing Europe's dependence on imported energy. The European nuclear sector as a whole is typified by cutting-edge technology and provides highly skilled employment for several hundred thousand people. More advanced nuclear technology could offer the prospect of significant improvements in efficiency and use of resources, at the same time ensuring even higher safety standards and producing less waste than current designs.

There are, however, important concerns that affect the continued use of this energy source in the EU. Efforts are still required to ensure a continuation of the Community's outstanding safety record and the improvement of radiation protection continues to be a priority area. The key issues are operational reactor safety and management of long-lived waste, both of which are being addressed through continued work at the technical level, though allied political and societal inputs are also required. In all uses of radiation, throughout industry and medicine alike, the overriding principle is the protection of man and the environment. All thematic domains to be addressed here are characterised by an overriding concern to ensure high levels of safety. Similarly there are clearly identifiable needs throughout nuclear science and engineering relating to availability of research infrastructures and expertise. In addition, the individual technical areas are linked by key cross-cutting topics such as the nuclear fuel cycle, actinide chemistry, risk analysis and safety assessment and even societal and governance issues.

Research will also be needed to explore new scientific and technological opportunities and to respond in a flexible way to new policy needs that arise during the course of the Seventh Framework Programme.

Activities

1. *Management of radioactive waste*

Implementation-oriented research and development activities on all remaining key aspects of deep geological disposal of spent fuel and long-lived radioactive waste and, as appropriate, demonstration of the technologies and safety, and to underpin the development of a common European view on the main issues related to the management and disposal of waste. Research on partitioning and transmutation and/or other concepts aimed at reducing the amount and/or hazard of the waste for disposal.

Figure 9: EURATOM FP7: Annex 1-2[18]

[18] EURATOM FP7 (Council of the European Union, 2021)

The 2006 FP document indicates the objective of fusion energy research as "Developing the knowledge base for, and realising ITER as the major step towards, the creation of prototype reactors for power stations which are safe, sustainable, environmentally responsible, and economically viable" (Council of the European Union, 2021). To do so, the activities of FP are dedicated to 1) the realisation of ITER, 2) R&D in preparation for ITER operation, 3) Technology activities in preparation for DEMO (demonstration reactor), 4) R&D activities for the long term, 5) Human resources, education and training, 6) infrastructure, and 7) Technology transfer processes (Council of the European Union, 2021, Annex 1) (see also Figures 7 and 8). Most of the activities are related to ITER, indicating that ITER is the EU and EURATOM's top R&D priority.

Shortly after a couple of years of construction, the ITER budget had increased significantly, and the EU needed to secure additional funding. Claessens (2023) provides an overview of the EU's struggle with this issue.

> *"Following explanations given by the European Commission in a communication published on May 5, 2010,11 calling for a revision of the project's governance and proposing some mechanisms to remain within budget, in July 2010 the Council finally approved additional funding of EUR1.4 billion using unused funds in the EU budget and redirecting EUR460 million from the Framework Programme for Research and Technological Development. This episode had a profound effect on EU institutions by pushing EU procedures to their limits.* ***Senior officials realised that ITER posed a serious double risk not only to the European Union's but also to ITER's very existence****. Therefore, just a week later* ***the Commission suggested removing ITER from the Framework Programmes that had funded the project up to that point and to creating a new line in the EU budget specifically for ITER****. Finally, on December 1, 2011, the Council and the European Parliament agreed to allocate unused EU funds worth a further EUR 1.4 billion as additional funding for ITER in 2012 and 2013 to fully cover the cost overruns" (Claessens, 2023, p. 125) (emphasis added).*

The budget separation highlights the importance of the EU budget for ITER and the EU's priority of providing consistent resources to ITER. The decision to separate the ITER budget from FP also reflects the criticism that the increasing budget of ITER should not pressure other science and research activities in the member states (especially France) and the EU (Claessens, 2023, p. 106).

As a consequence of the change from EURATOM to a centralised EU budget, the EU ITER budget is allocated within the multiannual financial framework (MFF) for the periods 2014-2020 and 2021-2027. The 2014-2020 MFF budgeted 2926,4 MEUR with full implementation (Delasnerie, 2024). The 2021-2027 MFF has almost doubled in size: 4,562.7 MEUR (European Commission, n.d.-b). The budget is continually adjusted to account for delays and conditions (see 4.4.1 for delays). While many other EU programmes are often funded by financial programmes such as NextGenerationEU or equivalents, ITER's MFF are allocated directly and independently from the EU budget. Yet, the EC emphasises ITER's financial contribution to horizontal priorities of Climate mainstreaming: "The Commission considers that 100% of the ITER-related expenditure for the 2021-2027 period contributes to the climate effort of the EU budget. […] The successful realisation of ITER would determine whether fusion can become a major sustainable energy source, contributing to the EU's strategy for long-term energy security. Fusion is likely to play a major role in the decarbonisation of our economies, as it can be a source of low-carbon, safe, reliable and predictable energy" (European Commission, n.d.-b). At the same time, the EC website highlights the achievements – job creation, operational contracts, financial contributions to European companies, etc. – with numbers (see Figure 10). These figures emphasise alignment with EU agendas and benefits, supporting the justification of ITER's massive budget through quantified impacts on employment and industry contributions as well as the project's novelty.

Figure 10:EC website on "Concrete examples of achievements" (European Commission, n.d.)

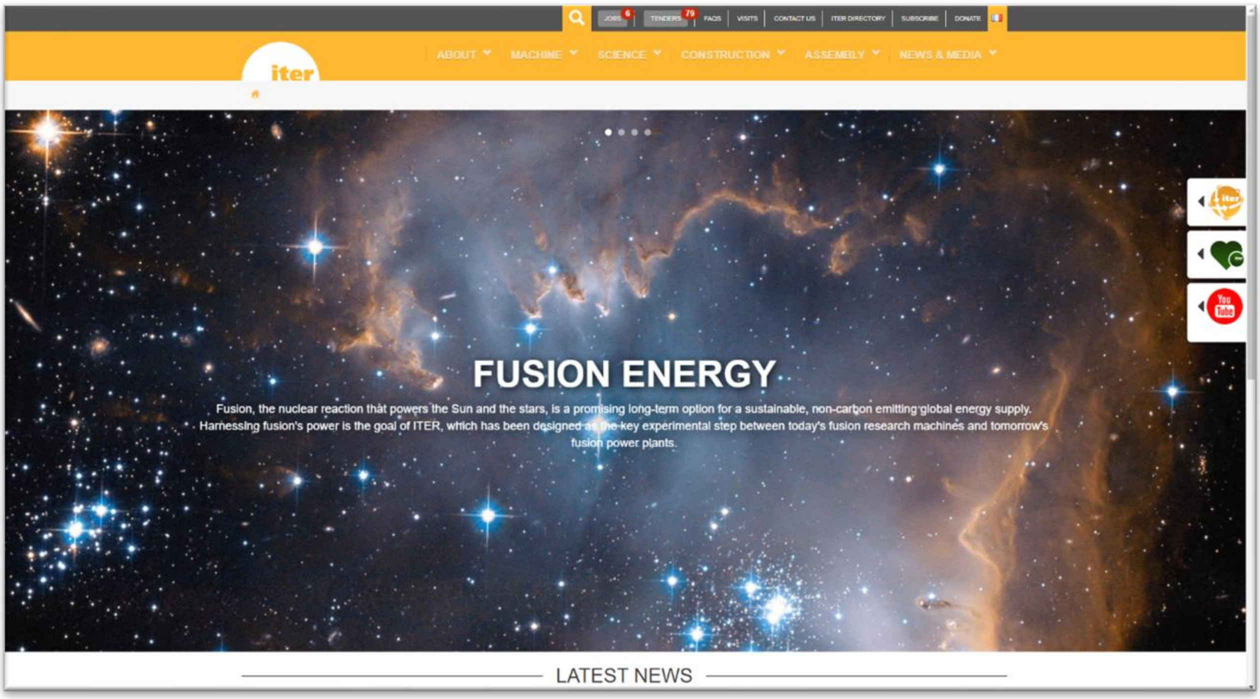
This section has investigated the highly technopolitical processes, from site selection to ITER member-contribution divisions, with particular focus on EU financing. ITER's division of contributions is carefully and strategically designed so that each Member would receive "returns" politically and techno-scientifically. The EU, the host, or the "winner of the game" (?), is largely investing budget under special conditions to ensure the existence of ITER and its own benefits. The processes of site setting and contributions demonstrate careful design and ongoing adjustments to persuade the actors involved.

4.3.2. Building the Sun or Building the Puzzle?

The previous section has shown the basis for the construction: site setting and member contributions. However, what does it really mean to construct the massive machine over such a long period? This section compares two distinctive narratives regarding the construction. One narrative has a mystical focus: building the sun on earth. The other has a technical focus: building the puzzle. Both of these narratives are constructed, represented, and reinforced through various practices. At first glance, they appear to be contradictory but coexist in ITER. They play different justificatory roles in different contexts. This section analyses interviews as well as visual materials from the website, the ITER visit, and the ITER virtual tour, in the wider contexts in which the visuals are situated.

Often, developing fusion energy is analogised as "building the sun or a star" because the basic physics of nuclear fusion is the same as it naturally occurs in space in a star or is artificially created on Earth (Turrell, 2021) (see also 2.4). This analogy, however, may mislead non-experts about the technical difficulties and material challenges of fusion energy development. Yet, fusion proponents, including European fusion scientists and the ITER Organization itself, draw this analogy when communicating with audiences.

Figure 11: Home of the ITER website (version until 2023) (screenshot: https://www.iter.org/) (retrieved on 28/9//2023)



The motifs of stars and the sun are ubiquitous on the official ITER website. The previous version of the ITER Organization's website featured pictures of space with many stars on the top page with a sentence:

> "*Fusion Energy:* ***Fusion, the nuclear reaction that powers the Sun and the stars****, is a promising long-term option for a sustainable, non-carbon emitting global energy supply. Harnessing fusion's power is the goal of ITER, which has been designed as the key experimental step between today's fusion research machines and tomorrow's fusion power plants*" (ITER Organization, n.d., emphasis added) (see also Figure 11).

This sentence and background picture create a strong connotation between ITER and the sun and stars when accessing the very top of the website.

Similarly, the ITER guided tour uses the motifs in the presentation and displays. Figure 12 is the slide at the beginning of the presentation (5th slide), right after problematising current energy systems and the high energy demand of the future. With the burning sun in the background, the slide introduces Einstein's mass-energy equivalence equation, E=mc2, which bridges the popular and the Nobel scientist's discovery to ITER's fusion energy development.

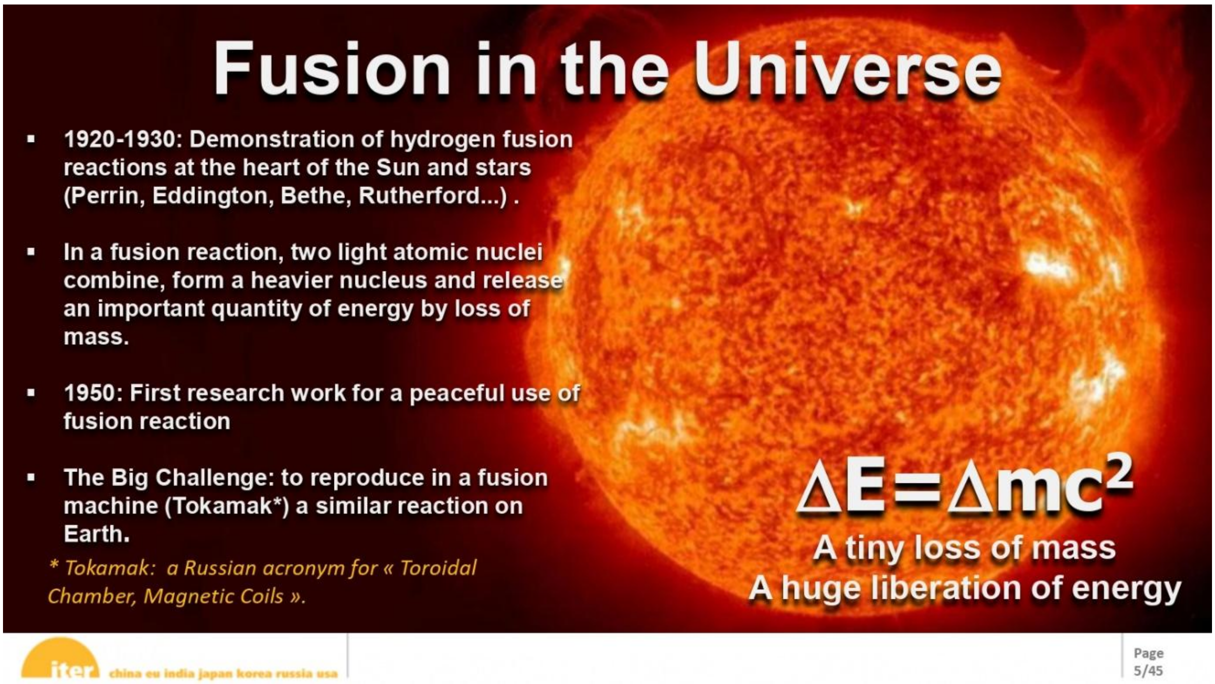


Figure 12: "Fusion in the Universe" (Delmotte, 2022, p.5)

The exhibition area that is used to welcome external visitors also has a large wall saying, "*The stars lead the way: Fusion is the energy that powers the Sun and the stars."* (Figure 13). Interestingly, in front of the wall, a microwave and other objects were displayed without any explanations. It might have been used on another tour to illustrate electromagnetic waves, much like the magnetic fields used in fusion reactors. The ITER virtual tour is consistent with the design on the top page. With the same slogan as the website's homepage, virtual visitors may feel as if they are travelling in space. Although this exact design has changed since the website renewal, the current website still features a space cloud image on the front page.

Figure 13: Exhibition space in ITER visitor centre (source: author)

These consistent representations of the sun and stars create an extraordinary atmosphere when entering the ITER construction site, website, or virtual tour. This symbolic association offers the audience a simplified explanation and a sense of mysticism about the project. STS scholars have studied the roles of enchantment and mysticism in science and technology. In particular, nuclear technology, often state-driven high technology, embraces (re-)enchantment to mobilise actors at stake, particularly when "scientific, technological, political, economic, and moral discourse is not sufficient to create political and civic support". As ITER faces uncertainties regarding technological feasibility and economic viability, the mystical theme plays a key role in garnering support.

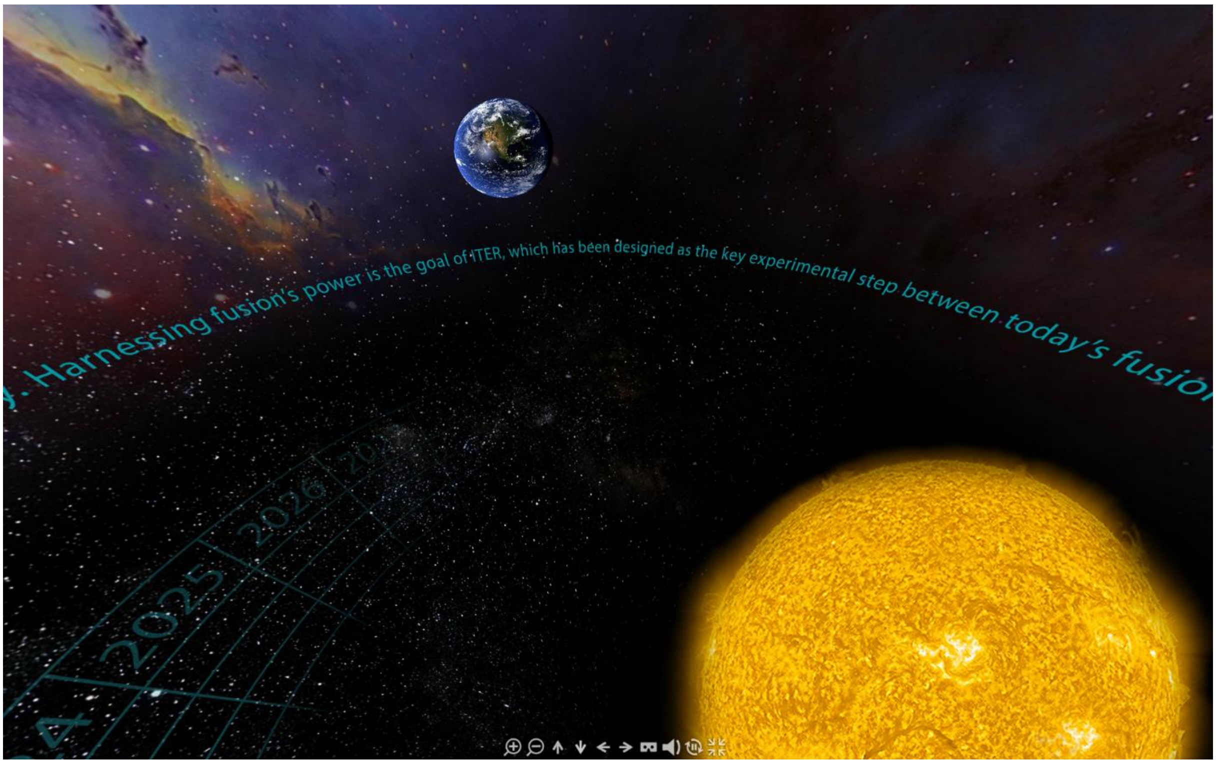


Figure 14: ITER virtual tour top page (screenshot: https://static.iter.org/com/360/calendar/2021-09/)

While mystical themes appear only at the beginning of the ITER guided tour, virtual tour, or website, mystical images are a double-edged sword that may mystify the audience but may also evoke scepticism when the audience becomes disenchanted. An interview with the EUROfusion researcher/officer reveals a discursive transition from the sun to technicalities.

> Interviewer*: So, when you are talking with politicians and the public, how do you kind of simplify it or how do you put it into a narrative? Because it is such a complex technology, how do you try to convince them?*
>
> Interviewee*: Well, one is that* ***fusion works already for millions of years because it's the energy source of the sun and the stars and in principle the process is very simple****. So, the fusion process can be very quickly explained; then to do it on Earth* ***is a little bit less easy****. So, I have to tell that we need to heat a gas to very high temperatures. I can explain how we do that and that we then at these very high temperatures. Since you have charged particles, you can confine these particles in magnetic fields. And I then also explain where the difficulties are, why it's taken so long, how far we are. I usually can explain that in five to ten minutes. So where are we, what are the challenges, why are we not yet there? What needs to be done?* ***It's not too difficult to explain it. It sounds simple. Of course, to do it is more difficult****.*[19] (emphasis added)

[19] Interview with the EUROfusion researcher/officer

This interview shows a smooth transition from basic science to technicality. The interviewee uses the argument, "to explain is easy, to do is more difficult", twice during this conversation. Indeed, ITER is "one of the most challenging scientific and engineering enterprises of this century" (Varandas, 2008, p. 1808). European fusion researchers also address this point: "As any nuclear engineer knows, there is much more to a working reactor and commercial power generation than a demonstration of scientific feasibility" (Smith & Cowley, 2010, p. 1104). Some say building ITER is like solving "a million-piece puzzle" (Pacchioni, 2019, p. 361) especially as the in-kind contributions from the ITER members should be perfectly engineered and matched.

The metaphysical motif of the space is then not sufficient to explain the technical development of ITER; ITER is also an assemblage of materials. The recent renewal of the ITER Organization's website marks a shift in promotional materials from space imagery to machinery masterpieces. While keeping a simplified space-inspired figure on the page, the very top of the website features a drone-shot of a tokamak reactor under construction (Figure 15). This emphasis on the machinery shows the reactor's massive volume and provides a materialised view of the project's progress. This shift may address the criticism of the delays and the increasing budget; it also corresponds to the sign "We have delivered" in the assembly hall (see also 4.1).

