UKAEA-STEP-PR(24)09

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This is a preprint of a paper submitted for publication in
Philosophical Transactions A

PHILOSOPHICAL
TRANSACTIONS A

Phil. Trans. R. Soc. A.
doi:10.1098/not yet assigned

Staying Positive – Producing Net Power

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Keywords: STEP, Power, Energy, Fusion, Powerplant, Thermodynamics

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Summary

The STEP Prototype Powerplant (SPP) will be a first of a kind powerplant - its prime objective is to export electrical power, to the grid, above 100MWe.
As part of a wider issue, addressing the STEP concept design, this paper seeks to explore how electrical power will be generated from a Spherical Tokamak heat source. Accordingly, the following key functions of the SPP Power Infrastructure, are reviewed:

- **Cool the tokamak:** Cooling of the tokamak while extracting useful thermal energy.
- **Generate power**: Conversion of thermal energy to electrical energy (power generation)
- **Manage energy:** Management of the site-wide distribution, storage, and energy export.

In each of these areas the design scope, challenges, and solution spaces have been discussed. This has shaped the design of the SPP Power Infrastructure, which in turn has ensured a powerplant design focused on operability and performance. Furthermore, it has been demonstrated that the SPP will achieve its prime objective in generating net power, which is enabled by a unique Power Infrastructure. Confidence in the ability to generate net power will be refined as the design matures. Finally, this paper recommends key opportunities that STEP could utilise to improve power generation and reduce the parasitic load of the SPP.

1. Introduction

Conversion of fusion heat into electrical power is the current paradigm of many fusion projects. Firstly, the neutron and radiative heat resulting from the fusion reaction must be removed via multiple coolants within the tokamak. This process employs dedicated coolants for each In Vessel Component (IVC). The heat from the IVCs must be integrated into a thermodynamic cycle, which in turn will generate electrical power. This power must then be managed across the plant, as tokamaks have notoriously high power demands which is unique for a modern powerplant. Magnets and the Heating & Current Drive (HCD) systems are some of the most significant power users. The power transfer and conversion paths are summarised in Figure 1.

The STEP Power Infrastructure team is responsible for the design of the thermal and electrical energy management across the SPP; it is also responsible for the thermal to electric conversion. The SPP Power Infrastructure is split into multiple systems to achieve its functions:

1. **Power Cycle and Cooling System**, which contains the following sub systems:

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- **Thermal Power Transfer System (TPTS)**: This system integrates the coolant and heat from the IVCs and transfers the heat to the thermodynamic cycle.
- **Working Fluid and Power Generation System (WFPGS)**: This system uses the integrated heat within a thermodynamic power cycle to generate power.
- **Site Water and Waste Heat System (SWWHS):** This system rejects the low-grade waste heat from the power cycle and parasitic loads to the environment using cooling towers.
- **Cryogenics System:** This system will meet the requirements of several subsystems that require cryogenic refrigeration, for example, superconducting magnets.

2. **Electrical Infrastructure**, which contains the following subsystems:
   - **Electrical Distribution Network (EDN)**: This system is responsible for the distribution of electrical power to different areas of the SPP.
   - **Grid Connection System (GCS)**: This system forms an interface between the SPP and the National Grid.
   - **Central Energy Storage System (CESS)**: This system stores energy which is dispatched during start-up of the SPP.

This paper will discuss the contextual background and design scope of the Power Infrastructure's primary functions: cool the tokamak, generate power and manage energy (N.B. certain functions are met by multiple systems). This paper will then focus on the challenges and technological solution space for the various systems. Critical design trades made, which will ensure an efficient, flexible, and safe integrated solution, will be discussed. In pertinent areas, the importance of commercial viability will also be outlined.
Finally, this paper will review the holistic challenges of achieving net positive power within the SPP during this conceptual design stage of the SPP.

2. Cool the Tokamak

Heat Generation from Fusion

The SPP tokamak relies on the fusion of deuterium and tritium nuclei. This fusion reaction releases large amounts of power (known as fusion power or P_{fus}) as both neutronic heating and alpha particle heating. The heat that must be removed from the tokamak is not solely from fusion power. Tokamaks use a Heating and Current Drive (HCD) system to sustain the plasma. This also adds power into the plasma, referred to herein as $P_{aux.}$ Within a powerplant setting, tokamaks must breed tritium as fuel. This is bred in the blanket using a mix of lithium isotopes and a multiplier; this breeding and neutron multiplication is typically exothermic and generates heat in addition to the neutronic heat deposited in the blanket. The heat generated from breeding and multiplication is additional to the heat from fusion and must be considered as part of the total tokamak thermal heat output during a steady state breeding operating scenario (which applies to both Spherical and Conventional Tokamaks [1]). The heat released from breeding is referred to herein as $P_{breeding}$. Heat developed from the neutron interaction with other materials in the vessel components (e.g. structural steels) is also accounted for in this $P_{breeding}$ term. Therefore, the total thermal power from the tokamak can be defined as:

$$P_{therm} = P_{fus} + P_{aux} + P_{breeding}$$

Equation 1 Total Thermal Power

For the SPP, a fusion power (P_{fus}) of 1750MWth is defined based on a range for the achievable plasma [2], the combined heat from breeding ($P_{breeding}$) and the HCD heating (P_{aux}) is 417MWth (based on heat injected into the plasma and neutronics analysis), resulting in a total tokamak thermal power (P_{therm}) of 2167MWth.

