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Abstract

Fusion is considered as one of the most attractive carbon-free energy sources with the potential to play a vital role in meeting long-term global energy needs. Research into fusion has accelerated over the past few years with more participation now seen from the private sector. Fusion is making an important transition from fundamental research to the delivery of power plants at commercial scale. Delivering fusion in a timely manner and at competitive costs still remains a challenge. This paper proposes the use of platform-based design approach as a means to address the challenges of high cost and long development times for future fusion power plants. A platform is defined as a collection of materials, parts, subsystems, interfaces, technologies, manufacturing processes and knowledge that are commonly shared by a set of products or product family in order to allow the development of derivative products faster and cost-effectively. Platform design delivers cost and time efficiencies through standardisation and economies of scale and increases design flexibility and future options. It can also allow ease upgradability of a powerplant in order to exploit future technological advances, maximise benefit from high initial cost of delivering a fusion power plant, reduce manufacturing complexity, help to create a sustainable and competitive supply chain, and enable development of designs that are easier to build, operate and maintain. Key areas of platform implementation for fusion are likely to be around standardisation and creation of designs that are flexible, modular and scalable.

Key words: fusion energy, power plants, platform design, cost, standardisation, flexible designs, modularisation, scalable designs

1. Introduction

Fusion is considered to be one of the most attractive carbon-free energy sources. It has the potential to play a major role as part of the future energy mix in order to meet long-term global energy needs [1]. Unlike other renewable energy sources such as wind and solar, fusion provides on-demand energy that is independent of weather and minimises land use thereby offering a more sustainable solution [2, 3]. When compared to fission, fusion energy is inherently safer and does not produce long-lived radioactive waste [4].

Although fusion was once looked at as a technology for the distant future, that is no longer the case as the delivery of fusion at a commercial scale is now only a decade or so away with fusion power plants expected to be operational as soon as late 2030s and early 2040s [5, 6, 7, 8, 9, 10]. The drive to make fusion happen has not been as strong as it has been over the past few years. This is reflected both in the rapid growth in fusion energy research and the increase in the level of funding and participation from the private sector. A survey by the Fusion Industry Association (FIA) in 2022 estimated a total of 33 private fusion companies and over US$4.7 billion of funding raised from private investments [11]. This represents an increase in funding of nearly US $3 billion in one year alone when compared to 2021 figures [12]. Figure 1 shows the breakdown of private investment into fusion as of the year 2022. Combined with public funding into national and international programmes such as EUROfusion ITER and DEMO [13] and the UK Spherical Tokamak for Energy Production [5], it shows an emergence of a thriving fusion industry. The level of investment also shows the confident that both public and private investors have in fusion becoming a commercial reality. Fusion is making an important transition from fundamental research where it has been over the past several decades to the delivery of power plants at industrial scale.

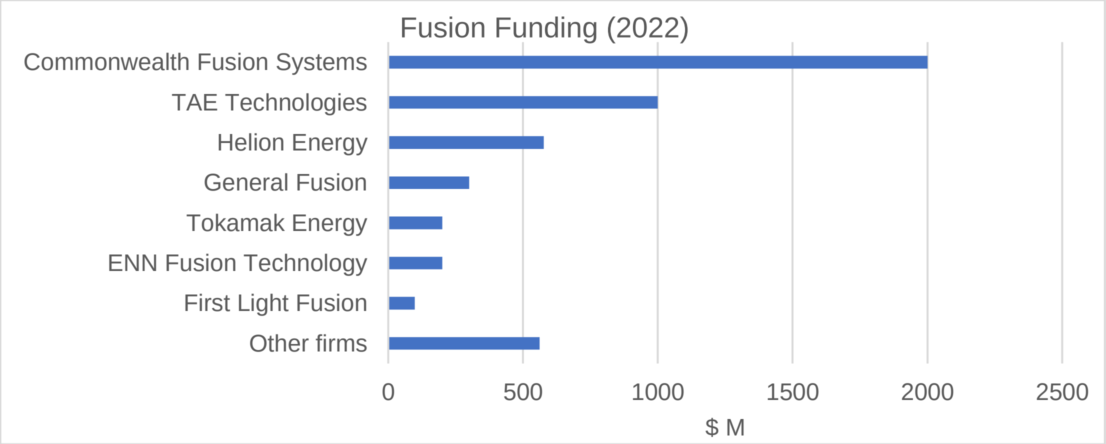

Figure 1: Total funding into private fusion companies as of 2022[1].