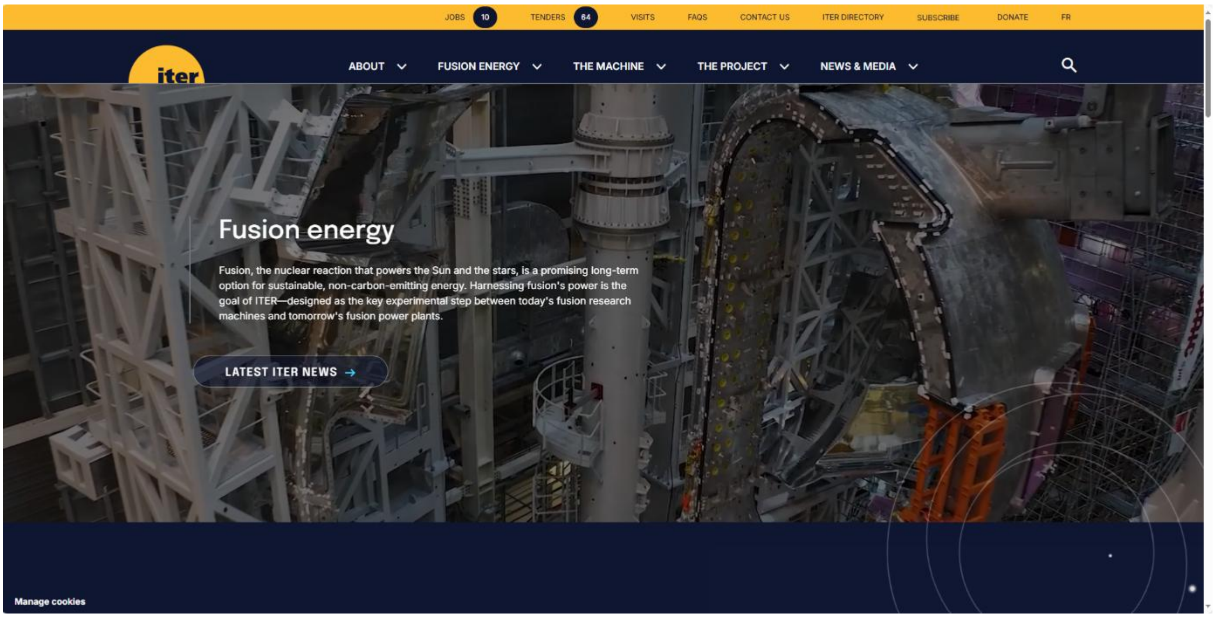


Figure 15: ITER Organization's new website (https://www.iter.org/) (accessed 06.07.2025)

However, ITER's representation of the machinery image did not begin recently; rather, it has complemented the space-inspired representations. Representations of metal, pipes, and concrete are well presented on the website, especially in the virtual tour (see Figures 16, 17, and 18). The virtual tour features 3D graphics of various construction areas, allowing the audience to immerse themselves in the massive site filled with construction materials.

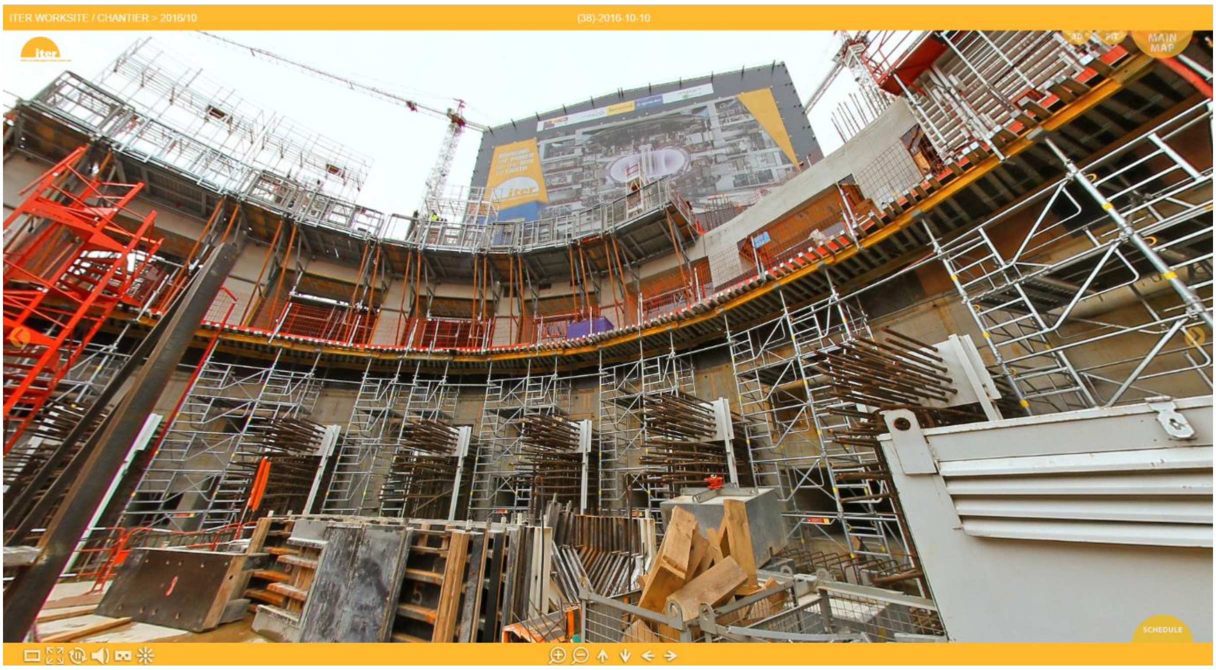


Figure 16: ITER virtual tour (ITER worksite – October 2016, Chaintier) (Screenshot: https://static.iter.org/com/360/2016-10/) (retrieved on 29 September 2023)

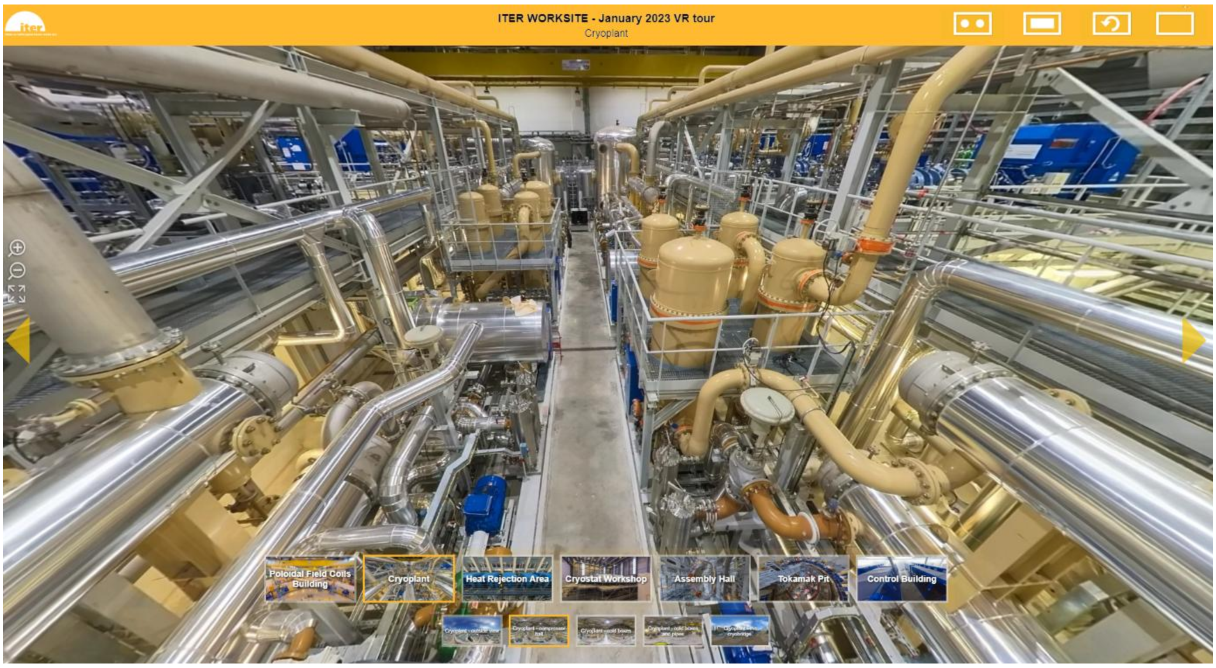


Figure 17: ITER virtual tour (ITER worksite - January 2023, Cryoplant) (Screenshot: https://static.iter.org/com/360/2023-01/index.html) (retrieved on 29 September 2023)

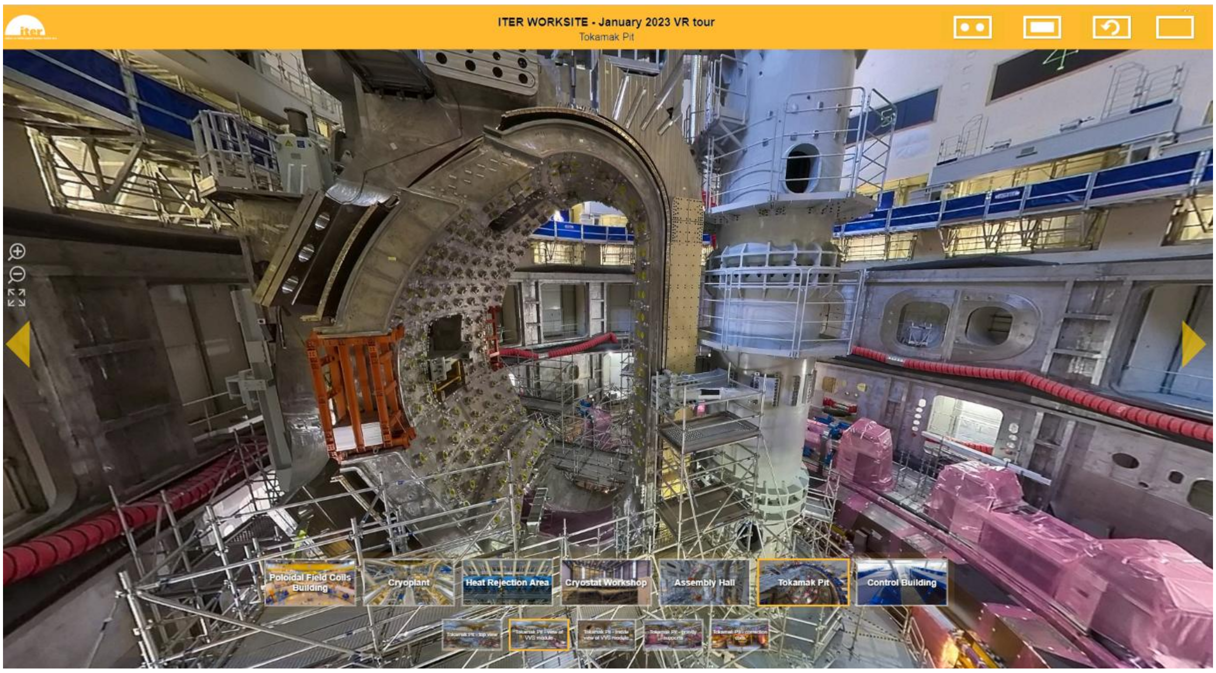


Figure 18: ITER virtual tour (ITER worksite - January 2023, Tokamak Pit) (Screenshot: https://static.iter.org/com/360/2023-01/index.html) (retrieved on 29 September 2023)

The power of this materiality resonates with the author's ethnographic note as the guided tour enters the site.

> *"After the presentation, we got on a bus to go around the site. The site was totally under construction and had **many engineers walking and trucks passing**. **Cables, metals, and concrete**…"*[20]

Fascination with massive structures is probably one of the reasons why guided tours at scientific or technological sites attract attention. "Spectacular Operation" was also one of the slides in the guided tour presentation (Figure 19). On the date of the guided tour I attended, I was not able to enter the assembly hall, which would have been the main attraction, because the hall was at the "critical moment" of assembling the tokamak capsule – "*even a millimetre gap can cause trouble*", the tour guide said. The guide responded to the participants' disappointment with their plans to reopen the assembly hall to visitors. Instead, we observed a site of poloidal-field (PF) magnetic coils (Figure 20).

[20] The author's ethnographic note from the ITER guided tour

Figure 19: "Spectacular Operation" from the ITER guided tour presentation (Delmotte, 2022)

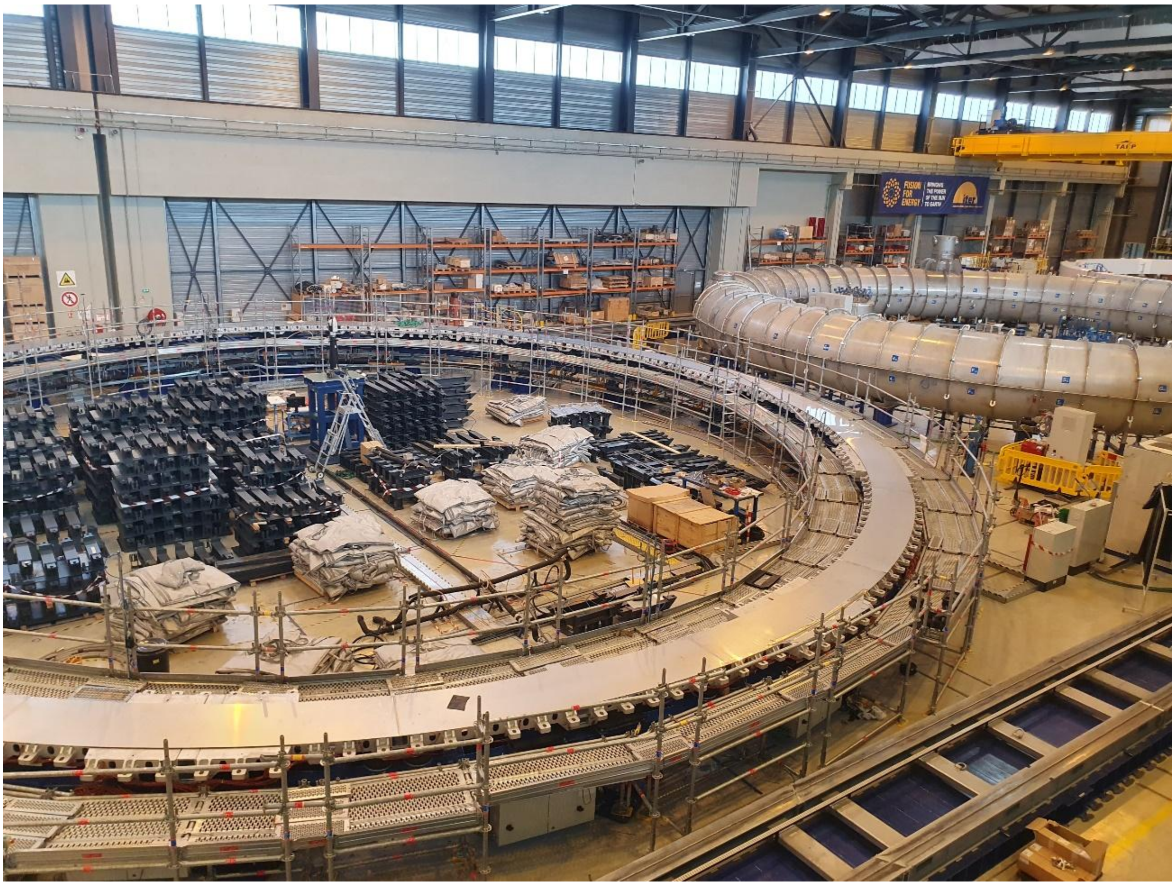


Figure 20: Poloidal field (PF) magnetic coils under construction (source: author)

The glorification of construction is also evident in the component delivery process. In-kind contributions are delivered by ships, aeroplanes, or trucks from each ITER member. Most of the components arrive in Marseille, the nearest large city with a major port and airport. Those components are carefully transported to Cadarache via the so-called “ITER Route” (Figure 21). The French government completed this 104km route by constructing new roads and enforcing existing regional roads in the area (Claessens, 2023). While the route is used daily by local residents, it is strictly controlled by the police when components are delivered at night. The moments of deliveries from thousands of kilometres away and the moments of arrivals are presented in a glorified manner (Figure 22). In the presentation, the tour guide described how slowly the trucks move to prevent component damage. Also, she mentioned how relieved and appreciated the employees of the ITER Organisation were when a component from Russia arrived, despite the war against Ukraine. As seen in the representation of deliveries with ITER member flags, arrivals of components symbolically and practically represent what ITER is – the international collaboration as the centre of the project (see section 4.2.2) – and how it achieves progress – also see the introduction (4.1) about the connotation and implication of “we have delivered”. Upon arrival, components are assembled into a single massive machine.

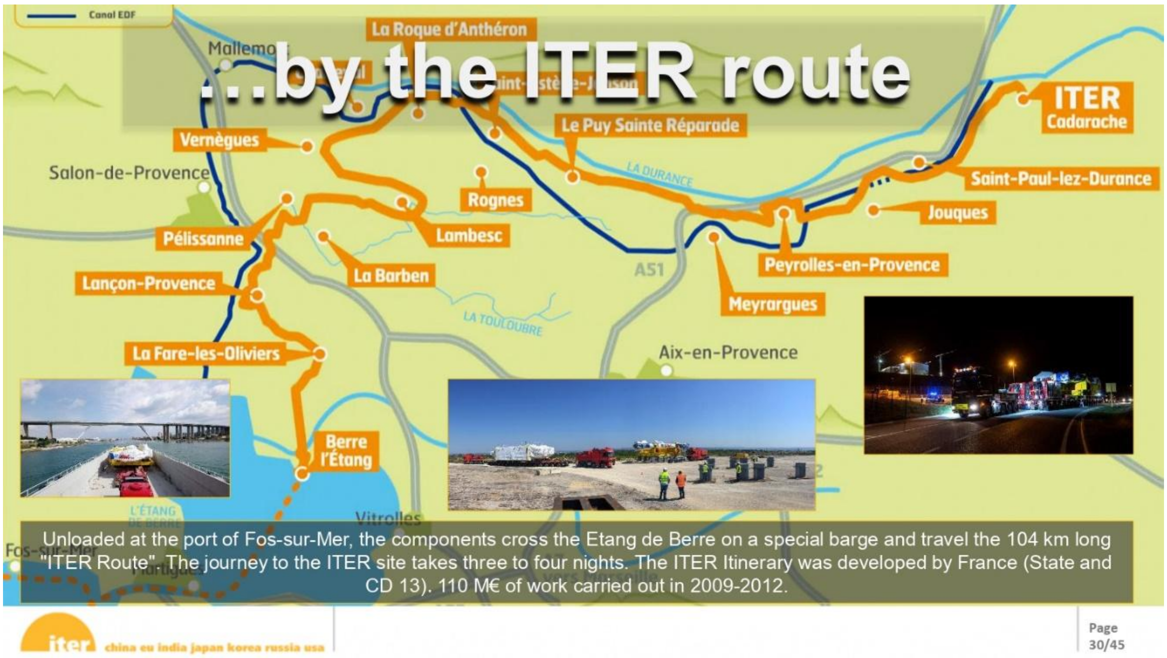


Figure 21: "... by the ITER route" ITER presentation (Delmotte, 2022)

Figure 22: "Massive arrivals" ITER presentation (Delmotte, 2022)

While the glorification of construction itself is widely presented in ITER, the author also noted its mundaneness in the ethnographic note.

> *"One of the reasons to do field research is to feel the reality and immerse the researcher themselves in the physicality of the object. In addition to the rapidness of the construction site, the massiveness of everything there. Diameters of coils are from 8 to 24 metres. A worker standing next to it looked so small. At the same time,* ***the mundaneness of the fancy technology is realised****.* ***A worker was walking with an electric screwdriver in his hand. The magnet coil is filled with epoxy glue, which people use for crafting****. Big technology always needs mundane skills and materials, which are often not advertised well. Any documents and pictures of ITER often emphasise the "greatness" of the technology, namely, the hugeness of the machine, the precision of construction, or the professionalism of the assembly processes – almost rocket science****.*** ***However, besides scientists and politicians, there are always technicians and engineers who work with their hands and bodies.*** *Indeed, the workers are the essential part of the technology."*[21] (emphasis added)

This note shows an interesting contrast between the official representations and visitors' perception. A visitor to the ITER site may see a different side of the construction: a very mundane character of the high-tech machine. Regardless of whether it is intended or not, in the guided tour a visitor may feel more connected to the project by seeing familiar construction work and materials. Yet, the "reality" of the

[21] The author's ethnographic note from the ITER guided tour

construction is a key element of the current progress in ITER; the mega technoscientific project needs to be materialised and made tangible for stakeholders.