To maximise power production, all heat from the tokamak should be captured and integrated into a thermodynamic power cycle, as far as reasonably practicable. The total P_{therm} heat developed within a tokamak can be categorised into different "types" of heat:

- **Neutronic heating**: this will be a "volumetric heat load" within the whole tokamak.
- **Radiative heating**: This is the radiation from the plasma, which will impact Plasma Facing Components (PFCs). This should be considered as a "surface heat load" on PFCs
- **Charged particle**: this is heat imparted from plasma inside the vessel via direct contact with certain PFCs. This should be considered as a "surface heat load" on PFCs (primarily divertor PFC).
- **Breeding**: This is the heat generated by nuclear reactions within the blanket (including breeding reactions). This will be a "volumetric heat load" within the blanket.

Understanding volumetric and surface heat loads is a key factor in defining the heat splits across the IVCs.

Design Challenges and Solution Space

Maximising Tokamak Heat Usage

Achieving net power is dependent on how much heat, generated within the tokamak's IVCs, can be used to generate electrical power rather than rejected to the environment. Each IVC has specific, and typically unique, cooling requirements [3]. Whilst it is recognised that maximising heat usage for power generation is important, there are instances where the heat from an IVC coolant cannot be used. If the temperature of the coolant is very low (circa 150°C or less), it is impractical to integrate this heat into the thermodynamic cycle. This is because there is already a significant amount of low grade heat (200-250°C) from the STEP Tokamak that displaces the ability to efficiently integrate further heat below this grade. This is the case for the inboard shield (inner) and the vacuum vessel for the SPP, where the coolant temperatures are too low, and therefore the heat from these components will be rejected to the environment (or if possible, used for utility heating)) - as seen in Figure 6 where a small portion (45MWth) of the heat is "dumped".

Conversely the heat from the blanket, first walls (inboard and outboard), inboard shield (outer), limiters, and divertors will all be used for power generation as shown in Figure 2. The combined heat extracted from these components make up 98% of the total Tokamak thermal power (P_{therm}). However, the integration of these heats into the thermodynamic cycle adds coolant parameter constraints for the IVCs in question (e.g. temperatures, discussed in section 3).

Choosing Tokamak Coolants

Coolant selection is important to many areas of the plant design, including in-vessel component design, power integration and tritium breeding. The SPP IVC coolant choices are summarised in Figure 2.

A number of critical design trades were made, as part of the coolant selection for the IVCs:

1. A liquid metal lithium breeder is necessary to achieve the desired Tritium Breeding Ratio (TBR). This causes inherent complexity in design and adds safety risks [4].
2. Water will be used in inboard components for moderation purposes, maximising magnet lifetime and limiting cryogenic loads. Water temperatures will be limited by component allowable operating pressures (as phase changes must be avoided) which in turn can limit heat integration into the power cycle and have a negative impact on net power. There is also a safety consideration when water and liquid metals are used in the same tokamak machine.
3. Water was selected to cool the high heat flux divertor PFC as it ensures a sufficient heat transfer coefficient. There are water temperature constraints, as discussed in point 2. The TBR can be marginally improved by using D_2O instead of H_2O. Molten salts and helium were de-selected due to poor heat flux handling. The use of lithium was not advised due to safety and Technology Readiness Level (TRL). Both molten salts and lithium pose a significant Loss of Cooling Accident (LOCA) risk.

4. The outboard first wall and blanket coolant needs to ensure neutron transparency (for improved tritium breeding), be safe to use with the liquid lithium breeder, minimise corrosion problems with structural materials and minimise activation products. Helium was therefore selected. This accepts the negative impact of net power due to the large parasitic load required for coolant circulation.
5. The number of coolants is limited to ensure that maintenance is viable. More than two coolants in the machine incurs machine and plant complexity, hindering design, installation, and maintenance [5].
6. There are no direct interfaces between reactive coolants (i.e. water and lithium).

Managing Multiple Coolants

The Thermal Power Transfer System (TPTS) is responsible for integrating multiple IVC primary coolant loops with the thermodynamic cycle. Among other things, the TPTS must ensure:

- **Coolant circulation (pumps and compressors):** Helium compressors at SPP's conditions will require significant technical development.
- **Coolant purification**: The coolants will be exposed to high neutron fluxes, and as a result are expected to develop harmful impurities that can reduce component lifetimes and impose safety risks; therefore, effective and on-going chemistry control is required. Moreover, coolants will become tritiated after exposure to the in-vessel components and must be de-tritiated [4].
- **Coolant inventory management**: Due to operational regimes of the SPP, routine filling and draining of coolants is required, and hence requires on site storage and disposal routes.

Minimising Pumping Powers

Gas coolants will incur large parasitic loads, via gas compression. The TPTS will minimise this by considering:

1. **Maximum Coolant Pressure** Ensuring a high-pressure gas coolant loop equates to a lower compression ratio, minimising compressor power demands. However, high pressures may limit the design of the IVC, for the blanket this can restrict the TBR (due to larger structural volume).
2. **Heat Exchanger Design** Adapting the heat exchanger design to minimise this pressure loss will be critical in reducing pumping powers. This will result in a trade between sensible heat exchanger designs and optimising for pressure loss, at a given heat exchanger efficiency.
3. **Loop pressure losses and layout** Pressure losses across the loop overall must be minimised, by maximising pipe sizes and minimising losses through manifolding and control elements. This can result in spatial design trades within allocated port spaces and in areas close to the tokamak.

Cryogenic Cooling

Cryogenic refrigeration is required by several SPP subsystems, such as superconducting magnets requiring 20 K cryogens. The thermal shield and cryopumps also require refrigeration. The cryogenic refrigeration will be supplied by a cryoplant with an associated distribution system and helium as the refrigerant. The total power consumption of the cryoplant is estimated to be 20-30 MW. The cryoplant will satisfy four temperature points.