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[1] Not every firm declared the funding received and hence actual figures might be significantly higher.

Furthermore, not only are there already several players in fusion there are also multiple approaches to delivering fusion energy. This is important as it increases the chances of success, de-risks the technology and accelerates the delivery of fusion. The five key approaches are magnetic confinement fusion [14, 15], initial confinement fusion [16], magnetised target fusion [17, 18], field-reversed configuration [19, 20], and stellarator type configuration [21, 22]. Figure 2 gives examples of fusion companies and programmes adopting these approaches. A brief description of the five approaches is given in Table 1.

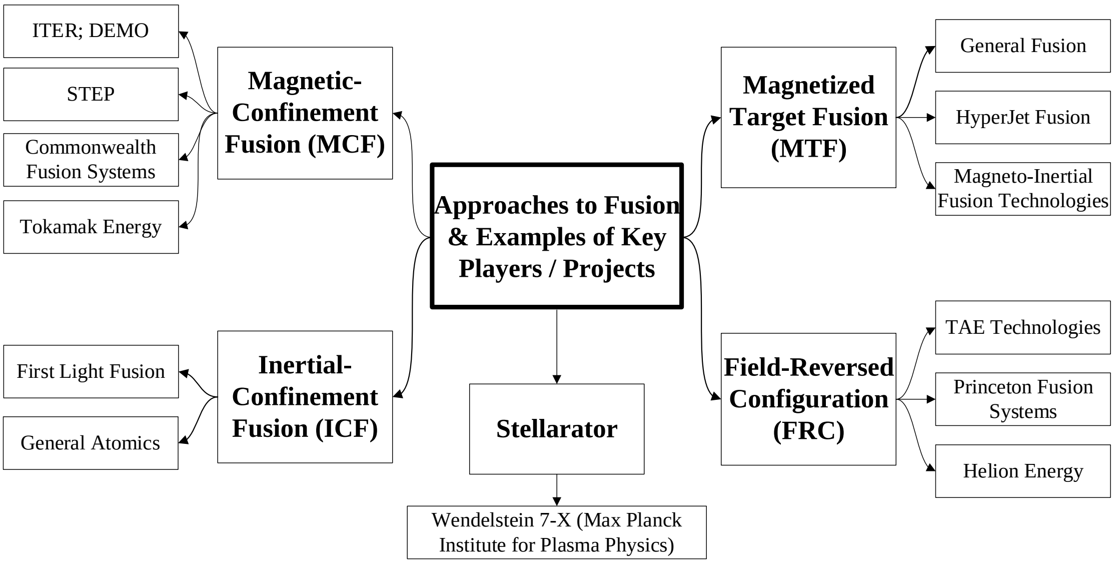

Figure 2: Different fusion technologies and key players

Approach to fusion (Technology)	**Working Principle**
Magnetic Confinement Fusion (MCF)	Utilises high magnetic fields generated by electromagnetic coils to confine a plasma in a torus vessel to enable fusion reaction [14, 15].
Inertial Confinement Fusion (ICF)	Uses lasers to externally heat and compress “fuel targets” to achieve high the right conditions (i.e., high temperature & plasma density) required for a fusion reaction [16].
Magnetized Target Fusion (MTF)	Hybrid approach utilising magnetic fields to confine a lower-density plasma, which is then heated and compressed using an inertial-confinement method [17, 18].
Field-Reversed Configuration (FRC)	A type of toroidal magnetic confinement where plasma is contained in its own magnetic field by inducing a toroidal electric current inside a cylindrical plasma [19, 20]. TAE Technologies’ design employs plasma guns to accelerate two plasmas into each other and then heats them with particle beams [23].
Stellarator type configuration	Another type of toroidal magnetic confinement that uses helical coils to produce a high-density plasma that’s symmetrical and more stable than a tokamak’s [21, 22].