This section has focused on two distinctive representations and practices in ITER that sometimes seem contradictory: space-inspired mystical representations and high-tech industrial machinery. However, these distinctive representations complementarily function for different purposes in different contexts. The former serves to familiarise the fundamental science of nuclear fusion; at the same time, it provides space-utopian images accompanied by implications of eternity and immenseness. The latter materialises the project's core goal and ongoing progress. While Einstein's equation explains nuclear fusion in the simplest terms, the construction of machinery reveals the complexity and technical sophistication of nuclear fusion reactors. The spectacular sci-fi look of machinery (and, of course, certain types of representations) fascinates people and convinces them of the plan. International collaboration is materialised through the practice of delivery and then assembly. Since ITER is a long-term project with an uncertain outcome, these representations play a crucial role in mobilising the actors at stake. Making the fundamental art simple and presenting the process as astonishing is a key part of the project practice, at least until the machine starts operating. These aspects are less pronounced in other nuclear fusion reactors, such as JET or JT-60SA. The specificity of ITER as an international project with a large budget makes these material-discursive practices relevant.

4.3.3. Building from the Past towards the Future: EUROfusion Roadmap

The previous section has shown how ITER's representational practices that justify and reinforce the project's aim and process. One of the findings is that the project's characteristic of long-term duration and uncertainty formulates a specific type of (justificatory) practices. This section expands the relationship between project characteristics and temporality by examining the European Fusion Roadmaps over a broader temporal scope. Analysis of roadmapping practices will show that timeline documents are constructive and performative materials in which agendas and strategies are materialised. The most important documents that address temporality, referred to both officially and unofficially, are the European Fusion Roadmap and the ITER Baseline. These two documents are comparable in how they project the future based on previous activities and current conditions. Also, despite their constructive features, the documents are often treated as "evidence" to act on. Additionally, both documents are subject to regular updates and have been drastically revised over time. This section focuses on the European Fusion Roadmap as the primary source, given that EUROfusion (formerly, EFDA) is the key actor in ITER development and the exploitation of its results. The later section (4.4.2) addresses the ITER baseline, focusing on amendments and adaptations as responses to delays.

The current European Fusion Roadmap was created by the EUROfusion consortium in 2018. This succeeds the EFDA's first-ever European Fusion Roadmap, "Fusion Electricity: A roadmap to the realisation of fusion energy", published in 2012 (European Fusion Development Agreement, 2012). The current EUROfusion Roadmap's original title is "European Research Roadmap to the Realisation of Fusion Energy" (EUROfusion, 2018b). The document has long and short versions. Both versions share a similar narrative, starting with executive summaries, background (in the long version, "Make fusion a credible option"), and a strong emphasis on climate change, the feasibility of fusion energy, the status of ITER, and plans for DEMO.

Besides the similarities, the two documents show differences in style: the 76-page-long version contains the more technical details and concrete plans (EUROfusion, 2018b) while the 24-page short version ("In Brief") emphasises key points in a short-text style with a more visually appealing design (EUROfusion, 2018a). Although it is not explicitly stated, the long version clearly targets a technical audience, whereas the short version aims at a wider audience, such as citizens or policymakers. This section covers both versions in the comparative analysis.

Firstly, both versions frame fusion energy as a legitimate way for "combating climate change" (EUROfusion, 2018a, p. 4). The long version starts with detailed technical descriptions about climate change based on reports from international organisations/initiatives such as the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC). The short version rather focuses on climate change as the status quo, stating that fusion energy has high potential to combat it: "*Fusion is the most extensively studied idea for a low-carbon primary energy source; it can be a new source that can deliver base-load electricity and complement intermittent low-carbon energy sources that are already being exploited*" (EUROfusion, 2018a, p. 4). These sentences highlight the extensive scope of research while implying uncertainties using "can" twice.

After identifying the problem, the long version explains the technical challenges of achieving fusion energy, including plasma operating regimes, heat exhaust, and neutron-tolerant materials. On the contrary, the short version does not include these challenges at all but emphasises the feasibility of fusion energy through research programmes such as ITER and DEMO. The long version also classifies eight missions to overcome the challenges, which are addressed individually in the roadmap (Figure 23). Here is a concise summary of the missions in an academic journal by the EUROfusion coordinator at the time:

> *"(1) Demonstrate plasma regimes of operation that increase the success margin of ITER and satisfy the requirements of DEMO; (2) Demonstrate heat-exhaust systems capable of withstanding the large power loads in DEMO; (3) Develop and validate neutron-resistant materials that can withstand the large 14 MeV neutron fluence without strongly degrading their physical properties; (4) Ensure tritium self-sufficiency through technological solutions for the breeding blanket; (5) Implementation of the intrinsic safety features of fusion into the design of*

DEMO following experiences gained with ITER; (6) Produce an integrated DEMO design supported by targeted R&D activities; (7) Ensure the economic potential of fusion by reducing the DEMO capital costs and developing long-term technologies; (8) Bring the stellarator line to maturity to be able to judge its feasibility as a long-term backup solution" (Donné, 2019, p. 3).

The mission statement specifies the problems, making long-term uncertainties manageable. The mission focuses on the future prospects for DEMO development. In that regard, the exploitation of ITER is considered a necessary step for DEMO. At the same time, the stellarator option is described as a "backup solution" that diversifies the pathway to DEMO and mitigates risks associated with the tokamak/ITER path.

In addition to the missions, both versions break the roadmap into three stages: short-term, medium-term, and long-term. The long version clarifies them as "First period: start ITER operation and complete DEMO conceptual design(s) (<2030); Second period: burning plasma on ITER and DEMO engineering design (2030-2040); Third period: plasma and technology optimisation on ITER and construct DEMO (>2040)" (EUROfusion, 2018b, p. 39). Interestingly, the short version of the document does not explain the timeline for these periods anywhere. The roadmap figure (Figure 23) repeatedly appears in both versions. However, as with the short version's absence of timelines, the roadmap figure does not include one. On the contrary, the long version includes a more detailed timeline, including ITER and DEMO schedules (Figure 24).

These delicate choices and its (not) indication of time show the sensitiveness of the long-term timelines in European fusion energy R&D. In general, roadmaps often explicitly show the temporal dimension so that they "provide a means of charting a migration path between the current state of the business (for each layer), and the long-term vision, together with the linkages between the layers, in a form that is flexible enough to be updated over time" (Phaal et al., 2004, p. 23). However, the EUROfusion roadmap deliberately obscures the exact timelines. It may be because the time horizons of 2040 or 2060 may appear excessively far in the future (also note that the document was published in 2018), especially for a wider audience without a technical background.

The roadmap also shows a strong orientation towards "Fusion Power Plants," as all activities, including ITER, DEMO, material research facilities, stellarators, and economic performance improvement, are consolidated into a single goal. As mentioned before (4.2.3), EUROfusion is a diverse research-oriented consortium spanning basic physics to materials research. The roadmap shows how the consortium stresses its ultimate goal to achieve "commercially viable" fusion energy through a "concerted", "long-term" programme (EUROfusion, 2018a, pp. 8–11). This emphasis is also evident in the recurring representations of electric power.

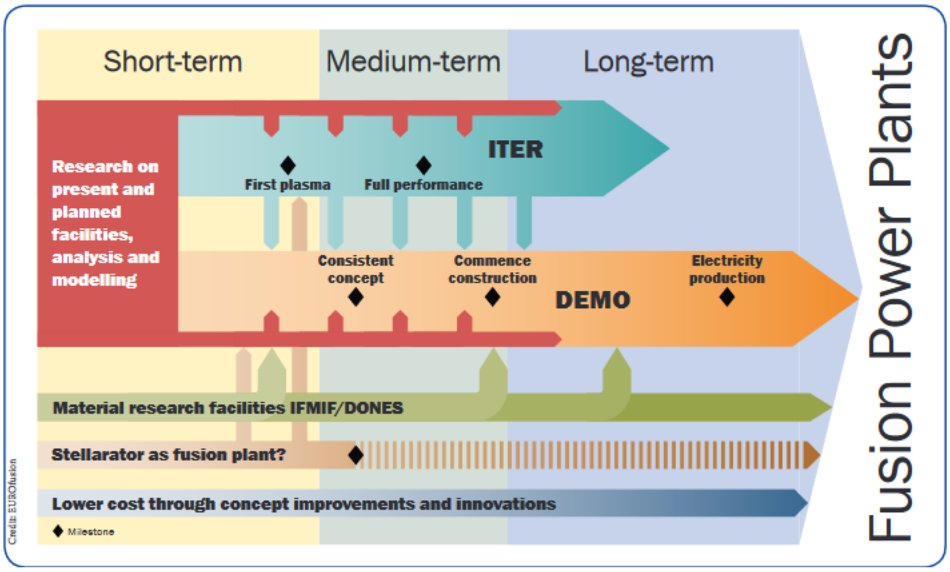


Figure 23: European Fusion Roadmap (source: European Research Roadmap to the Realisation of Fusion Energy [long version] (EUROfusion, 2018c))

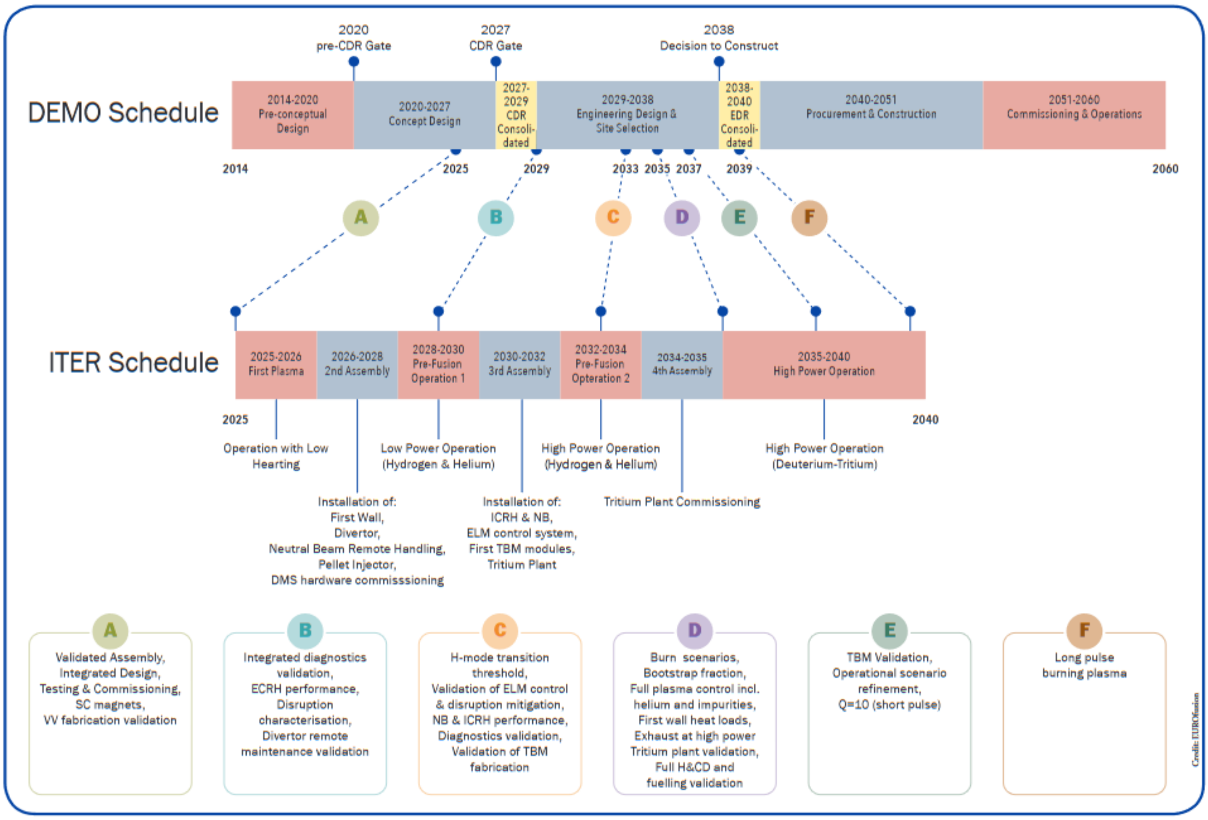


Figure 24: Schedule of DEMO and ITER (source: EUROfusion Roadmap (EUROfusion, 2018c))

A large part of the roadmap is dedicated to explaining the machines: ITER and DEMO. “The roadmap to fusion electricity rests on three main pillars: ITER, DEMO and a fusion materials testing facility (IFMIF-DONES)” (EUROfusion, 2018a, p. 11). Particularly, ITER and DEMO are presented as “key facilities on the roadmap” since “ITER and then DEMO-class devices are the critical stages to test the relevance of fusion power on a commercial scale” (EUROfusion, 2018b, p. 19). In the roadmap, ITER is considered crucial because it is “the key facility for the first stages of the roadmap”, while DEMO is “the step between ITER and a commercial power plant” (EUROfusion, 2018b, pp. 19–20). The machines- ITER, DEMO, and a commercial power plant- are presented in a linear way in the short version, making the transition from research to innovation and then implementation. Respectively, “ITER: Bringing together the world’s tokamak research”, “DEMO: Integrating science, technology, and innovation”, and the fusion plant as a result of “from prototype to power plant” (EUROfusion, 2018a, pp. 14–19). The machines have both symbolic and practical meanings in the roadmap. The machines are single physical entities that span diverse research activities across different countries. All research output, from theoretical research to materials science, is combined into a single physical machine. The meaning of the ITER and DEMO for the EUROfusion consortium repeats the role of JET in the early phase of European fusion research (see also 4.2.3) and the ambition of ITER for international cooperation (see also 4.2.2 and 4.3.1). The emphasis of the machines may also be regarded as a sort of “fetishism” that attaches great meaning to a physical object (Hornborg, 2001).

The machines are also expected to deliver crucial results for further development: from ITER to DEMO and, finally, towards commercial fusion power plants. In this sense, ITER and DEMO are depicted as “obligatory passage points” (Callon, 1984) for fusion energy. In other words, without ITER and DEMO, fusion power would not be achieved. Therefore, ITER and DEMO are presented as essential elements for achieving fusion power.

The roadmap uses the machines as representative players in the evolution of fusion R&D. Such a view corresponds to the classic view of technology development that is often represented in a conceptual tool, such as the technology readiness level, that starts from research to development, deployment, and then operation (cf. Prinja, 2020). This trajectory creates a narrative of a smooth transition from basic research to ITER, DEMO, and then fusion energy. The paragraph from the long version clearly shows the transition:

> *“The evolution of the fusion programme requires a shift “from pure research to designing, building and operating future facilities like ITER and DEMO”, as recognised by the Panel on Strategic Orientations of the Fusion Programme. This transition requires strengthening the available engineering resources, with a marked change from non-nuclear to nuclear technologies, and has to be facilitated by specific measures in support of training, development and education.”* (EUROfusion, 2018b, p. 47)

At the same time, the linear trajectory allocates the machines to a long-term timeline, retrospectively from the time when a commercial fusion power plant is achieved. This reflective character of the roadmap legitimises the current activities as integral to the development of fusion energy.

To follow the trajectory, the roadmap document also highlights the need for coordination. The following paragraph outlines the roadmap-setting process and the roadmap's roles among stakeholders.

> *“Achieving commercially viable fusion requires a substantial amount of coordinated resources deployed at a European level over a long period of time.* ***In order to structure the required effort, a roadmap to fusion energy was developed and agreed upon by the fusion stakeholders****.* ***This roadmap forms the basis for the programmes of EUROfusion and Fusion for Energy. It provides a clear and structured way forward to commercial electricity from fusion.*** *The rate of progress depends on various critical technical milestones and on the resources available.”* (EUROfusion, 2018a, p. 11) (emphasis added)

This shows that the roadmap concisely represents the key stakeholders’ perspectives on the European fusion programme. At the same time, this paragraph shows that the roadmap itself has a performative role in the European fusion programme. The document is legitimate due to its development process and stakeholder approval. The imprint shows the detailed process as follows:

> *“In 2018* ***the European Fusion Community*** *finalised the ‘European Roadmap to the Realisation of Fusion Energy’ which outlines the steps to the realisation of fusion electricity. The same year* ***the EUROfusion General Assembly*** *approved the document. Additionally,* ***the Euratom Scientific and Technical Committee*** *reviewed the roadmap and supported it with a positive opinion paper.* ***The Governing Board of Fusion for Energy*** *welcomed the initiative, which is in line with* ***the European Council*** *conclusions of April 12th 2018.”* (EUROfusion, 2018a, p. 22) (emphasis added)

Both the long and short versions of the document are available on the EUROfusion website, ensuring accountability, transparency, and openness. A. J. H. Donné, the EUROfusion manager at the time, also reproduced the same content in an open-access academic journal, thereby communicating the roadmap to a wider audience in a scientifically rigorous medium (2019). The document, with its legitimacy and credibility, streamlines the different stakeholders’ interests and perspectives into a single, consistent framework. Phaal et al. emphasise the role of roadmapping: “Technology roadmapping represents a powerful technique for supporting technology management and planning, especially for exploring and communicating the dynamic linkages between technological resources, organisational objectives and the changing environment” (2004, p. 9). The roadmap, therefore, includes powerful statements as well. For example, the roadmap confirms the confidence and strong agenda towards the European fusion community: “Europe has a leading position in the international fusion research community and has developed expertise in all relevant areas, so it is well placed to implement the roadmap” (EUROfusion, 2018a, p. 18). Also, the roadmap implicitly pressures the funders to secure resource allocation: “The present roadmap relies on the assumption that adequate resources will be made available, both by the European Commission and the national research programmes”, including support for decisions on some programmes and facilities (EUROfusion, 2018b, p. 57). It also calls for industry involvement in DEMO design phases, with a view to the realisation of a fusion power plant. These statements in the roadmap define the European fusion community's position and mobilise actors in a particular way. The short version of the roadmap concludes the document with ambition, expectation, and promise.

> *"The ambition is high. The rate of progress and success will all depend on the resources and stakeholder support, and the increasing engagement of and innovation in industry.* ***With strong support it is expected that fusion electricity can be generated in Europe early in the second half of this century, leading to the introduction of commercial fusion power plants as part of a future energy mix.*** *"* (EUROfusion, 2018a, p. 18) (emphasis added)

This also aligns with the narrative of the EUROfusion researcher/officer.

> *"Now,* ***even if you extrapolate wind and solar so they will always be intermittent****. So, either you need to have perfect storage which compensates for the day-night rhythm, but also the seasonal variation. And if you just extrapolate how much batteries you need, you don't have that material. So even for only a country like the US. I've seen extrapolations that the world supply in lithium is not enough for only the US. So, we never can resolve that in Germany. Now there's Germany spending two gigawatts electric on average sloshing energy because of the intermittency they continuously need to switch the electricity in different directions, cost two gigawatt electric on average.* ***So, to really add to, I think renewables is good, we need renewables, but we need additionally baseload electricity.*** *And* ***the only CO2 free forms of baseload electricity are hydro, are nuclear fission and nuclear fusion. So, we need nuclear fusion.*** *Of course, if we go for nuclear fission, for SMRs and that's great, that's very good. Of course, fission has the waste problem and* ***the waste problem in fusion is much more benign****.* ***Fusion has a longer development path. But I still think as soon as we make fusion to work it will slowly start replacing fission****.* ***Fusion will not replace renewables. So, fusion will come in addition to renewables, but we need them.*** *"*[22]

This narrative of fusion's advantages and potential highlights what Mehnert clarifies about technofutures, drawing on Nordmann's "if-and-then" causal structure (Nordmann, 2007, in Mehnert, 2024). He sees this causal structure as consequentialist thinking, as such, "(t)his structure suggests a function of an emerging technology ("if") and continues with a positive or negative consequence that demands attention ("then")" (Mehnert, 2024, p. 133). In this case, if there are resources, stakeholder support, and increasing engagement and innovation in industry, then fusion electricity can be generated in Europe early in the second half of this century (and can be introduced as part of a future energy mix). These last sentences crystallise a *Leitbild* that is "a general ideal or vision of a desirable future moment associated with the means of technology, a family of technologies or a technical system" (Dierkes et al., 1996, p.18, in Mehnert, 2024, p. 141). More precisely, the *Leitbild* of fusion energy in this document is

[22] Interview with the EUROfusion researcher/officer

that 1) fusion electricity will be available in Europe early in the second half of this century and 2) a commercial fusion power plant will be introduced as part of a future energy mix. This *Leitbild* is "intentionally guiding the development process of an emerging technology" (Mambrey et al., 1995, Dierkes et al., 1996, in Mehnert, 2024, p. 141). With credibility and legitimacy, the EUROfusion roadmap serves as a guide to the long-term, uncertain technofuture of nuclear fusion energy. The interview with the EUROfusion researcher/officer also acknowledged the roadmap's importance.