3. Generate Power

Power Generation Methods

Once the heat has been generated and extracted from the tokamak it is transferred to a power generation cycle for conversion to electricity. By far, the most common power cycle in power plants today is the Steam Rankine Cycle (SRC), although other technologies exist such as variants of the Brayton cycle.

In a fusion context, primary coolants typically transfer the thermal energy gained into a separate working fluid (secondary coolant) via a heat exchanger. This working fluid is then used in a prime mover to create mechanical energy (for example, a steam driven turbine – where steam is the working fluid); this is an example of an indirect cycle configuration. Direct cycles, where the primary coolant and working fluid are the same, were discounted as a possibility in the design of SPP. A direct cycle simplifies the design of the total power plant. Conversely a direct cycle either constrains the power cycle or the IVC primary coolant conditions, resulting in an excessively low power generation or an unrealistic IVC design, respectively.

The mechanical energy produced in the prime mover is converted into electrical power in a generator directly connected. The generator producing electrical power is synchronised to the grid.

One of the challenges associated with the power generation system is sustaining the inherent flexibility to withstand prototypic activities, while also ensuring high efficiencies to deliver net power.

Thermodynamic Power Cycles Landscape

During the early stages of the SPP design, many thermodynamic cycle technologies, and combinations thereof, were considered for their applicability as the SPP power cycle. The performances of these cycles are summarised in Figure 3; this figure also shows a minimum viable efficiency threshold. This threshold is calculated by considering the thermal power which can be integrated into a power cycle from both the tokamak ($P_{therm} \approx$ 2120MWth) and the primary pumping (≈160MWth). The total added thermal power into the power cycle (≈2280MWth) and the total plant parasitic loads (≈ 780 MWe) are used to calculate a minimum viable efficiency of ≈ 39% needed for 100MW net power export to the grid.

This minimum viable efficiency assumes that the majority (98%, as defined in section 2) of the heat from the tokamak may be integrated into (ideally) one thermodynamic cycle or multiple cycles. For a single thermodynamic cycle, the turbine inlet temperature is driven by the blanket coolant temperature (or high temperature heat) and it is assumed the heat from other IVCs is integrated at various stages of the cycle (e.g. water pre-heat for SRC). Designs which use multiple cycles will have different turbine inlet temperatures driven by different IVC coolant outlet temperatures.

A summary of the possible cycles and cycle configurations for the SPP is outlined below:

- **Steam Rankine cycle (SRC)** (Superheated) is the paradigm for most fusion power plants [6]. It is a low risk, established technology that could potentially be adapted to suit the needs of a fusion power plant. The key challenges associated with this cycle (for the SPP) include risk of large heat rejection due to heat integration challenges, and low flexibility when coupled with a highly dynamic fusion application. Supercritical steam cycles can also be envisioned, in this instance a trade must be made to adapt a less established technology for slightly higher efficiencies at a given temperature.
- **sCO_2 Brayton cycle** and its variants present an opportunity for greater heat integration, whilst being better suited to the flexibility demands of prototypic operation. However, this technology is currently immature, with no demonstration at the required scale. The sCO_2 technology is inherently more compact which allows for more adaptability versus dynamic scenarios, it will also be cost effective (after first development) and will occupy less footprint [7].
- **Helium and Nitrogen Brayton cycles** will not meet the minimum required efficiencies at the temperatures of interest for SPP and therefore not suitable.
- **Organic Rankine Cycle (ORC) & Kalina Rankine Cycle** (two-fluid mixture, such as water or ammonia): are currently used for smaller scale applications. It has been considered for SPP in combination with other cycles to recover the low-grade waste heat – however evaluation of this

combined cycles technology has shown incompatibilities regarding safety, size and complexity aspects of the whole plant. For these reasons, these technologies are not suitable for SPP.

There are therefore only 2 viable options to ensure minimum viable thermodynamic efficiencies with the available heat from the tokamak: sCO2 cycle (a Recompressed Brayton Cycle (RCBC) variant) and steam Rankine cycle (superheated OR supercritical).

Design Challenges and Solution Space

Achieving Temperatures

To increase power output from the SPP, temperatures from the IVCs must be maximised. The efficiency of the power cycle is directly controlled by the blanket outlet temperature, as this is both the highest temperature achievable and the largest amount of heat. Nonetheless due to the heat splits and the large amount of heat deposited into the other in-vessel components, the temperatures of the other IVCs will have an impact on the ability to optimise the power cycle – ultimately impacting the thermal to electrical conversion.

It is important to maximise temperature for the prototype demonstration, but this is also a key factor for commercial viability. Furthermore, temperatures may be demonstrated for other high temperature industrial processes, supporting a wider global decarbonisation beyond the grid [8].

Integrating Heat and Ensuring Efficiency

Heat recuperation and integration within the cycle is critical when maximising efficiencies. Heat which is linked to individual IVCs of the tokamak and operating at different conditions, must be integrated into the thermodynamic cycle(s). A cycle that can add versatility and margin to heat integration, will be better placed to incorporate as much of the heat from the tokamak (P_{therm}) as possible, improving efficiencies and net power output. This has been an important factor in the power cycle development for SPP. Heat integration has been maximised for both the SRC and sCO_2 technologies (within a single thermodynamic cycle) resulting in comparable thermal to electric conversion efficiencies from a single tokamak design point.

The heats from the different in vessel components, which are extracted with coolants operating at varying temperature and pressure conditions, must be integrated sequentially and between turbomachinery components and stages. Heat must also be integrated between heat recuperative steps within a thermodynamic cycle, this is especially true for the sCO2 technologies [9].