Table 1: Fusion technologies

1.1. The Challenge of Technology Diversity and Role of Platform-Based Approach

While having a variety in approaches to fusion is important as it mitigates against development risk, increases chances of success and shortens time to deliver fusion, it is also likely to have a knock-on effect on areas such as supply chain if all these technologies where to be commercialised. One can anticipate a very complex fusion technology landscape which might affect the ability of the industry to quickly drive the cost down through “learning” and economies of scale. It has been shown in other industries that a high degree of variety usually has a negative impact on logistics, manufacturing costs, operational complexity, and development of sustainable supply chains [23, 24, 25, 26].

This paper explores how the concept of platform-based product design can be applied to the development of fusion devices to deal with the issues of design variety, accelerate leaning, shorten development timescales for future fusion devices, maintain flexibility and upgradability (i.e., future-proof design), and improve cost efficiencies through standardisation and economies of scale. It is important that fusion considers these aspects in order to have a more competitive offering in terms of development times, costs and ability to quickly integrate new technologies when they become available.

2. What is Platform-based Design?

A platform is defined as a collection of materials, parts, subsystems, interfaces, technologies, manufacturing processes and knowledge that are commonly shared by a set of products or product family in order to allow the development of derivative products faster and cost-effectively [27, 28, 29, 30, 31, 32]. Fundamental to this approach is standardisation, reusability and flexibility. The focus is on increasing commonality so that components, materials, processes and technologies can be reused to create a variety of derivative products instead of single one-offs. For fusion this would be about understanding which aspects of the design can be standardised and reused across the different designs and different technology approaches to fusion (e.g., magnetic confinement fusion, initial confinement fusion, magnetised target fusion, field-reversed configuration, and stellarator type configuration).

The origin of platform-based design approach can be traced back to real options theory in economics [33, 34], which is founded on the premise that flexibility in terms of having a broad range of options is extremely important. Therefore, platform-based design is not just about improving cost and time efficiencies through standardisation and economies of scale, it is also about the future options and opportunities that this form of strategic flexibility can present [35]. Having the ability to integrate new technologies as they become available without necessarily having to build a new power plant can be extremely beneficial given the significant upfront investment required to build a fusion power plant and the anticipated rapid advances in technology. Given the current pace of technological advances in areas such as materials, for example, it is easy to expect new materials to be developed in the next few years which might present a significant opportunity to extend the lifetime of fusion power plants. However, this opportunity can only be exploited if the design of the plant is such that it intentionally allows for future integration of such new materials or upgrades.

The three key benefits of platform approach can be summarised as follows:

- *A reduction in operational and supply chain complexity*. The use of platforms would enable suppliers to develop much leaner processes that target fewer variants, and hence in the longer term enabling improved efficiencies, process yields and lower costs through economies of scale. There is a big difference as shown by the Boston Consulting Group's experience curve if a supplier only makes one component occasionally (e.g., every after 10years) versus making the same component more frequently [36].
- *Increase in design flexibility and future upgradability*. Platforms increase future design options and ability to easily upgrade fusion devices when new technologies emerge in areas such as materials, magnets, and plasma heating and current drive among others. Platform-based approach has been shown to yield significant benefits as well as being a source of competitive advantage where the pace of technology change is high [37] or where there is a need for future upgradability or changeability [38], or in order to handle uncertainty in future operating contexts [39]. All these aspects are relevant to fusion power plants.
- *Reduction in development time and cost through standardisation, design reuse and economies of scale.* Planned design reuse yields high efficiencies and lower costs in the long term. It can substantially shorten design cycles by enabling quick derivative designs or upgrades once the basic platform is established and works.
- *Reduction in the level of risk through the reuse of already proven components, processes and technologies*. Using a large share of pre-verified components helps in the validation for complex designs and reduces the overall delivery risk. This is another reason why a level of standardisation across different fusion machines is important as it would accelerate learning and validation of technologies which can then be reused on future designs.

Platform-based design allows easy product modification [40] and product scaling [41] and provides future growth options [42, 40, 43, 44]. It also reduces incremental costs of developing subsequent derivative products because parts and processes developed for initial platform products can be reused and do not have to be re-developed and tested [30].

Manufacturing costs are also lower due to large volume production of common parts, thereby achieving economies of scale. Additionally, machinery, tooling, and engineering time can be shared across a family of products and for higher production volumes, which further reduce product costs.