> Interviewer: *"What would be the most important document for fusion to accelerate the research. Do you have any official documents?"*
>
> Interviewee: *"Well, at the moment I would say* ***the roadmap is kind of our bible, and still we are working with the 2018 roadmap."*** (emphasis added)

Yet by the time of the interview (2023), the roadmap had become outdated due to several problems that had caused at least a few years' delay in ITER construction. The interviewee mentioned plans to update the roadmap in light of the delays. The interviewee continues:

> *"**We are now discussing how we are going to change that** [the roadmap], but this is a slow process in the sense that we have to wait for ITER* ***because I could publish a new roadmap tomorrow in a sense, but then I have to change it again as soon as ITER comes out with the new time schedule****. […] So, we basically know more or less what we want and what we need to do* ***but just putting it then on paper is like you do at some moments, which are well strategic in time."*** (emphasis added)

The established roadmap provides guidance to stakeholders on future goals and their trajectory, mobilising resources, information, and emotion. However, roadmaps are subject to drastic changes based on updates. Along with progress since the Fusion Roadmap in 2012 (European Fusion Development Agreement, 2012), the roadmap notes on adaptation and amendment.

> "*This document has to be seen as* ***a living document****, with updates and reviews to be performed at appropriate times, based on strategic events. Reviews that are considered mandatory are listed below.* ***A review of the roadmap should be undertaken in the first half of the next decade****, this mainly to assess (1) the progress in the ITER project, (2) the situation on alternative exhaust configurations, (3) the outcome of the pre-Conceptual Design Activity of DEMO, including R&D results, (4) the status and the plans of the Early Neutron Source. Connected to this, it would be timely to have another facility review to decide on the most important supporting facilities once ITER is in operation.*" (EUROfusion, 2018b, p. 57) (emphasis added)

While the finalised and published roadmap provides a solid basis for the entire programme, it can be changed over time in response to other factors. Plans projected in the roadmap are not always reflected in actual activities. As the later section (see 4.4.1) shows, ITER has faced challenges since the project's inception. Therefore, the roadmap that highlights ITER as a critical point for fusion energy is now at risk of not achieving its original course. The later sections (4.4.2 and 4.4.3) focus in particular on how promises, once established, may be amended or adopted in light of changes.

4.3.4. Conclusion

This chapter has shown constructive material-discursive practices in ITER framed by a new materialist account. The three sections have provided diverse and dynamic aspects of how ITER has been formulated through political, representational, and material practices, all of which are intertwined. It started with the negotiation of site setting and member contributions (4.3.1), in which the physical presence of the machine and material elements plays a key role in decision-making and project development. That shows a different angle from the peaceful and harmonious international collaboration observed in 4.2.2. The second section (4.3.2) showcases contrasting representations of ITER. On the one hand, analogies with the sun and stars are often utilised to evoke fascination with the project's high technology and ambition. On the other hand, very material and physical objects are presented in the foreground, using immersive technology in a virtual tour with virtual reality and dynamic drone video. The assemblage of physical objects and their processes is presented as a fascination and materialisation of the international endeavour to achieve fusion energy. Lastly, analysis of the EUROfusion roadmap has identified a delicate mechanism to bridge the past, present, and future of fusion R&D (4.3.3). The roadmap has provided legitimate, credible consistency in European fusion R&D, with a continued path towards a successful future with fusion electricity. The document serves as a "bible" for stakeholders to align visions and expectations and to establish the imperative to secure support and resources. At the same time, the document is subject to amendment and adaptation for flexibility.

All the sections in this chapter highlight essential elements of a justificatory narrative for ITER. Firstly, as the long-term construction continues, the construction process itself has become a justificatory practice. Instead of Niccolo Machiavelli's famous saying of "The end justifies the means", one can say "The means justify the end" or "The means justify the means" for ITER's justificatory practices. The activities and actions are important from the design phase through operation, DEMOs, and commercial fusion reactors after ITER. Therefore, in a sense, ITER is already playing an important role in many areas, including international collaboration, Members' R&D, spin-offs, and more. Justificatory narratives and practices may emphasise and formulate some elements. Secondly, justificatory narratives and practices may be mythical or fictional rather than rational. This corresponds to what Beckert and Bronk argue: "narrative economics" and a theory of fictional expectation (2019). An analogy of the sun and stars with nuclear fusion, sci-fi-inspired representations of machinery, and a roadmapping exercise create emotional engagement as well as political and economic involvement in the project. Once (re-)enchantment of the technology (Anshelm, 2010) succeeds, the crafted imaginaries, narratives, and expectations mobilise resources with a degree of self-enforcement. Legitimisation and justification of the project acknowledge the past, present, and future through complex, diverse methods.

4.4. Reworking ITER

The last chapter has investigated practices and narratives in and for the construction of ITER. The diverse material-discursive practices show that the justification of the project is delicately inscribed before and during construction and reinforced during the processes.

However, there are always issues and challenges during projects: almost no project can succeed perfectly as planned. Interestingly, a physicist and former chair of the ITER Council, Robert Aymar, acknowledged that "Over a hundred people designed the detailed plans of the machine from 1994 to 2001, but only a small number of them joined the ITER Organization" in a conversation with Claessens (Claessens, 2023, pp. 119–120). Discontinuing personnel may create gaps and difficulties in implementing the plan during construction.

Additionally, ITER is renowned for its troubles, constant delays, and increasing budget. One of the most important aspects of the project now is to sustain its existence and presence. This mega-technoscientific project is perhaps too big to stop without exploiting the promised outcomes. Since the project has been running for about two decades, or four decades if counted from the initial conversation between Gorbachev and Reagan, it requires careful maintenance and repair, both materially and discursively. STS scholarship has formulated a field of maintenance and repair studies that addresses practices of "invisible", "dirty", "care" work that are often "taken-for-granted" (Denis et al., 2015). Denis et al. summarise that the interactionist approach in STS (actor-network theory, new materialism, ethnomethodology, etc.) has revealed the importance of maintenance and repair practices, which challenge the widespread image of innovation that always creates new things (2015). The authors emphasise the complex, continuous, and creative process of maintenance and repair:

> *"Most designers limit themselves to assembling elements that already exist, rarely introducing new elements. They verify or produce interoperability among the elements driven to converge in a new device, and their job is characterized by an extended use of the tools, infrastructures, and materials at hand. [...] Therefore, repair is at the heart of a continuous process that includes patching up, reconfiguring, interpolating, and reassembling settings from previous forms of existence."* (Denis et al., 2015, p. 9)

While Denis et al. focus on the maintenance and repair of physical and material entities, this chapter also includes discourses and narratives. As stated earlier (see 2.7), this thesis intentionally treats discursive and material practices as inseparable. That means that this chapter covers technical issues and repairs, as well as the maintenance and rearrangement of justificatory practices in the entanglement with materiality.

4.4.1. Fragilities, Failures, and Delays

During the ITER guided tour, I was unable to enter the assembly hall. The guide told me the reason: the assembling process is at "a critical moment", so even "a millimetre gap can cause trouble"[23]. The audience, including myself, was disappointed that they could not see the most spectacular sight of the ITER, also the "core" of the project: the fusion reactor. This restriction also highlights the technology's fragility, as the machine requires meticulous attention to detail; Otherwise, it would not work. To some extent, it gives a different impression from the simplicity of fusion as seen in the previous section (4.3.2). This section focuses on "instability", "potential failures", and "fragility" (Denis et al., 2015, p. 7) of ITER to reveal dynamic relationships between sociomaterial practices and justificatory narratives.

To articulate ITER's fragility, it is worth outlining the construction delays. In an article published in 2023, scientific journalist Seife ironically states that ITER could set "a new world record" without involving any scientific achievements:

> *"… ITER is on the verge of a record-setting disaster as accumulated schedule slips and budget overruns threaten to make it the most delayed—and most cost-inflated—science project in history."* (Seife, 2023)

The writer revealed the ballooned budget of ITER: the project started with an estimate of 5 billion euros in 2006 and then 20 billion euros in 2016, which was expected to grow even more (Seife, 2023). These persistent budget increases are due to project delays (see Figure 25). Claessens, who at the time was the head of the communications office at ITER, later became a whistleblower and criticised ITER for its budget increases and delays.

> *"Unsurprisingly, the project delays are already huge—the first experiments were initially scheduled to begin in 2016, now officially in 2025, and most probably in 2031. At its next meeting in November 2021, the ITER Council may only announce a 1-year additional delay (first plasma in 2026 instead of 2025) so as not to create a crisis. The total construction cost of ITER is now estimated at around 41 billion euros which means that the budget overruns amount to nearly 36 billion euros – which of course is passed along to the ITER members' citizens.* ***All these practices are unacceptable in a project funded by public money. The only explanation I found is that ITER is based on a political assumption—that fusion will soon become a commercial, safe and clean source of unlimited energy."*** (Claessens, 2022, p. 7) (emphasis added)

[23] From my fieldnote based on my ITER visit on March 16, 2023.

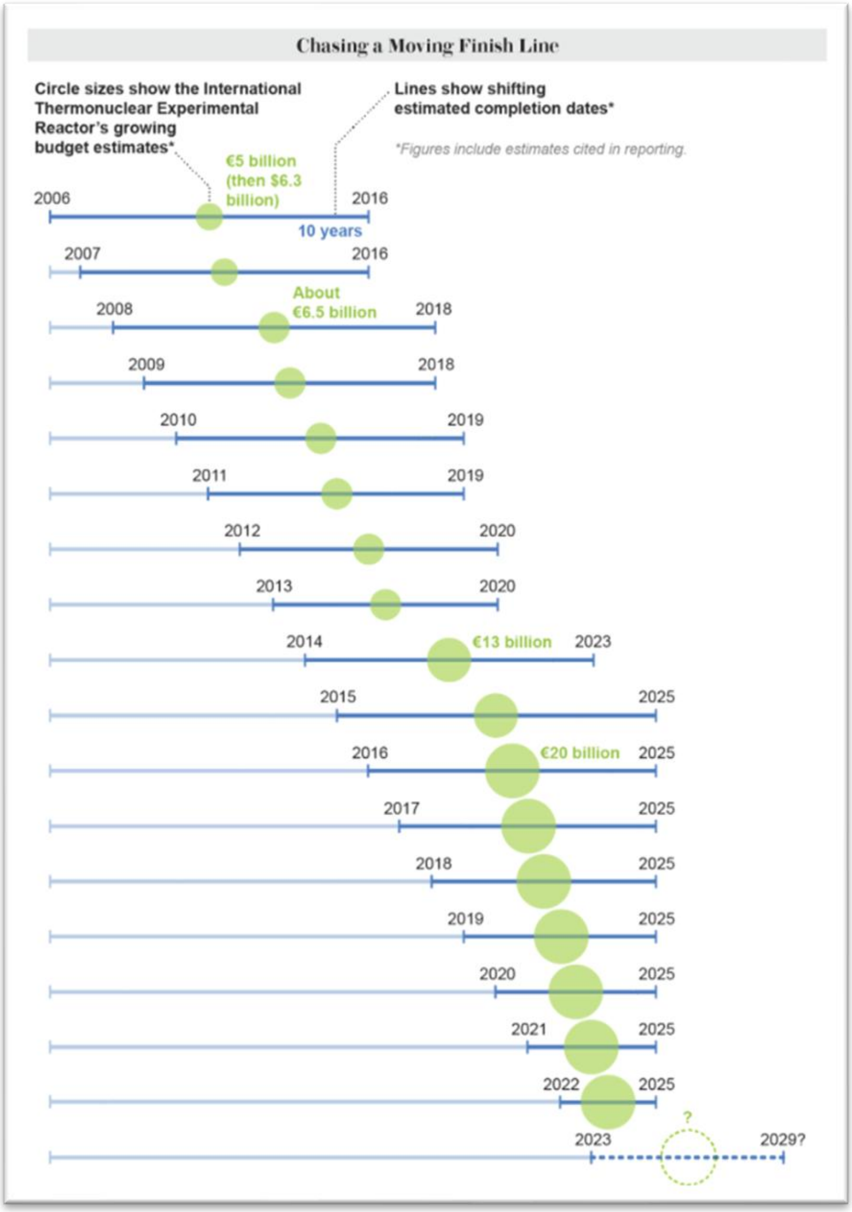


Figure 25: Construction of ITER: evolution of the timeline and overall budget (Credit: Amanda Montañez; Source: Charles Seife)

Claessens also argues that the exact total budget increase is unclear because ITER members do not disclose the exact cost of in-kind contributions, which account for nearly 90% of the total budget (Claessens, 2023, p. 120). In any case, at least an 800% increase in budget and delays of more than 10 years for the first experiments (see later for how the goals have been adopted over the years) are often criticised by the media and stakeholders. For example, in 2023, a member of European Parliament, Christian Ehler strongly signalled the necessity of clear communication of the project to the leaders of the ITER project, F4E, and the director general of the Commission's directorate for energy in a hearing in the Parliament's industry and research committee: "It's high time for […] a communication on fusion, because otherwise the project stays obscure, not well understood, [and] complex"; "If you want to have this parliament, as courageous as it had been in the past, ignoring all its own internal rules on budget control and on a lot of things, I think you have to put that in political proportion. Otherwise, we reduce [ITER] as a budget problem, and that doesn't make you survive" (Zubașcu, 2023). The demand for transparency regarding the publicly funded project is high, and the project's survival has also been called into question. After the discussion, in 2024, the EU policymakers decided to reduce funding for ITER by 120 million euros, affecting the EU contribution for the construction, operation, and exploitation of the ITER facilities managed by F4E (Naujokaitytė, 2023). This decision left a bitter taste in ITER's mouth, since the EU has the largest share of the project (see also 4.2.3 and 4.3.1).

To begin the discussion, it is worthwhile to investigate the reasons for ITER's persistent delays and budget increases. Both official explanations and insiders' perspectives (data from Claessens' work and interviews with the ITER Communication officer and EUROfusion researcher/officer) help to map out several issues. First, the ITER Organization has revealed one of the major issues causing a significant delay. The strong pushback on the physical and material significance has affected the modelled plan. The noted defects are about the key components: the thermal shields and the vacuum vessel sectors. Stress caused by bending and welding of the cooling fluid pipes to the thermal shield led to helium leaks on an element of the shield (see Figure 26) (ITER Organization, 2022). The article by the ITER Organisation highlights the reasons why the differences between modelling and actual construction have led to such defects.

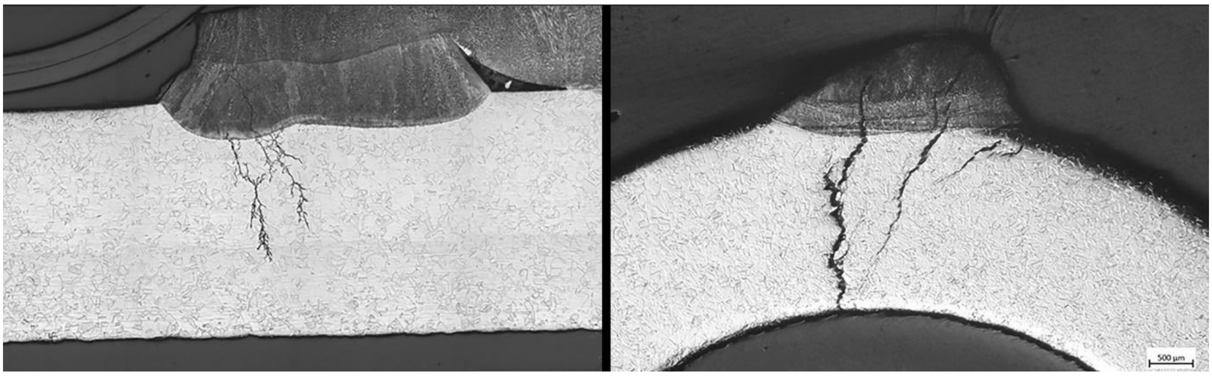


Figure 26: Cracks in thermal shield cooling pipes (ITER) (https://www.iter.org/newsline/-/3818)

> *"In ITER, as in many complex technological objects, fabrication is based on tri-dimensional computer-assisted blueprints.* ***In the ideal world of 3D design, a component's dimensions are by definition nominal and parts fit together like cogs and gears in a pricey wristwatch. In the real world of industry, however, things are different: deviations during the manufacturing process are inevitable and may lead to "non-conformities" that need to be addressed.*** *ITER,* ***like any industrial venture,*** *deals with such matters on a daily basis."* (ITER Organization, 2022) (emphasis added)

This narrative of "deviation" against "conformity" implies the issue's unexpectedness. This unexpected incident was caused by underestimating the material practices of welding and bending, which are the most common and oldest technical practices. In 3D models, these material practices are often ignored/underrepresented as something self-evident. However, these very mundane practices are invasive towards components, leading to a critical issue in the project. Materiality has played a key role in this incident. Even though "prototypes of key ITER components have been fabricated by industry and tested" (Smith & Cowley, 2010, p. 1102), components produced from a different technological setting create frictions in the assembling practice. Materiality is an essential aspect of technology that emerges especially when defects or failures occur (Bille, 2022).

The narrative of the ITER Organization's report on the website compares ITER to wristwatch manufacturing and to an industrial venture; the ideal world is the precision of wristwatch making, and the reality is a challenging, risky trial-and-error process, as in an industrial venture. This comparison tries to justify the technical difficulties and the resulting delay. In addition, the comparison between ITER and industrial ventures adds a new perspective on justification against the failures[24]. In the practice of venture/start-ups, failure plays as a legitimising discourse to create a start-up culture, which positively admits the reality of a high rate of start-up failure: Failure in ventures is often associated with creativity and disruptiveness (Koskinen, 2025). ITER, on the other hand, is a publicly funded project that operates under a different investment model and orientation towards profit generation. The comparison with industry ventures invites venture logic into the project. By doing so, it creates more space for tolerance and acceptance of failure.

In addition to the technical issue ITER is facing, Claessens (2023, Chapter 8) articulates the three major issues that caused significant delays by the time of publication (first edition in 2019, second edition in 2023). First, certain steel bars in the central reinforcement area of the tokamak complex were noncompliant with French safety regulations. This led to additional reinforcement of certain parts, causing at least a 6-month delay. Second, F4E's negotiation and adjustment of the tender for poloidal magnets lasted over a year. Claessens sees this as a management issue rather than a technical issue, generated by a mismanaged public procurement process (2023, p. 116). Third, there was a miscommunication between F4E and the Indian domestic agency regarding the size of the cooling towers, leading to an urgent modification of the building plans. This issue was caused by the division of labour across different locations and manufacturers, leading to incoordination of functional interfaces. This issue also led to another 6-month delay.

These three technical and organisational issues are deeply embedded in the project structure itself: international collaboration, in-kind contributions, and massive-scale construction. The ITER Communication officer recalled his arrival at ITER in the middle 2010s when there were many issues that had arisen:

[24] I thank Prof. Ulrike Felt for pointing out this aspect in the review process.