Other design parameters may also be considered to maximise the overall cycle efficiency such as:

- Cycle layout and location: in proximity to the tokamak, and component location relative to each other
- Component design: heat exchanger and turbomachinery efficiencies.
- Energy losses from the system: heat and pressure losses from components/piping.
- Heat rejection to the environment: considering seasonal impacts and cooling tower efficiency.

Ensuring Flexibility

Operational flexibility will be required during all phases of STEP prototypic operations. This is emphasized when considering the dynamics of plasma (as shown in Figure 4) and pulsed operations; translating into rapid and frequent start up/shut down regimes for the SPP relative to traditional power plants.

To support this dynamic requirement, the Working Fluid and Power Generation System (WFPGS) will provide the following functions:

- **Availability**: Ensuring that the WFPGS is available without fusion power and ready to receive fusion power.

- **Independence**: Ensuring the WFPGS equipment can be controlled independently; allowing a safe shut down of the systems during a trip and increasing chances of a recovery after a plasma disruption.
- **Variation Handling**: Ensuring consistent power plant performance during unknown operational regimes and plasma performance. This will ensure predictable external interface requirements.

Auxiliary heat, which can be used to run the power cycle independent of tokamak operations, will ensure the WFPGS can achieve these functions. Auxiliary heat may be provided from energy storage solutions or an alternative heat source – both have benefits and drawbacks [10]. As commercial viability is demonstrated, this need is diminished due to operational predictability.

Thermodynamic cycles which can accommodate auxiliary heat and supplement it, is an important factor in the WFPGS solution development. This will include how inherently adaptable and flexible a cycle is in these dynamic scenarios. The sCO_2 technology and its compact turbomachinery, lends itself well to these scenarios.

Whole Plant Power Cycle Solution Space

A power cycle solution is required to address the fusion-specific challenges of the SPP. The sCO2 technology presents an interesting opportunity to maximise both efficiency and flexibility around the SPP operations – and therefore is being pursued for the SPP. Nonetheless, the development risks linked to sCO_2 technology are acknowledged, hence the steam Rankine technology remains a fallback position and is studied in conjunction. Using figure 3, for an sCO2 cycle with a turbine inlet temperature close to 600°C (driven by the blanket coolant outlet temperature defined in figure 2), a thermodynamic efficiency of ≈ 45% could be estimated for the SPP design point. However, some conservatism must be applied to account for the added inefficiencies and energy losses (pressure and heat) linked to complex heat integration; especially due to the temperature loss across the primary blanket heat exchanger, impacting the maximum turbine inlet temperature. For these reasons an efficiency of 40-41% is estimated resulting in a 925MWe output as per figure 6.

4. Manage Energy

Overview of SPP electrical power demand

Initiating and sustaining nuclear fusion reactions requires a significant energy input. In a tokamak, the plasma particles must reach extreme temperatures, up to hundreds of millions of degrees Kelvin. On SPP, due to the "non-inductive" flat-top, which allows for continuous non pulsed operation ([11]), plasma current is induced exclusively with external radio-frequency heating sources. The heating and current drive (HCD) system transfers high frequency electromagnetic radiation to the plasma via radio frequency (RF) heating [11]. Existing HCD technologies remain relatively inefficient (40-45%), which results in significant parasitic losses throughout SPP operation (≈362 MW during steady state, see Figure 6). The primary source of this inefficiency stems from the conversion of electrical power to RF power (gyrotron efficiency).

Additionally, tokamaks utilise strong magnetic fields to initiate and control the plasma, this is another major source of power consumption. The SPP will use superconducting magnets to confine the plasma, which are deemed crucial due to the very high electrical currents needed to confine the plasma [12]. This necessitates a large cryoplant that can ensure the superconducting magnets are operated at suitably low temperatures. The electrical power demand of these systems is combined with other users including: the fuel cycle, water cooling and building loads, to give an "Additional Parasitic Load" of ≈248 MW, as shown in Figure 6.

Pumping of the primary coolants (as defined in Figure 2) will require a significant electrical supply (≈166 MWe), this is linked to the gas coolant requirements as defined in section 1. In addition, the compact nature of the Spherical Tokamak and its IVCs, will incur added pressure losses leading to high compression power requirements. The majority of this power (160MWth) will result in heating of the coolant, due to assumed motor efficiencies of ≈96%.

The thermal energy produced by within a tokamak is to be extracted and coupled with a thermodynamic power cycle technology (see section 3), aiming to export power to the grid. Losses linked to pumping of the working fluid and other inefficiencies in the cycle are accounted for in the thermodynamic cycle efficiency.

Future technology improvements could enhance the efficiency of the plasma HCD and thus reduce the total electrical losses of the system, but they will remain a challenge especially during the start-up and shut down of the plasma. A selection of SPP's steady state electrical loads are highlighted in Figure 6. The power cycle and plasma heating loads represent the bulk of overall electrical losses.

Design Challenges and Solution Space

SPP Operations and Dynamics

A simplified view of the operation of SPP is provided in Figure 4. The start-up period describes the state in which the plasma is ramped up and in which SPP’s parasitic loads are expected to reach their peak value. The SPP’s electrical power demand outside of steady state will need to be sourced independently of the SPP power generation and will be hundreds of MWe. The current concept design assumes that a combination of power import from the National Grid (at the 400kV transmission network connection node) and power from a Central Energy Storage System (CESS) (embedded within the Electrical Distribution Network) could cater for those high parasitic loads. The exact split between those two power sources will be dependent on the electrical characteristics of the 400 kV grid connection at West Burton. The majority of the SPP’s fast power transients are expected to be supported by the CESS, to minimise impact on the Grid connection.