2.1. Examples of platform-based product development

One good example of a platform-based design approach is the Volkswagen's MQB (Modular Transverse Matrix) platform [45, 46, 47] shown in Figure 3. It consists of standardised, interchangeable set of parts and subsystems from which Volkswagen Group can design a wide variety of transverse, front-wheel drive car models. These models range from small Golf to big Atlas SUV. The MQB is designed to deliver up to 60 different car models across several brands including Volkswagen (WW), Audi, Seat, and Skoda. All car models ("derivatives") share the same front axle, pedal box and engine positioning, despite their varying wheelbase, track and external dimensions. By creating this platform, Volkswagen reduced the time it took to build a new car by 30% resulting in lower costs and faster customer deliveries. Most importantly the approach significantly simplified the supply chain, which probably would be the biggest benefit of platform-based design approach for fusion where a robust and lean supply chain will be needed to deliver commercially viable fusion energy at competitive costs.

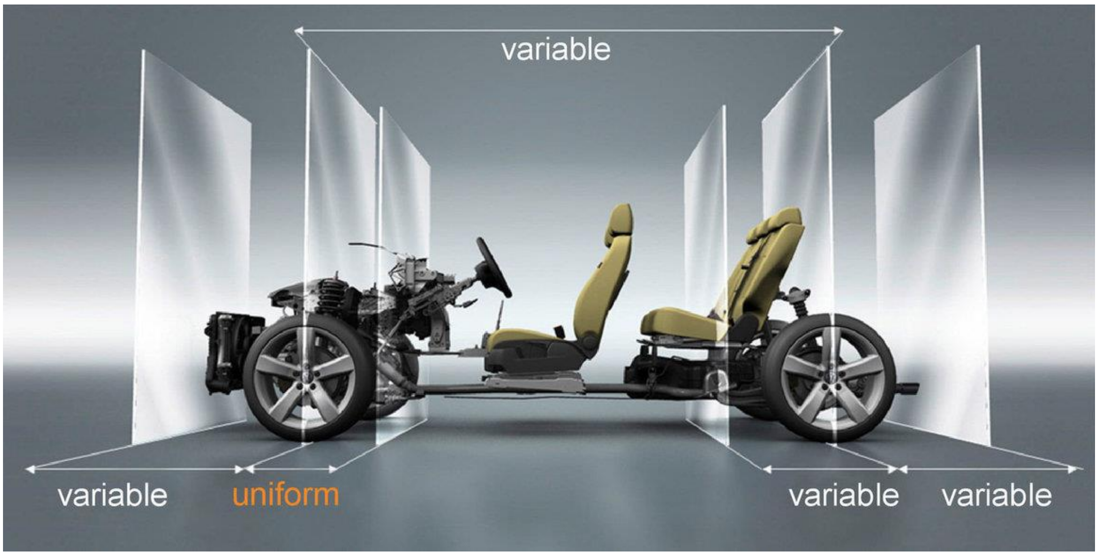

Figure 3: Volkswagen's MQB (Modular Transverse Matrix) platform (source: Modular toolkit strategy as recipe for success: the MQB celebrates tenth anniversary | Volkswagen Newsroom (volkswagen-newsroom.com))

Another example of platform-based design is the Sony Walkman from 1990s [48]. The Sony Walkman platform supported the development of more than 160 new models between 1980 and 1990, achieved by only making small improvements or changes. Platform capabilities were regularly upgraded with technical innovations to subsystems. Each subsystem enhancement enabled a new generation of derivative products. In the case of fusion this would be in terms of introducing systems upgrades in order to improve the performance of an existing powerplant.

Platform thinking has also been applied to several other areas including the design of personalized medicines [49], valves manufacturing processes for various types of hydraulic machines [50] and in the fashion industry [51]

3. Why Platform-Based approach may be important to the design of fusion power plants

There are significant benefits that can be realised by having a common lense through which technology challenges on fusion are viewed and addressed regardless of the differences in approaches mentioned earlier in Table 1. What platform design offers is the ability to increase commonality or standardisation and to develop technologies that can be reused across different product derivatives. This is important if one considers the rate at which new developments are taking place in different fusion technology areas. It is not unrealistic to expect that new alternative materials with improved properties will soon be available after the first generation of fusion power plants are built and operational in 2030s and 2040s. This is not restricted to materials but also applies to several other underlying technologies and sub-systems. New technologies for fusion machines are likely to develop rapidly over the next few decades which would quickly make the current ones redundant. Therefore, having a design where old technologies can be swapped out for newer versions without requiring a major redesign of a powerplant would be a key benefit. Design engineers should carefully ensure sufficient inbuilt flexibility to allow for such changes or upgrades to be made.