"The ITER project at that time was doing quite poorly. A lot of the complexity of the project was showing up, and the complexity both of building the machine and also the arrangement of doing that by making components from 35 countries on three continents and putting them into one machine."[25]

As seen in the previous sections (4.3.1 and 4.3.2), components are produced in the members' facilities and transported by air, sea, rail, or road to Cadarache. This project structure adds more complexity than a more focused production would. Claessens also mentions that the complexities and difficulties of building the machine are an inherent part of the project, based on the technopolitical decisions:

"Another fundamental difficulty has to do with the way the project is organised and the work divided. This is particularly the case for the vacuum vessel, but it also applies to other essential elements such as the magnets. Six countries were involved in the manufacture of superconducting strands, some of which were tested in Switzerland. Production of the cables was then contractually guaranteed by nine companies worldwide. They had then to be transported to Italy, Japan or the United States so that the magnets could be manufactured. ***Although the process can break down at many places and at any time, the components must be identical irrespective of the place of manufacture****."* (Claessens, 2023, p. 119) (emphasis added)

The division of in-kind contributions is based on the project's technopolitical return rather than practicality. Yet most technological products, such as laptops and phones, have long, extensive supply chains. In contrast to industrial supply chains, the highly technopolitical decision imposes inefficiency in the project development process. At the same time, this often-mentioned narrative reemphasises the project's most unique selling point and identity of international cooperation (see 4.2.2 and 4.3.1). Yet, this project setting also causes difficulties for technical modifications.

"After the project started in 2007, difficulties quickly appeared as a result of scientists and engineers proposing modifications to certain elements to improve ITER's performance. However, in some cases modifying a component or a system necessitated changes in other parts of the machine, sometimes even in other buildings. The experts speak in these cases of ***"nonconformities****" or* ***"physical incompatibilities."*** *In some cases,* ***the departments concerned refused the changes for technical reasons****;* ***in others, the Domestic Agencies in charge declined to bear the additional costs refusing to take responsibility for these changes or corrections****.* ***As a consequence, the list of Project Change Requests awaiting decision has been steadily growing since construction started in 2010****. This explains a good part of the delays that have accumulated over the years."* (Claessens, 2023, p. 86) (emphasis added)

[25] Interview with the ITER Communication officer.

The two quotes above show various aspects of friction between planning and construction. First, the initial planning of contribution distributions did not sufficiently address the complex interrelationships among elements and the technical adjustments required. The project setting was based on the assumption that the technical instructions would be sufficient to produce (sometimes completely identical) components in different locations and to assemble them into a single piece at Cadarache. Production practice might be influenced by local standards, common sense, tacit knowledge, etc., which cannot always be covered by the instruction.

Second, the assumption of seamless transitions from planning to implementation has led to inflexibility within the management structure, which does not align with the actual technoscientific practices of constant adaptation and adjustment amid uncertainties. Scientific research, especially in rapidly evolving fields such as nuclear fusion, discovers new materials, processes, potential risks, or failures that might alter a plan. The complex assemblage encloses interlinked components which might cause "chain-reactions" of adjustments. An unexpected event, such as the earthquake and tsunami in 2011 in Japan alone, delayed the Japanese contribution by a year and therefore the project as a whole (Claessens, 2023, p. 115). As Kester (2018) notes, events such as COVID-19 and the 2011 disaster in Japan surface the vulnerability of the system, particularly material relevance in the project arrangement.

In addition, the complex project structure has created many "bottlenecks" for such changes. ITER's bureaucratic-technopolitical management system does not allow flexible adjustment and adaptation across domestic agencies and companies in response to technical and financial changes. Claessens notes the visibility of the political dimension when the responsibility for manufacturing two components of the vacuum chamber was proposed to be relocated from Europe to South Korea (2023, p. 140). To sum up, delays and failures are inherent in the very essential features of ITER: a long-term, large-scale project, an emerging field, and international collaboration.

The interview with the EUROfusion researcher/officer also confirms this and addresses the consequences of the COVID-19 pandemic from 2020 to 2022.

> *"ITER is experiencing significant delays which are partly well, I think* ***partly due to the fact the way ITER has been set up****. Also,* ***the political compromises*** *which have been made in setting it up has led to delays. But also more recently,* ***COVID has not helped*** *because during COVID, it was* ***impossible to, for instance, go to the manufacturers to have proper quality assurance****. What happened is that* ***some components were delivered which are not conform the requirements*** *and these are* ***really big components like pieces of the vacuum vessel which now have to be modified and changed****. And this is giving certainly a number of years of delay."*[26] (emphasis added)

[26] Interview with the EUROfusion researcher/officer

While another interviewee from the ITER Organization Communication Office separately addressed the COVID-19 pandemic from technical issues – indeed, there were some factory shutdowns, etc.–, the pandemic's influence can be seen not as a separate problem but as a revelation of the vulnerability of ITER's project setting. The interviewee's note on quality assurance indicates that ITER's process for ensuring that components meet the same standards relies heavily on the international mobility of certifiers and international communication. ITER's widely distributed supply chains and multi-agency organisational structure have made it difficult to manage COVID-19-related issues.

A quote from the interview with the EUROfusion researcher/officer may conclude the discussion of the management structure and construction process that burdens the project's progress. Speaking of the DEMO, this person reflected on ITER's project setup.

> *"Well, if you really set up an aggressive program and this is a challenge because at the one end* ***you have to deal with politicians*** *which see the enormous delays in ITER, which see the cost rise in ITER because of the delay. And you need to go to the you know, "I have a brilliant idea to build this fusion reactor, but* ***we need to do it as a Manhattan-type project****".* ***My own conviction is that we can build the demonstration reactor for less cost than the ITER project cost. Now, if we set it up in a clever way so don't try to set it up in the same way as ITER but build DEMO.****"*[27] (emphasis added)

The interviewee highlights the difficulties originating from the project's distributed structure. DEMO, the next step from ITER, is expected to be built by each member at their location. A bitter lesson from ITER is that technopolitical collaboration can burden the process if not properly set up. The reference, "Manhattan Project", was indeed a top-secret national project to produce a nuclear weapon for the Second World War in a highly concentrated supply chain. And ironically, this mention of the Manhattan Project contradicts ITER's official narrative of international collaboration with shared knowledge for the peaceful use of nuclear technology.

At the end of this section, note that the ITER community's reactions to the delays and budget increase are surprisingly defensive and rather optimistic. That is because fusion's long-term energy potential differs from that of other energy sources, such as fossil fuels, nuclear fission, and renewables.

> Interviewer: *"How would you say to the opponents, especially some people say it's quite expensive, and there are alternative options like renewables, and also there's a development for small modular fission reactors. How would you situate nuclear fusion in this kind of picture?"*
>
> Interviewee: *"Well, about the cost, I just read yesterday an article which basically stated on* ***the world level the subsidies going into fossil fuels are €13 million per minute - per minute! - so it's really giant.*** *In Europe alone, the subsidies for fossil fuels – and we want to get rid of fossil*

[27] Interview with the EUROfusion researcher/officer

> *fuels – are 52 billion per year Europe-wide. The subsidies in Germany, where I live, for renewables are 30 billion per year. So, Germany has been subsidising renewables since 2011, since Fukushima, when they started this so-called Energiewende. And the CO2 emission by electricity generation in Germany is still the same as it was in 2011, even though they reach now a state where about 40, 50% of the energy comes from renewables. And the reason why it didn't affect the CO2 is, first of all, they got rid of all their nuclear. They stopped all the nuclear plants, which is kind of stupid, really stupid because nuclear plants are climate friendly, they don't produce any CO2, and instead of the nuclear plants, they have been using coal plants. So,* ***Germany has increased the coal uses because to compensate for the intermittent character of wind and solar****."*[28] (emphasis added)

The interviewee contrasts nuclear energy with fossil fuels and renewables in terms of subsidy size and climate effects. This argument relativises the ITER budget by comparing it with the huge subsidies for fossil fuels and renewables. Still, it is not necessarily comparable between the early stages of R&D in fusion and already existing solutions. However, the comparison also implies the potential for fusion to replace fossil fuels or fission as a baseload energy source, as the interviewee noted.

Budget allocation is a political choice. What is often emphasised in nuclear fusion discourse is the value of nuclear fusion within the bigger context of finance and, moreover, in "civilisation". Claessens' quote is an obvious example of the financial justification of ITER:

> "*Daniel Allen, an executive manager of several investment funds, confessed that he didn't understand why ITER's budget has created so many issues.* ***For a technology that could revolutionise the future and change the course of civilisation, EUR20 billion, EUR30 billion or even EUR40 billion are, he said, "peanuts."*** *Just compare that with the financial exchanges taking place every day and the amounts invested in some projects that clearly do not warrant the investment.* ***For example, the European contribution to ITER, which was valued at EUR 6.6 billion up to 2020, equalled the fine paid in 2013 by the French bank BNP Paribas to the US justice for unauthorised financial transactions. The estimated cost of ITER is about 1% of the civil research budget of its members****. Is it too much? Or not enough? What do you think? In any case, the decision to build ITER was a political one.*" (Claessens, 2023, p. 126)

This quote compares the ITER budget with other financial issues. Although Claessens himself does not take a clear stance on these comparisons, the comparisons themselves are a rebuttal to the criticism of the ITER budget. Yet public investment in a specific machine is not necessarily comparable to overall financial exchange, a bank's fine, or the entire civil research budget. Still, comparisons make statements.

[28] Interview with the EUROfusion researcher/officer

This section has explored fragilities, failures, and delays in the ITER project over the decades. ITER has faced many challenges throughout the process, from technical to political. Taking a closer look at the challenges helps investigate ITER's core characteristics. Also, as challenges are always a part of technoscience, it is noteworthy to reveal how actors cope with them. The next section investigates the dynamics of coping strategies in response to the challenges.

4.4.2. Aligning Visions and Promises

The previous section has explored fragilities, failures, and delays as consequences of material backlash as well as management and organisational issues, reflecting the core of the project setting. The project's continuous delays and increased budget over the decades since its start have been criticised by politicians, the media, and insiders, as mentioned above. This section examines how ITER has legitimised its activities despite the delays and budget increases. Particularly, this section focuses on project management and its representations.

One of the most relevant actors in this issue is the ITER Research Plan – or, more commonly, "ITER Baseline". The latest version of the document – the associated version of the 2016 baseline – is a more than 300-page detailed technical plan "to provide a guide to the overall program of research activities to be undertaken within the framework of the ITER Project and to develop a strategy towards the attainment of the level of physics and technology performance required to meet the ITER mission goals" (Campbell et al., 2024, p. 10). Sometimes, the baseline is also presented as a "scenario" that "describes the present vision for operating the ITER Tokamak" (ITER Organization, 2018). The document was developed in collaboration with the ITER Organization, domestic agencies, and experts (Campbell et al., 2024, p. 13). The official 2024 baseline has not been published on the ITER website to date, while many academic and non-academic publications have been published (Barabaschi et al., 2025; Coblentz, 2024b; Loarte et al., 2025).

The baseline document, however, has been drastically updated several times since the project began. Parry's (2017) briefing for the European Parliament outlines the evolution of the baselines. The ITER Agreement, concluded in 2006, was based on a 2001 baseline in which the participating members projected that constructing the facility would require €5.9 billion (in 2008 prices) over roughly a decade, with "the first plasma" — marking the transition from construction to operation — anticipated for 2016. Following the signing of the agreement, however, a comprehensive design review completed in June 2008 substantially revised these initial projections. Considering new scientific and technical developments, unexpectedly rapid increases in the cost of key raw materials, and administrative complexities arising from a larger-than-envisioned number of participating parties, the revised estimate placed total costs at approximately €19 billion and shifted the expected first plasma date to 2019. Subsequent delays and additional cost overruns — attributed by the ITER Organisation to management challenges and the unprecedented technical complexity of a project involving numerous "first-of-a-kind" components — further undermined the 2008 forecast. Consequently, on 27 April 2016, the ITER Council endorsed a new assessment that laid the foundation for an updated baseline, increasing the projected cost to around €20 billion and postponing first plasma once again, this time to 2025 (Parry, 2017, p. 7). The promises of this 2016 baseline were not met either.

These constant updates of baselines may, to some extent, delegitimise the project. The fact that the project has not delivered on its baseline promises leads to mistrust of the project management. A report of the ITER management assessment in 2013 argues that "No project or its leadership can maintain credibility if it continually denies reality and repeats statements that are widely disavowed, even by its own staff. ITER's schedule has slipped so consistently year after year that almost no one, including MAT (management assessment team), believes the announced dates for first plasma (FP) or other key milestones will be met, and urges the management to "Develop, and then hold to, an 'achievable and realistic schedule' for ITER as soon as possible" (Madia & Associates, LLC, 2013, p. 11). Also, as cited before, a member of the European Parliament criticised the leaders of the ITER project and the director-general of the European Commission for the delays and organisational issues, saying, "I'm not going to present the baseline which is based on dreams" (Zubașcu, 2023). If plans do not align with the reality of achievement, technoscientific promises lose legitimacy and may be considered "dreams".

Based on the technical difficulties and further delays, the baseline was further revised and updated in 2024 with a new timeline and milestones, with an additional 5 billion euros (ITER Organization, 2024c). The new baseline reflects harsh criticism of the previous baselines and their failures, and emphasises feasibility through the "staged approach". As "behind-the-scenes" of this baseline, an interview with an ITER Communication officer conducted in 2023 revealed the strategic and political features of this document.

> *"We can't just say, here's our timeline,* ***we have to present it to the ITER Council, the oversight group, and they have to approve the associated budget and schedule.*** *[...] So, when I came here in 2015, we established this and it became known as* ***the 2016 baseline****. In that baseline, it said we would have four stages. First plasma, which would be the first turning the machine on, making sure it's functional, would occur in December 2025. And then we would have four stages, 2028, 2032, 2035. And in 2035, we would get to full fusion power, where we start doing all of the full deuterium tritium experiments. [...] Because of the problems we've had with technical challenges and COVID, and* ***we now have these delays****, we are assessing five major factors and* ***trying to come back with a new timeline****. ... we are looking at* ***how do we compress these four stages****, because why? Many of the support systems are now basically finished. So those are in commissioning. But the main central*

machine, the Tokamak, is where most of the delays are coming. And we have a lot of in the idea of the original four stages. At each stage, you would do more assembly with more components, do more testing, then more assembly, then more testing, then more assembly and the final stage. But a lot of those components are now arriving. ***So, we are changing. Instead of what we call first plasma, which didn't have a lot of scientific value, we will probably add more components than was originally planned*. *So, the first scientific campaign will be later, but higher value and closer to the end goal. So, we're trying to compress those stages.*** *"* (emphasis added)

This long quote shows the process of creating the document through the ITER Council's decision-making body. This governance process for the document creates consensus among the ITER members and lends it legitimacy because, as mentioned before, the ITER Council consists of the members' representatives. To receive approval from the Council and other stakeholders, the document has reformulated the timelines. The official press conference summary also explicitly mentions the relationships with the 2016 baseline:

> "*We could have retained the Baseline 2016 roadmap, but this would have been illogical — based on the availability of additional key components to construct a more complete machine. Therefore, the new baseline has been redesigned to prioritize the Start of Research Operations. It was important to make up for past delays, as much as possible, but above all to ensure that the causes of these delays were understood and corrected."* (Coblentz, 2024b, p. 2).

Until the 2016 baseline, the "first plasma" had always been presented as the first operation of ITER. However, the interviewee downplayed this event, calling it an activity "which didn't have a lot of scientific value". Instead, the press release for the new baseline introduced a term, "the Start of Research Operation (SRO)" (Barabaschi et al., 2025; Coblentz, 2024b; Loarte et al., 2025), which implied "higher value and closer to the end goal" as the first operation of the machine. This narrative is well coordinated among the ITER communication, management, and research departments, as seen on the ITER website and in academic literature by ITER personnel and scientists. Barabaschi et al. define the SRO phase to "largely demonstrate the integration of systems needed for industrial-scale fusion operations" (Barabaschi et al., 2025, p. 1) starting with "the demonstration of the first tokamak plasma" and "concluding with the demonstration of tokamak operation up to the nominal design parameters of 15 MA / 5.3 T in a diverted plasma configuration, including the use of the electron cyclotron (EC) and ion cyclotron (IC) heating and current drive (H&CD)" in the time duration of 27 months (Barabaschi et al., 2025, p. 3). The SRO includes DD (Deuterium-Deuterium) plasma and is followed by two phases of DT (Deuterium-Tritium) operations. This change to a stepwise approach, they argue, reduces technical uncertainties (e.g., "dust formation", "tritium retention", etc.) and ensures safety before proceeding to the full demonstrations (Barabaschi et al., 2025). In summary, they argue:

> "*Whereas the 2016 baseline envisioned a "First Plasma" in 2025, as a brief, low-energy machine test (**relatively low scientific value**) leading to full plasma current in 2033, the new schedule targets **a full field demonstration without plasma in 2034** followed by 27 months of substantive research operations. During this phase, ITER will operate the machine in pulses with several tens of seconds at full magnetic energy and plasma current, **mitigating operational risk** and **substantially preparing for deuterium-tritium (DT) operations**.*" (Barabaschi et al., 2025, p. 13). (emphasis added)

Indeed, in the 2024 baseline, the "first plasma" is not used as a "milestone" but is instead reformulated within the SRO, with a different machine configuration closer to Fusion Power Operation (FPO)/D-T operations. To summarise, the term SRO can be understood as the material-discursive reformulation that surrounds the new baseline. Figure 27 shows the detailed adjustments and reformulations from the 2016 baseline to the 2024 baseline.

Barabaschi et al. argue the logic behind this substantial change of the plan: "The new baseline schedule has been redesigned to prioritise SRO, making up for past delays on several key components and installation activities, to introduce risk-reducing components and start operation with a more complete machine" (2025, p. 13). And therefore, "the new baseline is a more robust way to achieve ITER's performance goals" (Coblentz, 2024b, p. 2). Reflecting the criticism towards the delays and overall management, the new baseline is presented as a realistic and convincing plan for ITER.

The baseline reformulation emphasises accounting for the past delays. To accommodate the schedules, the project term "milestone" serves as a reference point. The comparison between the 2016 and 2024 baselines is presented side by side (Figure 28). Some milestones are delayed by 3-9 years, while the DD operation is planned to occur earlier than the 2016 baseline. In total, the full operation,

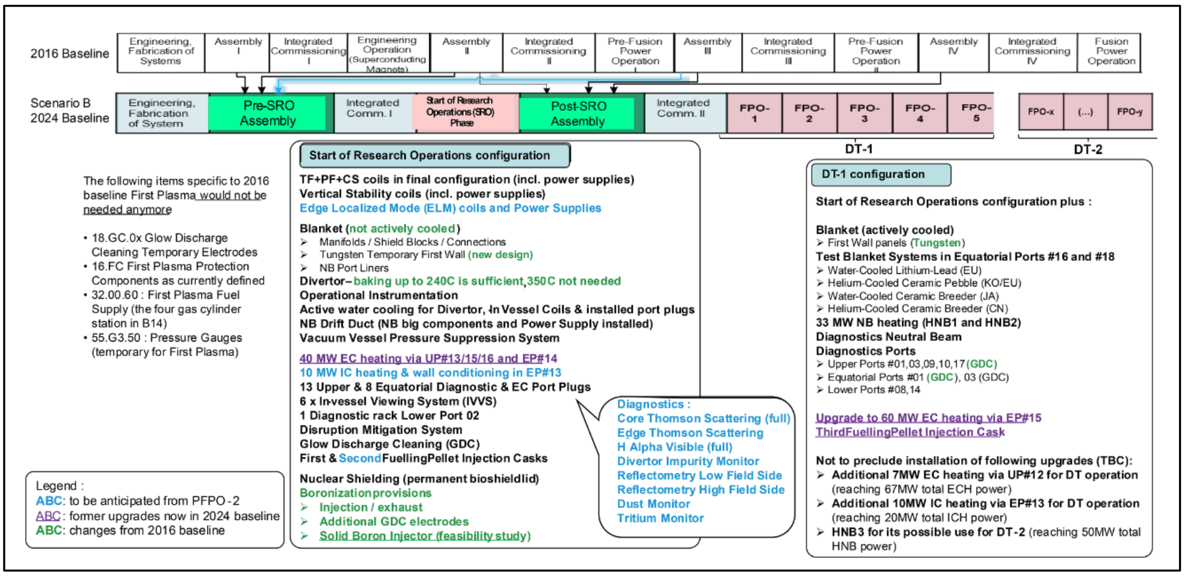


Figure 27:Configuration of Systems for SRO with a focus on the differences against 2016 baseline PFPO-1 configuration.(Barabaschi et al., 2025, p.10)

Milestone	Original Baseline (2016)	New Baseline (2024)
Cryostat Closure	Dec-24	Mar-33
Divertor Plasma	Mar-29	Dec-34
Full Magnetic Energy (field and plasma current)	Jun-33	Q3–36
DD Operation	Jan-36	Q3–35
Start FPO-1 / DT-1	Dec-35	Q3–39

Figure 28: Key milestone comparison between 2016 and 2024 baselines (Barabaschi et al. 2025, p.12)

FPO (Fusion Power Operation) or DT, is about 4 years delayed. In the end, the DD operation, one of the most "scientifically important" operations, will catch up from the 2016 baseline, while the delay for the first FPO will be minimised.