Once steady state/ flat top operation is achieved the fusion power then can be used to drive the power cycle and thus the SPP could start producing its own electric power. This process would not be instantaneous as the power cycle will possess its own time constants and thus electric power production would lag. The time that it takes for the SPP to output its full electric power, and thus supply both its internal electrical needs as well as export net power to the Grid, would determine the requirements for electrical energy that would need to be sourced from the GCS and the CESS.

Procuring such large amounts of electric power and energy (like the ones described in Figure 6) to initiate and sustain the fusion reaction, is a significant challenge for any electrical infrastructure system that aspires to support a fusion powerplant. At the same time maintaining voltage levels within acceptable limits across the Electrical Infrastructure would add more complexity to this challenge requiring adequate reactive power compensation mechanisms to be deployed. Establishing a strong electrical connection with the National Grid could reduce this challenge, but for future commercial applications where strong grid connections may not be available, there will be potentially a stronger dependency on a large CESS to support both active and reactive power requirements.

SPP Electrical Distribution and Power Source Integration

A high-level overview of the SPP’s Electrical Infrastructure is depicted in Figure 6. The Electrical Distribution Network (EDN) will distribute electrical power to all plant’s electrical loads according to their nominal ratings. It will comprise of an array of protection, control, and conditioning (reactive power compensation and harmonic filtering) equipment which will ensure that all site areas receive adequate levels and quality of power in a safe and reliable way. The current concept design splits the SPP loads into two with the steady state loads, mainly non fusion loads, connected to a 132 kV distribution network node (Steady State EDN) and the pulsed loads connected to the 400 kV transmission network (Pulsed EDN). This approach ensures that the constant power loads are decoupled from the power transients linked with the fusion loads.

The interconnection of three different power sources (CESS, Grid, Power Generation) through the SPP Pulsed EDN is another significant challenge. Each power source will have a unique operational profile and dynamic characteristics. Hence, the integrated control of the three power sources must achieve a balanced overall power and energy flow across all operational phases. Handling different load dynamics and responding to off-normal events would add complexity into this control task [13]. On top of that the current concept design assumes a single point of connection for power import and export at the 400 kV transmission network connection node. A design that would deploy local electrical energy storage (independent to the CESS) or load shedding equipment closer to the systems that exhibit fast dynamics could provide isolation from their transient effects and ensure that the Power Generation does not loose synchronism with the grid. Some of the fastest dynamics in the SPP are related to controlling the magnets and the HCD output. These systems are connected to the Pulsed EDN through a series of power converters, each with different technical requirements ranging from high voltage and low current to high current and low voltage. These power converters will be the backbone of every fusion powerplant and must have very high efficiency (to minimise overall parasitic losses) in all operating regimes as well as exhibit very high reliability. Power converter topologies (see Figure 5), inspired by the renewable energy industry, could enhance the control of plasma current and improve plant operations during transient events.

5. Staying Positive: Net Power Holistic Evaluation

Net Power Definition

Net power is defined as the net electrical power produced during steady state “flat-top” D-T operations after accounting for all parasitic loads required for operations. SPP aims to demonstrate a 100 MWe minimum export to the national grid. As a prototype, the following conditions apply to SPP when demonstrating net power:

- Only electrical power converted from thermal power (defined as P_{therm} in Equation 1) from the tokamak will be used to count towards net power generation and to meet all parasitic loads.
- Net power demonstration at flat-top does not require net energy generation over the course of a whole pulse or any other time period (i.e. net power pulses need not account for additional energy required for start-up and shut-down, or to sustain system between pulses).
- Net power operation must be repeatable and stable.

It is expected that a commercial plant will run for order of magnitude longer periods, making some of these considerations irrelevant.

Net Power Evaluation and Design Impact

Net power to the grid is evaluated using the net power equation:

$$Net\ Power\ Export\ to\ the\ Grid\ =\ Electrical\ Power\ Generated - Internal\ Parasitic\ Loads$$

Equation 2 Net power to Grid

Figure 6 illustrates how the different elements of this equation sit within the conceptual architecture of the SPP Power Infrastructure. The blue arrow represents electrical power generated (925 MW), the red arrows represent internal electrical parasitic loads (776 MW in total), and the yellow arrow represents net power exported to the grid (149 MW). These numbers represent a best-guess scenario, around which there remains uncertainty stemming from performance uncertainty of both plasma and individual technologies.

As per Equation 2 and Figure 6, to maximise net power and improve confidence, one should focus on:

1. The ability to maximise power generation (see sections 2 and 3).
2. The ability to manage energy as efficiently as possible, minimising parasitic loads and distribution losses across the power plant (see section 4).

Net Power is not the only consideration of the SPP and many design trades are necessary to achieve a feasible, holistic plant design. Key examples of design trades have been discussed in this paper (i.e.: coolant selection, coolant temperature, spatial constraints, and direct vs indirect power cycle). Further design trades include:

- Fusion power – higher fusion powers can increase net power but will increase size and costs.
- HCD requirements for the plasma – plasma scenarios that require the least HCD input (high-confinement mode operation) are also more susceptible to Edge Limiting Mode (ELM) disruptions, creating a trade-off between the likelihood and simplicity of achieving stable and safe power producing plasmas, and the net power they may produce [11].
- PFC Heat fluxes – designing a more compact plant may reduce capital expenditure but increases heat fluxes on the plasma facing components thereby increasing coolant pumping powers [3].
- Maintainability – remountable joints in the Toroidal Field (TF) coils improve the ability to carry out plant maintenance and reduces its cost. However, coil joints introduce resistive losses in the magnets, increasing their power requirement and increasing the size of the required cryoplant [12].