It is also important to note that although there are different approaches to fusion, most of the designs share the same basic technologies as shown in Figure 4 and Table 2. At a high level the electricity producing part of any powerplant (e.g., conversion of thermal energy into electric power) is largely generic. On the other hand, the system design for generating e.g., useful thermal energy from a nuclear reaction (represented by the nuclear zone in Figure 4) depends on the type of technology employed. However, even in this case many aspects of the system are commonly shared and are independent of the approach to fusion except for the plasma confinement technology. This already existing commonality is another reason why platform design would be a sensible approach to the development of fusion energy.

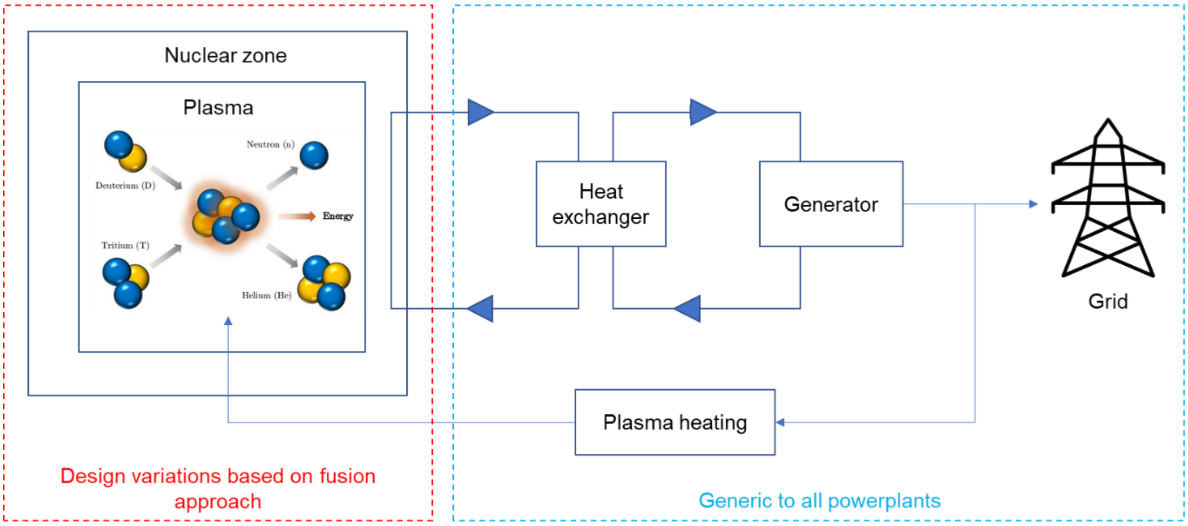

Figure 4: Distinguishing between what is unique to fusion (in red box) versus what is generic to all power plants (in blue box)

Variations based on fusion approach	
Unique to fusion approach	Independent of fusion approach
• Plasma confinement (magnets, lasers, etc.)	• Materials • Cooling systems • Plasma heating and current drive • Control and diagnostics • Fuel handling system • Vacuum system

Table 2: Comparison of what is unique to the design of fusion devices based on approach and what all fusion devices share in common

There are at least four reasons why platform-based approach should be considered in the design of fusion power plants. These are (i) ability to readily exploit future technological advances on an existing fusion powerplant, (ii) maximise the benefit from the high investment cost of delivering a fusion powerplant (i.e., maximise the return on investment), (iii) simplify and mobilise supply chain, and (iv) think long-term.

3.1. Ability to exploit future technological advancements on already built fusion power plants

The pace of technology development and change is such that new advanced solutions (e.g., new materials for fusion) are likely to be available in the next few decades. While fusion programmes cannot wait for this to happen before designing and building power plants (if these are also to be delivered in the next 2-3 decades) and as a result may have to use solutions that are currently available, they should still seriously consider designing power plants in such a way that it is relatively easy to integrate new technologies at a later stage once they become available. As demonstrated in other examples of platform-designs, this has to be done through careful planning as integration of new technologies on already existing systems is not trivial and, in some cases, maybe completely impractical. However, if this flexibility is incorporated into the thinking at design stage it will make future integration of new technologies not only possible but also easier and less costly. Platform-based approach prioritises this flexibility in order to increase future options and upgradability. This might be probably the most beneficial attribute of platform approach, offering increased design flexibility through the use of interchangeable modules, thereby enabling late-stage integration of new technologies.