The reformulation of project plans depicts the crucial role of (re)presentation in the project. It is intended to show the credibility of the management and the legitimacy of the project plans. The new baseline is constructed to convince stakeholders while mobilising internal and external actors to act in a coordinated way. Making and reformulating the baseline are therefore essential material-discursive practices for recreating stability and legitimacy in the ongoing construction of ITER.

As seen in the baseline documents and interviews, the notion of "milestone" plays a key role in the plans. While ITER baselines are over 300-page technical documents with scientific and technical details, the milestones within them serve as understandable reference points for stakeholders. Milestones are ubiquitous in the baseline documents with decorative words; technical milestones are often described as "specified operational milestones", "specific scientific and technical milestones" or "performance milestones", while important milestones for the project are emphasised as "major milestones", "key milestones", "outstanding milestones", "significant milestones" (Campbell et al., 2024). The ITER website also visually presents milestones in an interactive format. Those milestones on the website necessarily correspond to the ones in the baseline. Rather, those are remarkable activities such as "US delivers fifth control solenoid module" (ITER Organization, n.d.-e). The linear presentations of milestones, metaphorically represented as a road, "On the Road to ITER", show the project's temporal dimension: from the past towards the future (Figure 29). As the project runs over the long term, envisioning and presenting progress concisely is a performative act that legitimises it.

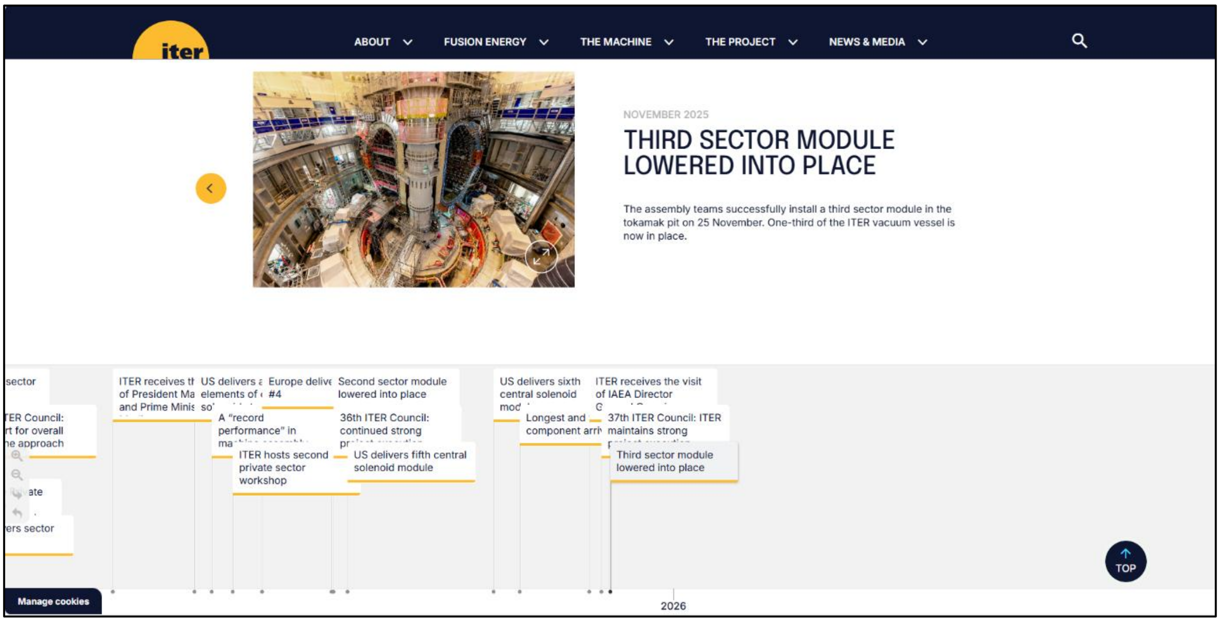


Figure 29: "On the Road to ITER" (screenshot: https://www.iter.org/proj/ITERMilestones) (retrieved on 3 January 2026)

In comparison to milestones, the notion of breakthroughs (Nowotny & Felt, 2002) emphasises achievements. Brown argues that "The 'breakthrough' motif today serves as one of the most pervasive temporal abstractions for describing key events in science and medicine" (2000, p. 87). This notion is often used in nuclear fusion research and development, as in ITER. The interviewee from the ITER Communication Office used the concept to describe achievements that overcame technical difficulties.

> "*They had to **invent new technology**. Now, the good part of that is that each of the governments has committed some of their **most advanced companies**. So, in Korea's case, that would be Hyundai Heavy Industries. For example, in Japan, it's Mitsubishi. In the US. It's General Atomics. You have **many major, major companies who are working on these breakthroughs**.*"[29] (emphasis added)

Here, the interviewee states that breakthroughs are "inventions" that solve problems and advance the project. The interviewee cites the contributions of major, advanced companies as the key factor in the development of new technologies. Breakthroughs, as the word's literal meaning suggests, imply sudden, dramatic discoveries or developments that bypass and accelerate projects. This notion creates the project's disruptiveness, emphasising novelty.

In the media, the notion of a breakthrough is more prominent. For example, the recent news of JET's world record of 59 megajoules of sustained fusion over five seconds drew attention and was applauded as a breakthrough toward fusion energy (Amos, 2022). This world record was also presented as the bridge to the far future of nuclear fusion. The EUROfusion website writes: "Record JET results announced in February 2022 were the clearest demonstration worldwide of the potential for fusion energy to deliver safe and sustainable low-carbon energy in the future" (EUROfusion, 2022).

[29] Interview with the ITER Communication officer

Breakthroughs are associated with hopes, dreams, and promises. Regarding JET's record, the EUROfusion officer/researcher was careful about pursuing scientific records.

> *"Because still, after the last DT (Deuterium-Tritium) campaign, there's some gaps in the science and technology database which we want to fill. Because at the end of this year, we stopped with JET.* ***And for us, it's more important to understand the physics thoroughly than trying to push for another record****. So, we are not going to push for another record. I don't completely exclude it. We try still to see how far we can get in the end.* ***But it's not the aim. It depends also how the progress is during the campaign whether, let's say, we have enough time. I think certainly ITER will go further****."*[30]

The scientific data from JET are used to inform ITER's experiments. Because JET has only "old-fashioned"[31] copper coil, it cannot handle a fusion reaction for more than five seconds. Rather than "pushing for" another record, the interviewee considers the scientific data for ITER more important. Data from JT60-SA in Naka, Japan, which uses a superconducting tokamak similar to ITER, would complement ITER's performance. This interviewee highlights the difference between media representations of achievements and research priorities. Similarly, the interviewee remarks on the difference between a breakthrough and a milestone:

> Interviewer: *"Do you see any breakthrough for recent (R&D in fusion)? I remember JET was reaching the fusion for some seconds. What is a recent breakthrough in your prospective?"*
> Interviewee: *"Yeah,* ***I wouldn't call that a breakthrough, because a breakthrough is something you discover very unexpectedly****. So,* ***we have been planning for, let's say operating JET with DT for many years and we finally achieved it****. So,* ***it's more like a milestone*** *which we received very much like the results at NIF in America. They have been working for many years, and they finally reached it so."*[32] (emphasis added)

This response suggests that the framing of achievements is both political and performative. The use of "milestone" conveys a sense of planned and orderly scientific progress, in contrast to the unpredictability associated with "breakthrough." The distinction between these terms shows how fusion researchers and communicators actively shape the temporal dimension of project development. By rejecting the idea of breakthroughs as sudden discoveries, the interviewee reframes achievements as incremental and carefully managed, thereby reinforcing the credibility and legitimacy of the long-term project. In doing so, this narrative sets ITER apart from hype-driven media discourse and emphasises controlled progress. Milestones, therefore, function not only as technical markers but also as justificatory devices that help sustain technoscientific promises under conditions of uncertainty.

[30] Interview with the EUROfusion researcher/officer
[31] Interview with the EUROfusion researcher/officer
[32] Interview with the EUROfusion researcher/officer

The plans, with a set of milestones to justify the project, can, however, also cause friction in research agenda-setting, such as the EUROfusion roadmap. The following shows how the reformulation of the baseline forces translations and adaptations. As noted earlier (see 4.2.3), the EU has been a major contributor to ITER, making the research body EUROfusion an integral part of ITER development. Consequently, the EUROfusion roadmap (see 4.3.3) aligns with ITER's overall development plans. Yet, the changes in the ITER baseline cause friction between ITER and EUROfusion. The interview conducted in 2023 shows the tensions before the publication of the 2024 ITER baseline:

> *"Yeah, we still have a roadmap.* ***Presently, we are considering how to adapt a roadmap because, on the one hand, we want to give the fullest support of ITER, and of course, the difficulty in drafting a roadmap is that you would like to have the time schedule of ITER****. And the ITER team says, well, we have, let's say, our new time schedule by the end of next year, because it takes quite some time to figure out how they are going to repair the components.* ***This means that we are thinking of how to adapt****.* ***One of the aims we have is we don't want to delay the time to fusion electricity. So, this means for DEMO we are taking somewhat more risk. We are going to test some components in different facilities than an ITER.*** *Originally, we wanted, for instance, to test away how we breed, treat them in ITER, but that will come very late now. And so, we are looking for other means to test these components such that DEMO will still be, let's say before the middle of this century."*[33] (emphasis added)

The interview shows a strategic disalignment between EUROfusion and ITER. The interviewee re-emphasised that later in the interview:

> *"****We now are discussing how we are going to change that*** *[the roadmap], but this is a slow process in the sense that we have to wait for ITER* ***because I could publish a new roadmap tomorrow in a sense, but then I have to change it again as soon as ITER comes out with the new time schedule****. So, we are now focusing mainly on* ***how we are going to accelerate DEMO or to prevent that DEMO is being delayed by ITER.*** *But then the new roadmap will come out probably by the end of next year [2024], as soon as ITER will have the timeline and then we can put everything together. So,* ***we basically know more or less what we want and what we need to do but just putting it then on paper is like you do at some moments, which are well strategic in time****."*[34]

These two interview quotes highlight how the overall agenda of ITER may be misaligned with EUROfusion's research goal of realising fusion electricity. Alignment and disalignment between the two research entities. As argued earlier (see 4.3.3), the EUROfusion roadmap inherits the visions and promises of the roadmapping practice. Formulation and publication of the visionary document require

[33] Interview with the EUROfusion researcher/officer
[34] Interview with the EUROfusion researcher/officer

attention to related issues and actors. Disalignment between the ITER baseline and the EUROfusion roadmap might face criticisms about the legitimacy of both ITER and European fusion R&D. The interviewee's answer on the agenda, that DEMO and fusion electricity can be potentially delayed by ITER, undermines the narrative that ITER has been presented as an "obligatory passage point" (Callon, 1984) for DEMO and even fusion energy itself (see 4.2.2). As EUROfusion itself needs legitimisation, it must be coherent with its own narrative of "before the middle of this century" for the European DEMO. Similar documents (ITER baseline and EUROfusion roadmap) delicately deliver alignments and disalignments based on needs to legitimise their own practices.

This section has explored the dynamics of visions and promises, focusing on the ITER baselines and related issues. The detailed planning practice, enforced through the packaging and reformulation of milestones, ensures the project's legitimisation and justification. The baseline is political, which might reinforce or undermine narratives and practices in related areas.

4.4.3. Reformulating and Recontextualising Narratives

The previous two sections on fragilities, failures, and delays, as well as the refocusing of planning, have revealed a weakened narrative for the justification and legitimisation of ITER. The ongoing delays and ever-increasing budgets have led to unfulfilled promises and heightened uncertainties. This final section of the empirical part explores how ITER has coped with such difficulties by shifting and reemphasising its narratives.

As mentioned previously (4.2.2), the political legitimisation of ITER rests on international cooperation for fusion energy. However, in addition to the delays, rising geopolitical tensions and the prioritisation of short-term economic benefits for their own nations could undermine international cooperation on the project. The Russian invasion of Ukraine since 2022 has isolated Russia from international research and economic cooperation, especially with the EU. The political and economic tensions between the US and China have been further fuelled by the second term of US President Donald Trump, who has aggressively withdrawn the country from international cooperation. Nationalism in ITER members prioritises short-term national benefits and does not advocate international cooperation, especially for long-term scientific projects. The supranational EU has been irritated by its member states. These situations endanger the project's core ambition and legitimacy.

This ever-changing situation requires delicate maintenance practises to keep the justificatory narratives functional. The interviewee of the ITER Communication Office revealed concerns about stakeholder relations:

> "*And stakeholder relations at that time, 2015, the member governments really were concerned about whether the project would succeed. So,* ***the U.S. was threatening to pull out****.* ***If that had happened, then maybe others like Korea or India would have pulled out****. I would say Japan is extremely loyal to the project. I don't think they would pull out.* ***Europe was discouraged, but they're the host, so they can't now pull out****.*" [35] (emphasis added)

The threat of withdrawal of ITER members was clearly recognised by Classens as well. He states that withdrawal of ITER members would endanger the project's existence.

> "*Due to the recurring delays and the exponential increase of the budget, two of the seven ITER members, specifically the United States and India, have considered withdrawing from the project.* ***If this happened, would it mean a major delay or even the death of ITER?****"* (Claessens, 2023, p. xv) (emphasis added)

The strong discursive practice of international cooperation (4.2.2 and 4.3.1) may lose credibility if members, especially rival countries, such as the USA, Russia, and China, withdraw from the project. In fact, the US has threatened to withdraw a few times already, including the actual withdrawal under Bill Clinton's presidency and rejoining under George W. Bush[36]. Especially amid the current global tension, the stability of members' contributions is crucial to maintaining the narrative of global cooperation. The ITER Communication Officer shared the narrative formulations for ITER promotion.

> *"One narrative is the promise of nuclear fusion: what a real solution it means. So, no matter how long it takes, we have to keep going in the face of challenges like climate change.* ***The second narrative about ITER is that we have all of these countries working together.*** *So if you look on our work site out here, I have the flag of Russia flying next to the flag of the United States, the flag of China flying next to the you know,* ***if you look at those countries in the news, they're always in competition or trade wars or Europe is sanctioning Russia for the invasion of Ukraine, et cetera.*** *So,* ***the idea that all of these countries really can work together because they share a common vision for their children, that's a very powerful narrative****."*[37] (emphasis added)

This interviewee emphasises the importance and power of the narrative of a common vision for future generations, which strongly resonates with the justification for "common dignity" by Boltanski and Thévenot (2021). This narrative has been consistent from the ITER Agreement (4.2.1). The common vision shared and practised by the ITER members provides a strong narrative to legitimise the project's challenges.

[35] Interview with the ITER Communication officer
[36] Interview with the ITER Communication officer
[37] Interview with the ITER Communication officer

Yet, as the members' political actions are unpredictable, there is a need for an alternative narrative to strengthen the justification for ITER. The interviewee continued:

> *"I would say the third narrative,* ***which we're just starting to push****, is that* ***ITER is both applied fusion energy as its long-term goal, and it's also basic science like CERN****. So, if you look at the investment we make in CERN, it's also very large and it's not really questioned. It's questioned at times.* ***Or the International Space Station, for example****.* ***Those are projects that don't have an immediate, obvious practical application, but they have a lot of spinoffs that come out of them that make it worth it. And in the case of ITER, there are a lot of those spinoffs' examples, stories that we can also push as the narrative.****"*

The comparison with CERN (the European Organization for Nuclear Research) and the International Space Station (ISS) shows how ITER science communicators align with existing established scientific programmes. The comparison draws on stabilised legitimacy and applies to ITER's unstable legitimacy. The boundary-making of shifting ITER's characteristics from a "new" scientific project to an established "basic research project" shows the introduction of a new justificatory practice in ITER. Contrary to the interviewee's argument, the basic science projects have been questioned over time; for example, the justificatory narratives on CERN have been reconstructed over decades, reflecting a new imaginary of Europeanness (Mobach & Felt, 2022). The initial, and still core, promise of testing the technological feasibility of nuclear fusion has been postponed for years. Consequently, a new introduction of justificatory narrative as a basic science programme that produces basic research outcomes and spin-offs reinforces the project's legitimacy, as spin-offs are commonly used as key indicators of the exploitation of the programme (e.g., Bach et al., 1992). The concept of spin-off refers to the application of basic science and technology to usable or profitable products. Regarding the spin-offs, the EUROfusion researcher/officer also emphasised:

> *"[Spin-offs can be found in]* ***Many different fields****. So, a very nice example is we were working together with a German company, [company name], in developing the superconducting cables for ITER. And the company has a number of patents, and they apply that now for medical resonance, imaging equipment. And the company has now, based on that, on these old patents, an annual turnover of 2 billion per year. And they're world leader. So****, this is direct fusion technology which is used for medical equipment****. ... I was trying to involve a Dutch company which was doing explosive forming into ITER. ... So, we had a joint study and then they showed for played by two-by-two meter, that they can do it. We took them to several industrial exhibitions, and they got an order for making the cockpit of the Airbus A 380 by that technology. So,* ***you could say the Airbus is now made with fusion technology****. [...] So,* ***there's plenty of***

***spin-offs constantly. So many companies which are involved in building components for fusion reactor, they see also an increase in adjacent markets**."*[38]

Emphasising the spin-offs reinforces ITER's significance while also highlighting the technical challenges that must be overcome for the project to advance. The development of new inventions and innovations for ITER components is presented as one reason the substantial resources devoted to the project can be justified. In this sense, the value of ITER is not framed solely by its potential to achieve fusion energy, but also by the broader technological outcomes it generates along the way. Put differently, ITER is considered worthwhile because it is a cutting-edge technological endeavour that produces a range of spin-offs with wider benefits. From this perspective, ITER's worth cannot be assessed only by the success or failure of fusion experimentation itself, since its significance also lies in the technological development, knowledge production, and innovation it enables.

In relation to the agenda to present the "basic science" motif for ITER, it began to expand cooperation and collaboration beyond ITER members' public fusion R&D and into the private sector. In the event, at Fusion 24 on June 28, 2024, the head of the ITER Communication Office, Laban Coblentz, mentioned that ITER has noted this shift.

> *"About two weeks ago, [...]* ***we took a 90-degree turn in our mission****, I think. We held a workshop for people [...] that are building fusion plants in the private sector.* ***So, we started a private-public collaboration. That's a big switch for us."*** [39] (emphasis added)

The communicator acknowledges the significant shift in ITER's communication strategy from member-focused cooperation to a more open format with the private sector. In response to the November 2023 ITER Council's request (Coblentz, 2024a), in May 2024, ITER organised the first "ITER Private Sector Fusion Workshop" with approximately 350 stakeholders from private startups, industry suppliers, public laboratories, the ITER domestic agencies, and the ITER Organization (ITER Organization, 2024b). The workshop, alongside planning and the ITER Council's requests, contributed to the official launch of the Private Sector Fusion Engagement (PSFE) project in ITER (ITER Organization, 2024d). PSFE initiative includes the setup of the PSFE Help Desk to coordinate "access to ITER documents, connections to ITER experts, and technical questions" that can lead to official user agreements, and is expected to be followed by open-source Integrated Modelling Analysis Suite software, the ITER Design Handbook, private sector participation in International Tokamak Physics Activity and fusion resources (ITER Organization, 2024d). As a part of this initiative, the second workshop was organised in April 2025 (ITER Organization, 2025).