Net Power Holistic Challenges

Driving Efficiencies Across Multiple Concepts

The Power Balance Model (PBM) software has been developed by STEP Power Infrastructure to analyse the power balance of a fusion powerplant. The model estimates electrical power consumption of different SPP systems and the plant's power generation using a suite of bespoke models that are inter-linked with a python Application Programming Interface (API) [14]. The PBM was used extensively throughout early stages of the SPP concept design as it enabled an assessment of many configurations and their ability to export power. It was also used to validate design decisions that could improve the efficiencies of various SPP systems and hence would improve confidence in net power export. As the SPP concept has evolved, the evaluation of net power has matured. Power generation and coolant pumping powers are defined with high fidelity process modelling. Individual parasitic loads are determined by system design following a single design point (with upper and lower predictions). The data captured is combined allowing an overall estimation of net power and its uncertainty to be made. The process helps drive efficiencies across the SPP design by integrating estimates from multiple teams, firmly embedding the net power target in the design process.

Reducing Uncertainty and Driving Confidence

Confidence in net power is driven by uncertainty within the underlying parasitic load and power generation estimates. This is related to the maturity of the SPP concept design, as well as the inherent uncertainty in achievable plasma performance. As the SPP design evolves, so will the constituent systems; ensuring a better understanding of performance after the refinement of power generation and consumption data. Furthermore, as the SPP plasma scenario and tokamak structure develop, there will be an improved performance understanding, which will reduce uncertainty in the total power generation available during flat top.

Critical Opportunities to Increase Net Power

Part of SPP's mission is to provide a *path to commercial viability of fusion.* To be cost-competitive a commercial fusion plant will need to increase the overall efficiency with which fusion power is converted to exportable net electricity. This paper has discussed key technology areas that impact net power, and it is of no surprise that many of these present the main critical areas of opportunity moving forwards:

- **Fusion power optimisation** – For a given design, and a constrained geometry, fusion power should be optimised, capturing holistic impacts on net power, which may be counter-intuitive.
- **Power cycle efficiency** is critical in maximising net power – this is largely dependent on IVC temperatures. Research into new materials may present opportunities to increase the temperature of coolants – thereby unlocking new power cycle efficiencies and improving heat integration.
- **Pumping powers –** Pumping of the primary coolants is a significant parasitic load. Altering and optimising the design around relaxed IVC requirements may provide the space for radical changes (such as coolant types), significantly reducing pumping powers.
- **Plasma performance and HCD efficiencies** – HCD is predicted to be the largest parasitic load for a STEP-like power plant. To increase net power, plasma scenarios with low HCD input requirements utilising efficient HCD technologies, such as EBW, need to be realised. System efficiencies of the HCD systems have an impact but become less important as the required amount of HCD reduces [15].
- **Magnet & cryopump technology** – this is a significant parasitic load in the current SPP concept. Key opportunities lie in exploring the use of superconducting cables for distributing power to the magnets and optimising the cryoplant and cryo-distribution systems. Exploring even higher temperatures superconducting technology is also critical.

6. Conclusion

As part of the wider STEP concept design, the SPP Power Infrastructure design must ensure both plant operability and the achievement of STEP's prime objective: the generation of net power. To this end, the following Power Infrastructure functions have been discussed:

- **Cool the tokamak**: Cooling of the tokamak while extracting useful thermal energy results in a complex design space where many integration trades must be made. The IVC coolant selection has been managed holistically to ensure the STEP objectives are met. Heat splits, temperatures and operating/configuration parameters have been shown to be important factors.
- **Generate Power:** Multiple thermodynamic technologies have been discussed with the merits and disbenefits illustrated. The sCO_2 Brayton cycle is being investigated for its applicability to the SPP design and operation. However, it is recognised that there are development risks linked to the sCO_2 technology, hence the steam Rankine cycle is still studied as a fallback option.
- **Manage energy:** The SPP electrical infrastructure manages energy across the plant. Significant parasitic loads, unique fusion power dynamics, and the integration of multiple power sources have been shown to be key requirements. A robust design, that incorporates a balance of electrical systems (e.g. energy storage) and a strong grid connection will be essential to support SPP operations.

The current design point for the SPP shows that it will generate net power. The power infrastructure enabling this will also support SPP operations at all stages. Moreover, Net Power holistic evaluations have identified opportunities to further drive efficiencies and improve confidence bands, as the SPP design is matured. Overall, this remains an exciting design space for the first of a kind SPP. An atypical approach to power generation and energy management is presented which will address the unique elements of the SPP and achieve its prime objective of delivering power to the grid. This has resulted in a novel concept design for the STEP Power Infrastructure which is based on a Spherical Tokamak heat source.

Acknowledgments

This work has been funded by STEP, a UKAEA programme to design and build a prototype fusion energy plant and a path to commercial fusion. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ukaea.uk.