3.2. Maximise benefit from high cost of delivering a fusion power plant

The high cost of delivering a fusion power plant only make sense if you are thinking of a fleet of power plants instead of one-offs where the technologies developed from the initial designs can be reused across multiple future designs. This would also help to quickly achieve economies of scale, which will be key to drive the cost of fusion power plants down and make fusion commercially attractive. From studies by [52] and others, it is shown that a typical commercial-scale fusion power plant will cost several billions of dollars. This is a significant upfront cost. Therefore, being able to reuse technologies developed for the first-generation power plants in future designs would not only reduce the costs of future power plants but also maximise benefit from the initial investments. Platform design thinking also allows for the life of the power plant to be extended through upgrades, thereby further maximising the return on investment.

3.3. Mobilisation of the supply chain

A platform-based approach to fusion will help to build a supply chain faster. Developing bespoke components is not the best way of building a sustainable supply chain due to the enormous cost (i.e., unit cost) that comes with the manufacturing of single one-off parts. It also prevents the exploitation of the benefit of experience as articulated in the Boston Consulting Group experience curve [36]. Having highly customised components is less attractive to most suppliers who would like to maintain a wider customer base at competitive costs. Therefore, the idea of increasing commonality and standardising components and technologies becomes more attractive to suppliers as it helps them to deliver large quantities of standardised parts and do not have to frequently adapt or change manufacturing processes. This also gives confidence in the longevity and availability of demand.

3.4. Thinking long term

Fusion should be thinking long-term beyond the first prototype machines to the n^{th} product, especially in terms of the development of a fusion ecosystem that delivers long-term benefits. Key questions that should be considered in this long-term strategy should include how to reduce development and operating costs, how to speed up design and development of future fusion power plants and how to increase design flexibility to better exploit future options. Addressing all these requires a platform mindset to the development of fusion power plants and supporting technologies.

4. Application of Platform-Based Approach to fusion?

There are several ways in which a platform-based approach can be applied to the design and development of fusion power plants. The key ones are standardisation, creation of flexible designs to maintain future options, modularisation and producing designs that are scalable.

4.1. Standardisation

Standardisation is key to reducing operational complexity and achieving economies of scale. It is the central basis of platform design and can lead to significant cost benefits. At the same time standardisation means that products are less customised. This might not be desirable if having highly customised designs is a key source of competitive advantage or unique selling point. Therefore, when considering platforms and standardisation, one should carefully look at areas where the benefit of cost and time efficiencies outweigh the disbenefits of less customised products. For fusion power plants this means focusing on areas where standardisation would result in significant reduction in cost, reduce manufacturing and supply chain complexity, and reduce delivery times in relation to long-lead items or systems requiring multiple years of development time such as magnet systems for magnetic confinement fusion devices [53] and gyrotrons for plasma heating and current drive [54].

Since reducing cost is one of the drivers for standardisation, it is also important to focus efforts on technologies which account for the majority of the power plant cost. Using example shown in Figure 5 of a magnetic confinement fusion, these would include magnets, buildings, reactor systems and heating and current drive system.