[38] Interview with the EUROfusion researcher/officer

[39] From the recording of the event (UKAEA official, 2024)

In contrast to ITER's active initiative in public-private cooperation, fusion researchers in the public sector have shown scepticism toward collaboration with the private sector. The EUROfusion researcher/officer problematised the technical sufficiency and timelines for fusion energy in the private sector, criticising that private companies have publicity: "whenever they achieve something small, they make a storm in a glass of water, and they say they have major breakthroughs"[40] to present the achievements more attractively to investors. As seen in the previous section (4.4.2), the motif of breakthroughs is a common way to present achievements in the hype-driven technoscience. Regarding overrepresentations, private fusion companies often propose timelines that follow a different logic from ITER's research plan. The EUROfusion researcher/officer continued to talk about the temporal dimension of the private sector with focused development:

> *"And these ten years, that's just the horizon for the investors. If you go to an investor and say, 'Well, I'll build a fusion plant for you, and it will work in 20, 30 years from now, the investor says, 'Well, no, sorry, that's too far away, I'm not going to invest in that. So, they set targets which are really unreachable, and they focus on just one or two aspects"*[41]

This criticism is based on the comparison with ITER as "comprehensive" research covering various aspects of fusion energy, including systems and materials essential to achieving fusion energy, such as tritium breeding and high-heat-tolerant materials, as the interviewee clarified later in the interview. The public fusion researchers undervalue the private sector's outcome-focused fusion energy R&D. Criticising short-term goals, in turn, contributes to the legitimisation of ITER's long-term goal-setting based on its comprehensive research programme. In this sense, collaboration with the private sector might be a double-edged sword for ITER. The interviewee's concerns are consequently the public investment and allocation to the comprehensive public research programme:

> *"So, it is of course a worry because these companies very often have also very good relations with politics, and they succeed in acquiring money. And a politician who is big ignorant might think well these companies deliver fusion in ten years. […] And* ***the public fusion takes such a lot of money, and it takes such a long time. So, let's stop this all and let's put all the money in the private basket. In the end, we never will get fusion because all these companies are concentrated on one or two technology advances, but they don't have the holistic view which we have in public research****"*[42] (emphasis added)

The interviewee highlights dynamics about resource allocations based on distinctive technoscientific promises. The comparison between the private and public fusion sectors highlights differences in the temporal dimensions of development, R&D foci, and, consequently, resource allocation logic. The

[40] Interview with the EUROfusion researcher/officer
[41] Interview with the EUROfusion researcher/officer
[42] Interview with the EUROfusion researcher/officer

public fusion researcher's criticism legitimises R&D activities of EUROfusion/ITER as a programme with a "holistic view" in contrast to "one or two technology advancements" in the private sector. Therefore, the claim is that the wide coverage of ITER's technological advancement supports the credibility of the ITER programme. The researcher underscores the importance of the public fusion programme, expressing concern that "in the end, we never will get fusion". The harsh criticism of politicians ("ignorant") reflects frustration with resource allocation based on a hype-driven narrative about fusion. This criticism reinforces the stability and credibility of public fusion compared with the private sector. After the criticism, the interviewee continues the vision of public-private cooperation:

> *"In my vision,* ***we should find a way where private and public are going to work together, where you have a kind of holistic view****. Well, talking now, I just saw the Oppenheimer movie, but you need a kind of* ***Manhattan-type project*** *where, let's say,* ***all the researchers are working together, where there's one goal, and that's to build this fusion reactor where you bring in the competencies from both the industry, the private fusion, but also public fusion****."*[43] (emphasis added)

This also supports the argument for a "holistic view" of fusion R&D. However, this part of the quote highlights the importance of comprehensive R&D, which may be achieved through collaboration between private and public fusion R&D. Additionally, the interviewee mentioned the Manhattan Project, for the second time (also see 4.4.1), as an ideal fusion R&D effort in which the public and private sectors are coordinated to achieve the goal of fusion energy. Here, the orientation toward the goal "fusion energy" serves as the consolidating force across different approaches among public and private actors. While comparing the approaches of public and private fusion, this quote shows how public fusion researchers incorporate growing attention to the private sector into a coherent narrative toward the common goal. This new narrative of goal orientation is prominent in the first paragraph of the webpage, where the ITER Organization announces the launch of the PSFE project.

> *"We don't all agree on the best technological path to fusion power. We often disagree on the timeline to commercialization.* ***But we largely agree on the challenges that remain. We certainly have the same end goal: the realization of fusion power as a safe, abundant source of clean energy****. And—critically—we agree that sharing our knowledge, in the framework of a global fusion R&D innovation program, could* ***help us all go faster.****"* (ITER Organization, 2024d) (emphasis added)

Similar to the EUROfusion researcher/officer, the ITER Organization focuses on goal orientation with the same goal. The coordinated narrative among ITER-related researchers and communicators presents a stable picture of the disruptive initiative. The passage also indicates the temporality aspects, "go faster",

[43] Interview with the EUROfusion researcher/officer

through public-private cooperation. The initiative, which appears to disrupt core cooperation among ITER members, serves to strengthen fusion R&D overall, reinforcing the necessity of ITER. The extension of international cooperation, "us all", can also be seen in the slogan of a signature board in the second private sector fusion workshop, "Fusion Energy FOR ALL - ALL FOR fusion energy" (ITER Organization, 2024d). While the public and private sectors compete for investment opportunities and technological progress, the challenge of achieving fusion energy is shared by all sectors and can/should be overcome by sharing knowledge. The normativity of cooperation implies the necessity of cooperation as well as the fusion R&D progress. In terms of knowledge sharing, the ITER communication office presents ITER as the centre of knowledge production in fusion R&D.

> *"You probably heard earlier this year when the National Ignition Facility in the US did its inertial confinement experiment. Well, when that happened, you can see that suddenly the private sector decides, 'let's build inertial confinement'. So new inertial confinement, things broke up.* ***So there is a public-private symbiosis that occurs****. You can look at it as a competition and many journalists misunderstand and think [that]* ***if the private sector gets there first, ITER will become obsolete. But it's not the case****.* ***Why? Because there is actually new basic science that is coming out of ITER. That is different. And I'll explain. There is no other machine that is like ITER.*** *[…] ITER is building a machine that is* ***like a national lab*** *where we will have pulses of six minutes and 40 seconds at least. That's a design which means that,* ***as opposed to a microsecond, you can really study this data about a controlled burning plasma and if we're really lucky, maybe even ignition."***[44] (emphasis added)

The quote, "There is no other machine that is like ITER," emphasises ITER as a legitimate research facility rather than merely a technology-only fusion device. Using the analogy of "a national lab," the communicator highlights the importance of an evidence-based research orientation in the broader context of fusion research. This contextualisation serves to stabilise ITER's legitimacy as a unique and comprehensive fusion research laboratory. Hereby, this argument justifies the complex and long-term process. The research-oriented goal of ITER is bridged to the prototyping of fusion energy. The communicator drew an analogy with the "Model T Ford" in the context of automotive technology development.

> *"So, 20 years from now, I think there's a very good chance that we will have pilot plants built that are in different types of designs that are some like ITER, some very different from ITER, but* ***ITER's experimental data, those will essentially be****,* ***if you think of it like cars, those will be like the Model T Ford****. Yeah,* ***the experimental facility that ITER is and the experimental data coming from ITER will help you to build, to move from the Model T Ford to the BMW***

[44] Interview with the ITER Communication officer

> ***or the Tesla or whatever your illustration is. So, I think ITER will continue to be a very relevant machine for decades.***"[45] (emphasis added)

This analogy implies the classic concept of "diffusion of innovations" (Rogers, 1983) where, in this case, ITER is described as an innovator, and the private sector as an adopter. Providing a "model" or prototype for fusion reactors is emphasised as an important role of ITER in overall fusion energy R&D. Through this argument, the communicators justify the comprehensive R&D programme in ITER. The future of nuclear fusion – different types of fusion reactors – is projected in the timeline of 20 years. Backcasting from the ideal future (or presented as a realistic future via an analogy with a familiar example) creates a technological development trajectory, in which ITER is presented as a necessary step as a prototype.

As the above has shown through the interviews and official narratives, the "radical shift" of ITER to cooperate with the private sector is recontextualised as part of international cooperation and broader fusion R&D. As an example of this recontexualisation in action, the narrative of the ITER Communication Office presents a smooth transition. With a quote from the ITER Communication Office head, Coblentz, "How can ITER help?", in the title, the report says that, ever since the 1956 visit of Russian researchers to the UK, "worldwide sharing of knowledge and experience" has "characterized fusion research" (ITER Organization, 2024b). The interviewee included the positionality of the publicly funded project.

> *"Fusion has long been a science where international cooperation is* ***the norm****. And I consider that we have to* ***give back to the private sector*** *what we have achieved with the public money of our stakeholders."*[46] (Emphasis added)

There are two strong arguments combined in this quote. First, international cooperation is presented as "the norm" for fusion science, with the word carrying a strong normative connotation. And then, returning to the private sector is an additional normative obligation of the publicly funded project. This section has explored the dynamics of narrative adjustments in ITER. As the project has been delayed, the emphasis on international cooperation has been reformulated amid geopolitical tensions among the ITER members and has additionally been extended to the private sector. These strategic choices reinforce the legitimisation of ITER as a comprehensive research facility, comparable to CERN and ISS. Legitimisation and justification are not a single, static action but rather a dynamic, recursive performance.

[45] Interview with the ITER Communication Officer
[46] Interview with the ITER Communication Officer

4.4.4. Conclusion

This chapter has investigated dynamics within the project's progress. Using the concept of maintenance and repair in a broader sense, the delicate actions of maintenance and (re-)arrangement have been examined in both technical and political ways – more precisely, often in an entangled way in discursive-material practice. The chapter began by mapping the fragilities, failures, and delays over the decades, which reveal the technology's materiality as inseparable from the project's socio-political settings. Presenting fragilities, failures, and delays is itself a delicate justificatory practice, which sometimes reemphasises the project's characteristics (e.g., high-tech precision, long-term timeline, and high ambitions) rather than weakening them. In response to the challenges, the ITER scientists and communicators strategically align or disalign their visions and promises through re-planning, as seen in the case of ITER baselines. Documenting and updating project processes are material-discursive practices of legitimisation and justification, often involving milestone markers in project language. Challenges in ITER may cause friction with related actors, such as EUROfusion's DEMO construction plan, where strategic disalignment of visions and promises is coordinated. In addition, ITER's institutional narratives are reformulated from and recontextualised with the existing narratives. Reemphasis on international cooperation for the peaceful use of nuclear technology is set against a backdrop of geopolitical tensions, while the scope of international cooperation is expanded to include public-private partnerships. Maintenance and rearrangement are continuous practices in both material and discursive senses, particularly in a mega-technoscientific project like ITER.

5. Discussion

The previous chapters have revealed the complexities and dynamics of the ITER project through empirical data from interviews, fieldwork, websites, documents, and literature, adopting a new materialist perspective. The empirical study has provided answers to the research questions on the legitimisation and justification of the mega project. The main research question, "*How is the ITER project assembled through justificatory practices that satisfy technoscientific expectations and promises?*" addresses the dynamics and complexities of the project's legitimisation and justification. ITER is an exceptionally complex technopolitical project, from the initial agenda-setting to the current controversies. Looking at the socio-material configuration of ITER reveals the historical and technopolitical contexts and actions that have evolved over the long project period amid sociotechnical uncertainties. The research has shown that **ITER is assembled through material-discursive practices that stabilise legitimacy by repeatedly dis-/re-/aligning future-oriented promises with institutional, technical, and geopolitical arrangements**. Various justificatory practices continuously transform uncertainty, delays, and complexities into legitimacy, credibility, and political endurance. These practices are not limited to discourse; they include planning arrangements, institutional coordination, material construction, milestone-making, and the repeated rearticulation of promises in response to problems and controversies. In this sense, ITER is not simply "supported" by justification from the outside but is actively constituted through it.

To reflect on the empirical chapters, the following focuses on three overarching themes in ITER regarding the legitimisation and justification of the project: 1) embraced temporality and spatiality, 2) ITER-fusion exceptionalism, and 3) ITER-fusion optimism and imperative. These three themes emerged inductively from the empirical chapters. Across the analysis of planning, construction, and reworking, the material repeatedly pointed to the importance of long-term temporality and spatial reach, the construction of ITER as an exceptional fusion project, and the framing of fusion as both a hopeful vision and a practical imperative. In the discussion, these patterns are consolidated into three thematic arguments.

These three themes also address the three sub-research questions (SRQs). Yet, before moving on to the three aspects, the following provides concrete answers to the SRQs.

SRQ1: *How is ITER situated within the sociomaterial landscape of wider nuclear fusion energy R&D, particularly in the European context?* – **ITER is situated as the central node in a broader sociomaterial landscape of nuclear fusion energy R&D that is shaped by European energy transition agendas, security concerns, institutional roadmaps, and long-term expectations about future energy systems.** The research shows that ITER is not isolated but embedded in a wider assemblage of international and European actors, infrastructures, policy frameworks, and future-oriented visions, particularly through the relations among ITER, EUROfusion, Fusion for Energy, and European energy policy discourse. This positioning helps explain why ITER is framed not only as a scientific experiment but as part of a larger political and strategic project.

SRQ2: *How do the future-oriented documents in ITER situate promises and perform to justify the project?* - **The future-oriented ITER documents (the ITER Agreement, ITER baseline, and EUROfusion roadmap) do not merely describe the project's goals; they actively perform the project's legitimacy by framing its promises as necessary, credible, and desirable.** These documents situate ITER within a horizon of scientific progress, long-term climate relevance, and technological necessity, while also translating uncertainties into managed expectations through milestones, deliverables, roadmaps, and progress narratives. In this way, the documents function as justificatory devices: they not only communicate the project but also help stabilise it by making its future appear both attainable and worth the investment.

SRQ3: *How are ITER's promissory and justificatory practices maintained, adjusted, or rearranged over time to preserve the project's legitimacy amid sociotechnical uncertainties and controversies?* - **ITER's promissory and justificatory practices are maintained through continuous adjustment and reconfiguration whenever the project encounters delay, fragility, criticism, or controversy.** Rather than undermining legitimacy, such disruptions are absorbed into renewed narratives of patience, controlled progress, technical novelty, and long-term necessity. The research shows that the project remains credible because its promises are not fixed once and for all; they are repeatedly reformulated, recontextualised, and dis-/re-/aligned with new institutional and material conditions.

This research has examined the justification and legitimisation of ITER. Although this thesis does not apply Boltanski and Thévenot's orders of worth (2021) in a systematic way, their work is useful for understanding how ITER is justified through multiple evaluative registers. Across the empirical material, the project is defended through references to technical progress, collective benefit, innovation, and long-term necessity. ITER's justificatory practices fall under the six different logics: civic, market, industrial, domestic, inspiration, and fame (Boltanski & Thévenot, 2021). Cutting across the different logics of justification, the justificatory moves help stabilise ITER's legitimacy by making the project appear both credible and worthwhile in relation to different audiences and expectations.

The empirical analysis suggests that ITER's legitimacy is not produced by technological progress or discursive claims alone, but through repeated justificatory practices that align future-oriented promises with institutional coordination and material reconfiguration. This finding speaks to the theoretical discussion of technoscientific promises and justifications, as it shows that legitimacy is maintained not only through claims about the future, but through practices that make such claims appear credible in the present. In this sense, the ITER case extends the theoretical framework by highlighting the roles of temporal management, milestone-setting, and rework in sustaining long-term projects.

5.1. Embraced Temporality and Spatiality

Throughout the empirical chapters, ITER is understood not as a single, definite object but as a massive, continuous assemblage that embraces multi-term temporality and widely dispersed spatiality. ITER is embedded in time, moving from the past towards the future and involving actors globally, which provides it with a sturdy basis for its presence. While the physical entity of the reactor is located in the small town of Cadarache, Saint-Paul-lez-Durance, in the south of France, has been under construction since the 2000s and is to begin operation towards the middle of this century, ITER is more than that; ITER is the realisation of space history towards the prosperous future of humanity with a collective commitment of international cooperation. Compared with the private fusion sector, which usually involves a single entity with a 5–10-year horizon, ITER encompasses extensive temporal and spatial dimensions. **Embraced temporality and spatiality are not merely ITER's neutral characteristics but are also actively used and performative in keeping the project legitimate.**

ITER, claimed as the most comprehensive nuclear fusion programme, is expected to reproduce one of the most basic reactions in space: nuclear fusion. The simplified depiction of a fusion reaction is derived from the Sun and stars, providing the astronomical timeline. In the context of ubiquitous phenomena in space, nuclear fusion itself is not a "new" technology but a realisation of a universal and timeless principle (see 4.3.2). The analogy conveys the impression that ITER encompasses billions of years of space history. However, actual technological development does not proceed according to such simple logic. Therefore, there are a variety of justificatory practices to satisfy the promise to reproduce the sun on Earth.

The temporality and spatiality of the practices vary in different parts of the assemblage. The official narrative originates from the 1985 Geneva Super Summit, which aimed to reduce geopolitical tensions and promote the peaceful use of nuclear technology for human civilisation (see 4.2.2). Materialised visions are presented and reinforced within the ITER Agreement (IAEA, 2007) as the legal basis (see 4.2.1). ITER is carefully designed and assembled to distribute the responsibility and benefits to the ITER members (see 4.3.1). The distribution of tasks reflects the future orientation of the members' fusion agenda, i.e., a projection towards DEMO construction and the commercialisation of fusion energy. ITER as "a necessary step", or "obligatory passage point" (Callon, 1984) enfolds the future visions and expectations (Brown et al., 2000) of the ITER members.

At the same time, ITER has a presence in a long-term European fusion programme dating back to the 1950s (see 4.2.3). There, ITER is conceived as the successor to JET, expected to demonstrate technological feasibility and serve as a bridge to the European DEMO in the second half of the century, as articulated in the EUROfusion Roadmap (see 4.3.3). ITER is an international collaboration project, but it is also heavily reliant on the European fusion programme due to its geographical location and funding mechanism. Especially for European fusion development, the connections with JET and the Japanese facilities (the JT-60SA, IFMIF, IFERC, etc.) are integral to stabilising European fusion's technoscientific promises through the continued development of European fusion R&D and an extensive network to complement ITER's activities (see 4.3.1).

ITER is, therefore, both a consolidation and a passing of the torch from the past to the future for ITER members around the globe. The heterogeneous assemblage spanning multiple temporalities is streamlined through shared visions and languages. The highly structured management style (see 4.3.1 and 4.4.2) is designed to ensure the project's consistency and coherence. However, this very structure also imposes challenges. The budgeting system lacks flexibility during the ever-changing processes (see 4.3.1 and 4.4.1). Negotiations between the ITER Organization and domestic agencies are often highly political and involve excessively bureaucratic procedures (see 4.4.1). As ITER has constantly faced sociotechnical challenges, the shared visions are in a state of dynamic change. The narrative of ITER as a necessary step for DEMO, or, more broadly, for fusion energy, has become obscure, as some ITER members, including the EU, begin planning DEMO without waiting for ITER to be exploited. Alignment and disalignment of the shared visions are technopolitical strategies. Amid the sociomaterial dynamics and controversies that might undermine the legitimisation and justification, ITER has maintained and rearranged its visions and promises through strategic (non-)alignments and recontexualisation (see 4.4.2 and 4.4.3). Re-emphasising international cooperation as a norm in fusion research, ITER has shifted its strategy towards private-sector collaboration.

The legitimisation and justification of ITER is not a single consistent practice but rather a constant reformulation and adjustment. Roadmapping with a motif of milestones serves as a projection of the future (see 4.3.3 and 4.4.2). ITER, as an assemblage, embraces multiple temporalities and spatialities within and beyond the machine.