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Figures

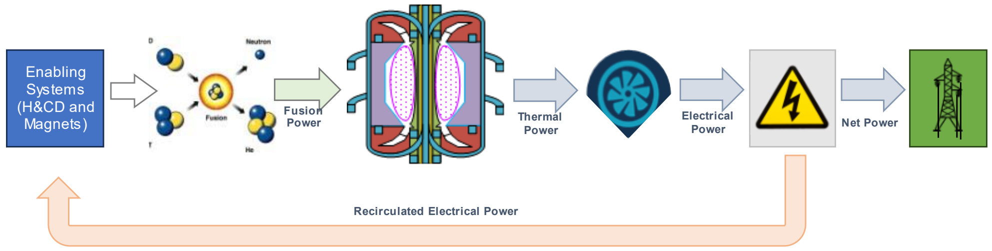

Figure 1: SPP Net Power Generation Flowsheet

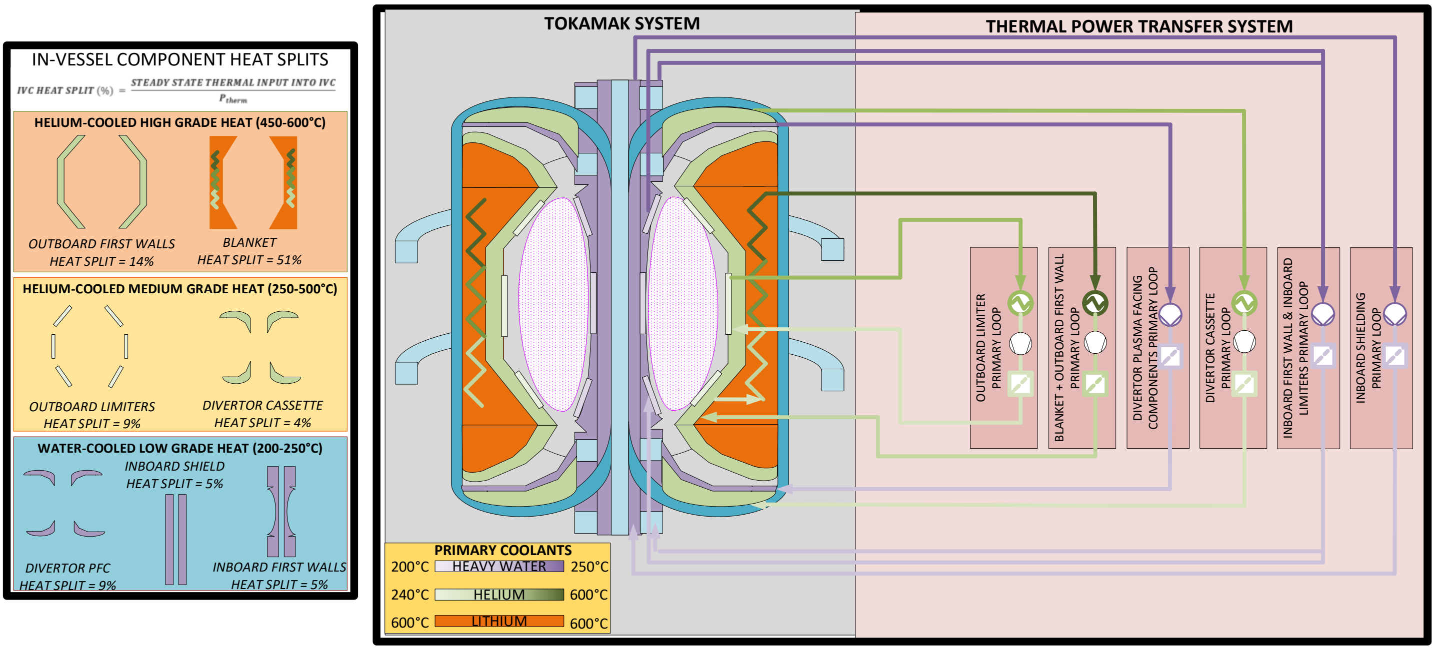

Figure 2: Overview of the primary coolant and Tokamak components heat splits

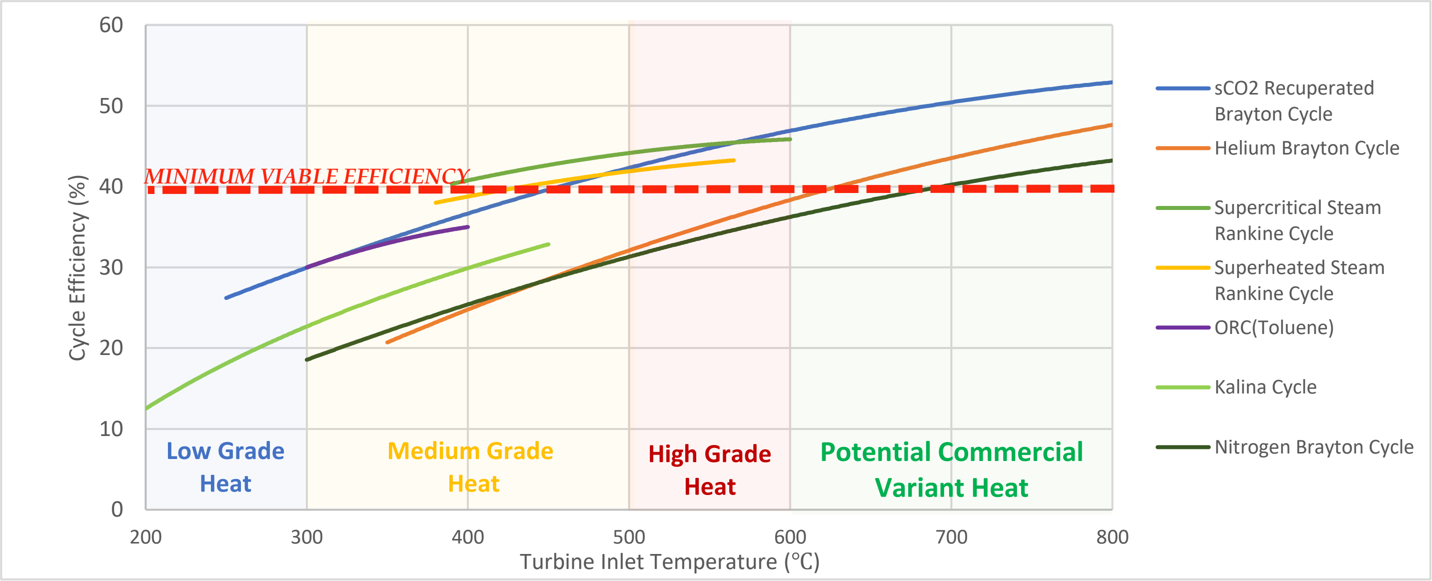