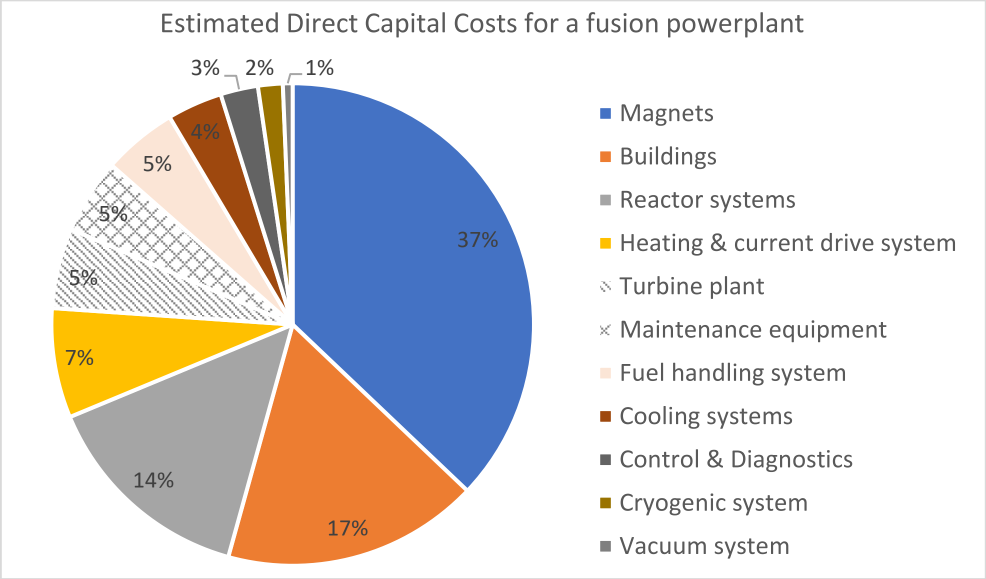

Figure 5: Pie chart based on Investment costs of the model DEMO2 in 2015, The presented costs do not include the cost of money (overnight costs type). [55, 52]

Standardisation can be applied at various points of the value chain and in multiple ways including standardising geometrical specifications such as magnet tape width and magnet coil size, manufacturing process, raw materials, or testing, validation, and qualification procedures.

4.2. Flexible designs

There is a real opportunity given the pace at which enabling technologies for fusion are being developed to allow for future upgrades of fusion power plants to incorporate new technologies as they become available in order to either increase performance of powerplants or extend lifetime. The development of advanced solutions that improve on the performance of current options in areas such as magnets, materials, plasma heating and current drive, cooling systems, and control and diagnostics is already underway. An example is work on development of high temperature structural materials such as ODS steels and non-metallic Silicon Carbide based composites that will increase the temperature operation window for fusion in order to deliver high thermal efficiencies [56], development of high-performance neutron shielding materials such as tungsten borides [57], and cleverly engineered plasma-facing materials [58, 59]. Similarly new developments in magnets [60], plasma heating and current drive [61], and control and diagnostics [62, 63] to increase performance, operating window, neutron irradiation tolerance and component lifetime are advancing at an accelerated pace. To benefit from all these developments fusion power plants should be designed in such a way that they allow for future upgradability where new technologies can be easily incorporated when they become available.

In addition, flexible designs may not be limited to replacing technologies with new improved counterparts. It can also be in terms of the ability to adapt the powerplant to a different operating context or market need than initially envisioned. This might include switching from for example electricity generation to hydrogen production.

4.3. Modularisation

Having a design based on interchangeable and replaceable modules would allow for ease of adaptability, upgradability, manufacturing and maintenance. This is one way of achieving a flexible design discussed in the previous sub-section. Modules can also be standardised across a family of fusion devices or power plants as shown in the example of the Volkswagen's MQB (Modular Transverse Matrix) platform example [45, 46, 47]. This is key to achieving the much needed cost efficiencies through economies of scale, as well as making it easier and faster to swap out parts without requiring significant modifications and dealing with long development times for replacement parts.

4.4. Scalability

Another way platform thinking can be applied to fusion power plants is by designing devices that are scalable. This is particularly in terms of the ability to expand the capability of a powerplant beyond what was initially envisioned. An example would be to increase power output of the plant by for example installing technology upgrades. The powerplant can also be scaled by adding a new capability such as the ability to harvest low-grade waste heat into useful energy utilising advanced fuel cell technology or adding a capability for hydrogen production in addition to electricity production.

5. Conclusions

Platform design approach can deliver significant benefits to the delivery of fusion power plants. These benefits include enabling ease future upgradability of a power plant to exploit new technology developments, helping to create a more sustainable and competitive supply chain, reducing supply chain and manufacturing complexity, reducing costs of developing and operating fusion power plants making fusion energy commercially attractive, maximising benefit from the high initial cost of setting up a fusion powerplant, and developing designs that are easier to build, operate and maintain. The application of platform design to fusion should target areas of the design where the greatest benefits of standardisation, reusability, flexibility and future upgradability can be realised.

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