To conclude, the vast temporality and spatiality are not a neutral background condition, but part of active material-discursive practices through which promises are sustained. The robust, enfolded interrelationships (or interdependencies) create resilient and adaptable justification for technical and social uncertainties. Hence, the embraced temporality and spatiality allow ITER to refrain from an ordinary short-term judgement. The literature on expectations highlights the quality and robustness of expectations and promises (van Lente, 1993) and promise-requirement sequences (van Lente, 2000), claiming that promises mobilise artefacts and actors at different levels over time. There, an expectation or a promise is often described as a shared format among the actors (Borup et al., 2006). In contrast, research on ITER shows that a project's technoscientific promise may be realised in multiple ways within a single claim. ITER's promises are not necessarily shared or agreed upon by all the actors; rather, they are consolidated and organised through alignment and disalignment. Based on the multiplicity, the justification of the project emerges at different scales, where flexibility and robustness are reflected in ITER's promises.

5.2. ITER-Fusion Exceptionalism

The previous section on the embrace of heterogeneous temporality and spatiality in ITER has also shown the attraction and accumulation of time and space towards ITER. One of the reasons why ITER has such a capacity to mobilise time and space is the potential of nuclear fusion energy. The potential – or rather, the promise – of extremely intensive energy with abundant resources enables investment in the long-term mega project. As an explicit example, Claessens' conversation with Daniel Allen, an executive manager of several investment funds, can be quoted again.

> "*For a technology that could revolutionise the future and change the course of civilisation, EUR20 billion, EUR30 billion or even EUR40 billion are, he said, "peanuts.'*"" (Claessens, 2023, p. 126)

This quote shows that the promise of ITER is so great that the investment in fusion is not commensurate with the benefits. While many technoscientific promises involve narratives of "revolutions" (Brown et al., 2000), the revolution in energy, one of the most basic yet essential infrastructures of human civilisation, has a strong narrative to mobilise resources. In terms of resource and energy intensity, fusion is not comparable with other energy sources – at least that is the narrative. The ability to differentiate from other energy sources is an important characteristic of fusion. In line with widely circulated narratives, it is common in ITER to criticise fossil fuels for their greenhouse gas emissions and renewables for their intermittency (see 4.3.3). As an interviewee of the ITER Communication Office said, fusion is "a real solution". Therefore, technical difficulties, budget increases, and delays do not significantly affect the project's legitimacy, at least in theoretical terms.

Comparison with nuclear fission is particularly noteworthy, as fusion and fission are often mentioned side by side and share commonalities in research, budget allocation (see 4.2.3), control, and public perceptions. Nuclear fission's characteristics of high-radioactive long-term waste and the potential danger of serious accidents are denied for fusion development, even though fusion reactors will still produce radioactive waste from the technology's broader system, such as reactor building materials. The non-proliferation characteristics of the tokamak-style fusion reactor enable international cooperation and focus on energy production rather than dual-use or weaponisation, unlike laser-based fusion technology, such as the National Ignition Facility in the US (see 2.5, 4.2.2, and 4.2.3). Nuclear fusion in ITER is particularly "safe" to be developed and shared compared to other fusion and fission. All the differentiation from fossil fuels, renewables, and nuclear fission is boundary-making work (Gieryn, 1983) aimed at distinguishing nuclear fusion from the others. In addition, importantly, ITER-related scientists and communicators tend to equate fusion energy with ITER; ITER IS "THE" FUSION; FUSION is ITER. Here, also, a specific attachment of the fusion future to a machine occurs, which, as Hornborg (2001) calls it, is "machine fetishism". Therefore, the analysis hereby adopts the word "ITER-Fusion" as an indistinguishable form of assemblages.

Gabrielle Hecht's notion of "nuclearity" (2012) has implications in the comparison between nuclear fusion and nuclear fission drawn by ITER. Similar to the boundary work (Gieryn, 1983), Hecht (2012) argues that the categorisation of "nuclear" is contentious in time and space, where the designation is based on technopolitical practices and relationships within the global nuclear order. While radiation matters for health and safety, its existence does not necessarily satisfy the criterion for being "nuclear". Nuclear fusion is not in the scope of Hecht's original work, with a focus on uranium mining (2012). However, the technopolitical differentiation between nuclear and non-nuclear is parallel to the discursive-material practices in ITER. As mentioned before, nuclear fusion and fission share commonalities in research, governance structures (e.g., the IAEA), controls (e.g., French regulations for ITER), and public perceptions. In fact, the ITER Organization has legal status as a "nuclear operator" under French nuclear law. Claessens, a former head of Communication of the ITER Organization, writes about the public perception of nuclear fusion:

> "*In Europe, many people react to the word "nuclear" in an emotional, often passionate way. So, the decision was taken to no longer present ITER as a "thermonuclear" project. Fusion is of course "nuclear," but different from fission. Unfortunately, the adjective "nuclear" evokes negative connotations that don't apply to ITER.*" (Claessens, 2023, p. 197)

The communicator highlights the delicate work to differentiate fusion from fission. Due to the negative connotation of the word "nuclear", ITER avoids using "nuclear" or "thermonuclear". ITER itself is an acronym of "International Thermonuclear Experimental Reactor" but is often presented just as "the way" in Latin: the top page of ITER says, "*ITER ('The Way' in Latin) is one of the most ambitious energy projects in the world today*" (ITER Organization, n.d.-b). Also, ITER often uses "fusion energy" without "nuclear" at the beginning (see, in particular, 4.2.1 and 4.3.3). These practices and narratives disassociate ITER or fusion from nuclear fission, making it "non-nuclear".

The boundary work (Gieryn, 1983) separating fusion from fission also leads to the association of fusion with different technoscientific practices. With the mystification of fusion and the glorification of the machine (see 4.3.2), ITER has served as a "high-tech", "first-of-a-kind" project, with its fascinating impressions conveyed through guided tours, virtual tours, and websites (see 4.3.2 and 4.4.1). The new narrative that categorises ITER as a basic research facility comparable to other facilities such as CERN or the ISS (see 4.4.3) is a strategic choice to legitimise the facility within the broader context of technoscience. As a research project on nuclear fusion, ITER's comprehensiveness and scale are presented as exceptional compared to other fusion projects. That led the EUROfusion researcher to say, *"There is no other machine that is like ITER,"* and the ITER Communication Officer to call ITER *"Model T Ford"* of fusion reactors. The study observed ITER's strong positionality adaptations, embedded at different scales, of disregarding the "industrial relevance" of ITER (Claessens, 2023, p. 174), while maintaining a reference to industrial venture, thereby creating ITER-fusion's promise as flexible and adaptable across different situations and scales. **ITER-fusion is positioned as beyond normal cost-benefit logic, short-term political cycles, and commercial expectations. The unique attribute of ITER fusion is not just rhetorical; it helps stabilise sociotechnical support and attention. The claims and practices of ITER-fusion novelty help sustain its legitimacy: ITER-fusion is the only machine for the energy future.**

The ITER-fusion assemblage is the promissory practice itself. Sustaining the construction is a set of justificatory practices for keeping the promise alive: ITER fusion serves as the energy future in the making. Yet this strong attribution of fusion to ITER also poses a risk of disappointment. If ITER fails, all the claims and practices of promising fusion fail. Therefore, the ITER-fusion assemblage expands its associations with others, such as private fusion sectors, so that claims and practices for the fusion future would survive in the event of the project's failure.

The literature on technoscientific expectations and promises has examined the roles that expectations and promises play in shaping technological development and sustaining support for projects over time (Borup et al., 2006; van Lente, 2000). However, it pays less attention to how such expectations and promises are actually formulated and made persuasive in the first place, with only a few exceptions to the author's knowledge, such as McCray (2012). The formulation of expectations and promises is itself analytically significant, since it is through this process that credibility and legitimacy are produced and stabilised. A notable contribution in this regard is Joly and Le Renard (2021), who distinguish between credibility, which they link to experience, and legitimacy, which they associate with radical novelty. In the case of ITER-fusion, however, this separation does not hold straightforwardly. **Rather, credibility grounded in previous experience and legitimacy grounded in novelty are produced together and continuously reinforced within the same assemblage. ITER-fusion exceptionalism thus relies on ongoing practices that combine continuity and novelty, as earlier practices are repeatedly adapted and rearticulated into future-oriented promises.** In this sense, the ITER-fusion assemblage is characterised by a constant movement in which past experience and future promise are enacted together.

5.3. ITER-Fusion Optimism and Imperative

In relation to the ITER-fusion exceptionalism, fusion is often associated with optimism and imperatives. One of the most often quoted phrases in the field of fusion is from the Russian physicist Lev Artsimovitch: "Fusion will be ready when society needs it." (e.g., Claessens, 2023, p. 216; IAEA, 2021, p. 1). While fusion's feasibility is sometimes questioned and ironically criticised by the common phrase "fusion is always 30 years away" (see 2.5), the empirical study shows strong optimism about fusion energy development and ITER's key role in it.

ITER's promise is larger than just technoscientific; it is a revolutionary change in energy in human society. With this strong promise, actors in ITER pursue the high ambition with little reluctance. The French President Macron said on July 28, 2020, at the ceremony for the official start of the reactor's assembly, in particular: "*ITER is clearly an act of confidence in future. At its core is the conviction that science can truly make tomorrow better than today*." (Claessens, 2023, p. 224). ITER is surrounded by and driven by hopes for the future. The strong promise for the future overlooks present difficulties and short-term interests, extending towards a vaguely projected future when fusion energy is achieved (see 4.4.1). The Director-General of the ITER Organization, Pietro Barabaschi's answer at the press conference to present the new baseline, is a great example of the long-term goal of ITER:

> *"Is ITER still relevant in the context of the immediate pressure of climate change and the emergence of fusion startups?*
>
> ***Fusion cannot arrive in time to solve the problems our planet faces today, and investment in other technologies, known and unknown, is absolutely needed,"*** *said Barabaschi.* ***"But I expect fusion will make a difference when it arrives, and let's not forget that there is not just the problem of solving global warming ... energy is also needed for life on Earth.*** *Fusion commercialization will require new ideas to make things simpler and cheaper, as well as a number of enabling technologies that ITER will not resolve. I very much welcome the new ideas that are popping up around the globe. Fusion should be thought of as an innovation program, and we all have our part to play."* (ITER Organization, 2024c) (emphasis added)

Interestingly, the sentence "when it arrives" is conditional yet a strong argument. The ITER Communication officer also argues that fusion is "the best" and "a real solution" and therefore, "*no matter how long it takes, we have to keep going in the face of challenges like climate change*"[47]. And regarding the flourishing of human civilisation with high-energy demands, "*So, either way, fusion plays a huge role if we can make it work*", as the interviewee continued. Realisation of commercial fusion energy remains highly uncertain. However, the strong promise of ITER-fusion already shapes the

[47] Interview with the ITER Communication officer

prospect of a specific future – a nuclear fusion future. ITER, as the *Leitbild,* consolidates humanity's dream of a technofuture (Mehnert, 2024), in which fusion energy serves as the ultimate energy resource in the future energy mix. This is a great example of nuclear utopians, or what Peoples (2016) called "nutopians", who argue that atomic energy is the ultimate energy solution for humanity and saves civilisation (see 2.3. and 2.4.). The distinction between nuclear realists and utopians (Abbott, 2012) does not function; instead, it becomes blurred. In particular, the temporality of the future is organised through different mechanisms: the short- and medium-term future rests on a realistic, stage-based approach that smoothly transitions to the long-term future, in which fusion energy becomes widely available.

The strong connection between the current ITER R&D and the future of fusion creates a sense of imperative. Claessens captures this power of the promise when asking: "*So, to develop fusion or not? Nobody can argue that having a new source of energy, safe and clean and using a very abundant fuel, would not be a great news for humankind*" (Claessens, 2023, p. 9). This formulation resonates with what Boltanski and Thévenot (2021) describe as justificatory appeals to common humanity, human dignity, and the common good, which are among the strongest forms of legitimation. In the case of ITER, international cooperation and the promise of fusion are repeatedly framed through narratives of shared benefit for humankind, making the project appear not merely desirable but morally difficult to oppose. As a result, criticism of ITER can be reframed as criticism of humanity itself (see 4.2.2 and 4.4.3).

This illustrates one of the strongest forms of technoscientific promise: a "forceful future" within the promise-requirement sequence, in which technical progress is presented as self-evident and therefore difficult to contest (van Lente, 2000, p. 60). **The promises surrounding ITER fusion do not merely envision a preferable future; they pressure present actors to continue the project despite uncertainty, delays, or controversy. From this perspective, criticism of ITER fusion can be deemed irresponsible or short-sighted, since it appears to stand in the way of a future framed as beneficial to everyone.** At the same time, this techno-solutionist and elitist logic raises moral and ethical questions, because a justification mechanism that claims to speak for humankind can crowd out alternative visions of the energy future. A centralised fusion system would not only shape energy supply but also influence governance arrangements and broader social imaginaries. In this sense, as with nuclear fission's historical entanglement with centralised governance and state formation (Hecht, 2000), **the forceful fusion future helps configure specific visions of techno-society.** Read through a new materialist lens, this also shows the vulnerability of such high claims, since their authority depends on continuous material-discursive work and remains open to contestation.

6. Conclusion

ITER, as a mega-technoscientific project, can be understood as an assemblage of sociomaterial entities: an inseparable configuration of narratives, agendas, materials, and resources. This research has sought to capture the dynamics and complexities of this project by emphasising the inseparability of the discursive and the material. **By providing a rare case study of one of the most expensive ongoing scientific projects, the thesis has illuminated how technoscience is legitimised and justified amid sociotechnical uncertainties and controversies. ITER is sustained through material-discursive practices that repeatedly connect future-oriented promises to present-day arrangements, institutional coordination, and ongoing repair. Uncertainty and delay are therefore not external problems that simply threaten the project's promises; rather, fragility is part of ITER's mode of existence, absorbed into the project and continuously reworked in ways that reinforce its justification.**

This thesis began with "Situating ITER", which presents the state of the art in nuclear fusion R&D and associated practices and narratives, as well as the theoretical background needed to capture the complex topic. Instead of artificially sorting out and systematising the complexities, this research employs assemblage theories and methodologies (Baker & McGuirk, 2017; DeLanda, 2006; Wahlberg, 2022a) to explore some elements of the borderless assemblage of ITER. Due to the research methodology and time span, this research captures only certain elements of ITER, as it is not possible to capture the assemblage as a whole, since the assemblage itself, by definition, lacks a complete body. Some elements in the assemblage are interacting through different material-discursive practices. The dynamics of such practices are driven by what STS scholarship has argued in the name of socio-technical imaginaries (Jasanoff & Kim, 2009), technoscientific promises (Brown et al., 2000), and justification (Boltanski & Thévenot, 2021) which are closely intertwined. Empirical research through interviews, fieldwork, and document and media analysis has shown that different scopes reveal distinct modes of gathering temporality and spatiality.

The research demonstrates that promises are not only discursive claims, but also performative properties of an assemblage produced by heterogeneous actors, infrastructures, milestones, and institutional relations. The writing of the empirical chapter was inspired by ITER's chronological timeline, from planning and construction to maintenance practices. However, some topics – or assemblages – are stretching the timelines, issues, and actors. "Planning ITER" has started with the core document of ITER, the ITER Agreement, as the official basis for the project, complemented by the international and European perspectives that follow. International cooperation, as a core of the project, is ensured by the project's specific management systems, while the "Europeanness" of ITER is maintained. "Constructing ITER" treats construction as dynamic material-discursive practices, rather than the mere realisation of the plan. The technopolitical dynamics of site setting and resource allocation show how technology is both material and symbolic. The mega project also invites effective engagement with analogies with astronomical motifs and fascination with the construction. The EUROfusion roadmap is a materialisation of technoscientific promises, including a specific type of temporality. "Reworking ITER" focuses on maintenance and repair as a broader concept, capturing sociomaterial practices that sustain the machine (Denis et al., 2015). In particular, it captures the material-discursive practices of repair, adjustment, and reinforcement when the project's fragility, failures, and delays have become a central image of ITER. Delicate practices of alignment and disalignment are prominent in this phase. Particularly, the maintenance of technoscientific imaginaries and promises is an under-researched area in STS scholarship (Duggal & Faulkner, 2020; Joly & Le Renard, 2021). The rare insights from the ongoing mega-project significantly contribute to the discussion of technoscientific promises, drawing on rich material on ITER. The discussion section summarises the research with three core themes: 1) embraced temporalities and spatiality as a robust and flexible promise-making, 2) ITER-fusion exceptionalism as generalisation and differentiation principles, and 3) ITER-fusion optimism and imperative for the forceful fusion future. Overall, it would not be an exaggeration to say that ITER itself is an ongoing dream construction for humanity in the long run.

The combination of new materialist analysis and justification theory helps explain why ITER remains legitimate and credible despite long timeframes and repeated setbacks. Paying close attention to the materiality of technoscientific promises enables examination of how they operate within the assemblage. **The research suggests that materials themselves can also serve as part of the project's justification: the very process of assembling ITER becomes evidence of what has been achieved and of the direction in which the energy future is claimed to be moving. The stabilisation of legitimacy is therefore not a fixed state, but a continuous process of alignment and disalignment, consolidation and fragmentation.** Rather than systematically analysing regimes of justification in the sense of Boltanski and Thévenot, this research examines justificatory practices that span multiple regimes simultaneously. Among these, the most overarching logic is that of commonality, including common humanity, common dignity, and the common good (Boltanski & Thévenot, 2021). At the same time, ITER appears as a project whose legitimacy is sustained through shifting justificatory appeals rather than through a single stable principle. Although this research does not systematically apply the six logics of justification — civic, market, industrial, domestic, inspiration, and fame — (Boltanski & Thévenot, 2021), these logics nonetheless appear in overlapping and sometimes contradictory ways within the assemblage. For instance, the domestication of ITER within European fusion research may sit uneasily alongside appeals to common humanity, yet both can coexist within different parts of the heterogeneous project. Similarly, the inspirational imagery of the sun and stars can transition seamlessly into civic and industrial arguments about necessity through the promise of a fusion future. From an assemblage perspective, justifications are therefore distributed across practices that combine multiple themes. Taken together, these justificatory practices give ITER a robust but flexible legitimacy, making the promised ITER-fusion future appear necessary, credible, and worthy of continued investment.

Overall, the research demonstrates that ITER is sustained by a dynamic interplay of promises, material arrangements, and justificatory practices that make a long-term, highly uncertain project appear stable enough to continue. The findings show that the project's future is not merely anticipated but actively produced in the present through coordination, repair, and repeated acts of legitimation. In this sense, the thesis offers both an empirical account of ITER and a conceptual contribution to the study of technoscientific promises.

This thesis is limited by its case-specific focus on ITER, particularly in the European fusion R&D context, which means that its findings should be understood as analytically rather than universally generalisable to all fusion R&D. In addition, the empirical material reflects a particular selection of documents, interviews, and observations, and therefore does not capture every aspect of the ITER assemblage. As ITER remains an ongoing project, the analysis can only address a specific phase in its development. Finally, this research does not assess the validity of the legitimacy and justification. It examines how promises and justifications are constructed and practised, but it does not focus on the perceptions of these claims and practices, which could be the subject of further research.

Further study could deepen the study of technoscientific promises in fusion energy by addressing aspects not covered here. One promising direction would be an in-depth historical analysis of the trajectory of ITER's promises over several decades, since earlier promise-making remains underexplored in this research. Another would be to examine the recent shift toward public-private engagement in ITER-related fusion research, which is only partially captured in this thesis due to the timing of the research. Comparative work between public and private fusion sectors would also be valuable, especially given the different temporal horizons, investment logics, and promise structures that shape each field. Private fusion startups, in particular, appear to operate under shorter timelines and different forms of risk management, making them a useful contrast for understanding overpromising, hype, and credibility. More broadly, further STS research could help clarify how fusion promises evolve across institutional settings, while the field itself continues to develop in ways that will only later reveal which promises were fulfilled, transformed, or abandoned.

7. References

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