Figure 3: Efficiencies vs Temperatures of state-of-the-art thermodynamic cycles

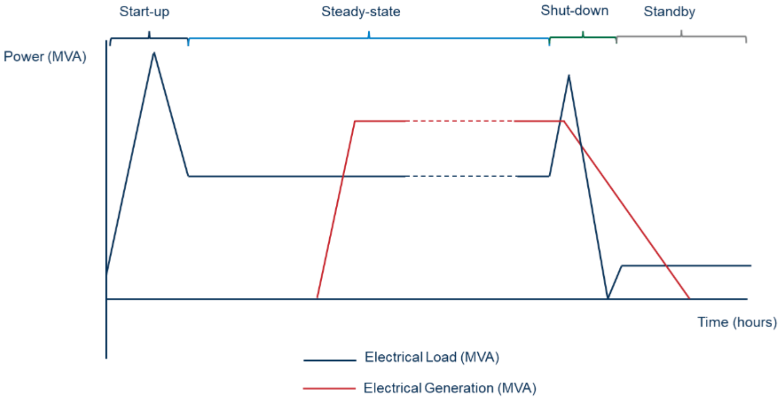

Figure 4: SPP Power Profile

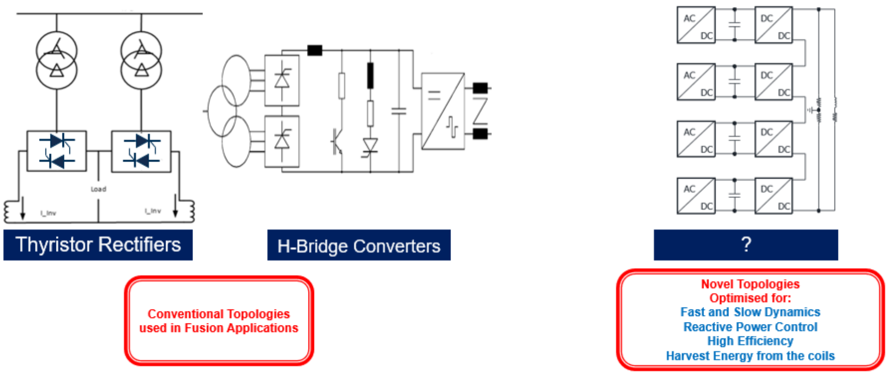

Figure 5: Power Converter Technologies for Fusion Power Plants

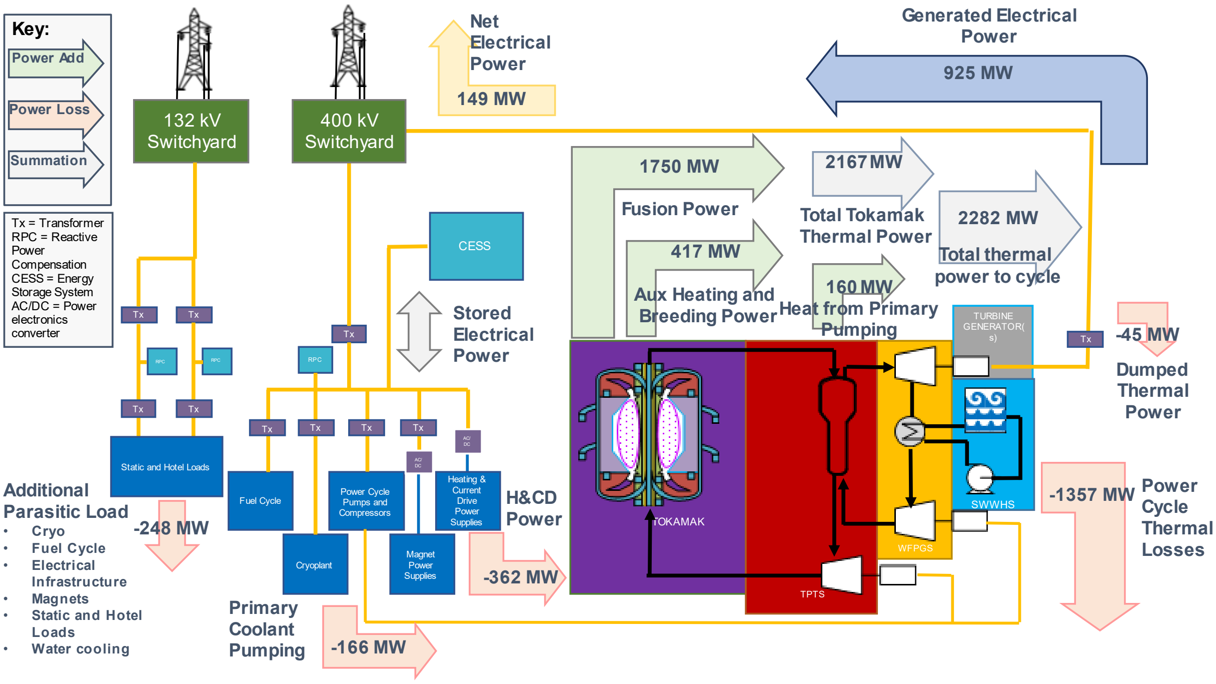

Figure 6: Power Infrastructure conceptual architecture, showing net power flow.