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STEP: NOVEL POWER INFRASTRUCTURE FOR FUSION POWERPLANTS

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Abstract

The Spherical Tokamak for Energy Production (STEP), a programme pioneered by the United Kingdom Industrial Fusion Solutions (UKIFS), seeks to develop a first of a kind demonstration fusion pilot plant based on a spherical tokamak: the STEP Prototype Powerplant (SPP). The SPP must demonstrate generation of at least 100 MWe net power to the national electrical grid network (in the UK: the *National Grid*). The SPP must therefore develop, not only a novel tokamak core, but a much wider holistic and integrated powerplant. The powerplant design must include the extraction and conversion of fusion energy, which is traditionally delivered by the "*Balance of plant"* systems. On STEP, the *Power & Cooling (P&C)* systems and sub systems, will deliver a similar function by:

- Cooling the tokamak components, while extracting useful thermal energy.
- Generating power: conversion of thermal energy to electrical energy (power generation).
- Managing energy: management of the site-wide distribution, storage and energy export.

Ensuring highly efficient *P&C* systems is vital in achieving STEP's primary 100 MWe goal. In the paper it is shown that flexible *P&C* systems are also required to match the dynamics of a fusion heat source, ultimately ensuring operability; this is the same as any demonstration/prototype fusion powerplant. For the SPP, these flexibility requirements are especially challenging when considering its scale and prototypic nature. STEP has made a number of key decisions and technology selections which has heavily influenced the integrated powerplant design. The highly adaptable yet efficient *P&C* systems, in turn will need considerable technology development, due to the holistic novelty.

1. INTRODUCTION

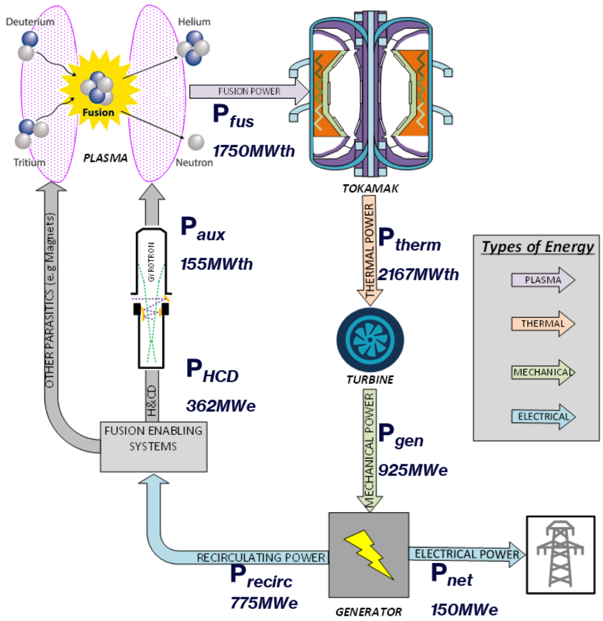

FIG. 1. Summarised SPP power balance

Tokamak systems are highly dynamic. While STEP is targeting a steady state, non-inductive plasma scenario, tokamaks operated in a standard scenario are inherently pulsed [1]. Solutions have therefore been developed to show how thermal power across the plant is managed in frequent dwell/pulse arrangements as well as how the electrical power to the grid is sustained in dwell periods [2].

This has led to the development a specific and unique architecture for the wider powerplant, namely the *P&C* systems, which will be the focus of the paper. The P&C systems must be highly efficient to enable 100MWe production during flat top, this is largely driven by the power balance previously established [3] and summarised in *FIG. 1*. Indeed, *FIG. 1* highlights the notorious challenges of achieving net power from a tokamak heat source. Many of the systems enabling fusion, such as the heating and current drive, magnets, or even circulation of tokamak coolants, require significant power. This power that must be supplied to the various SPP sub

systems, known as the recirculating power or also as the "parasitic loads", is a significant portion of the power generated in the first place; 750 MWe of the 925MWe generated on the SPP must be supplied to the various sub systems. This is much more significant than incumbent technology but is also a factor of the prototypic nature of the powerplant [4].
The *P&C* systems must also be highly flexible to adapt to uncertain prototypic operations. That is to say, these systems must have the ability to switch on and off, or ramp up and down, in similar timescales as the sudden generation/extinguishing of thermal power from the tokamak; even at unexpected times. The *P&C* systems have been broken down into sub systems that support these operations, aligned with their main functions:

- Cooling the tokamak components, while extracting useful thermal energy.
- Generating power: conversion of thermal energy to electrical energy (power generation).
- Managing energy: management of the site-wide distribution, storage and energy export.

This paper will explain the challenge of generating power from the SPP focusing on the dynamic elements, building on the efficiency requirements already established [3]. The dynamic rationale will be explained expanding on the highly dynamic plasma operations and the requirements it imposes on the *P&C* systems. The *P&C* system designs will then be described, detailing the technology and design choices, and discussing technology development where required. The decisions and rationale that have led to these technology choices will be elaborated on, highlighting how they ensure a powerplant that is both efficient and flexible as appropriate for the SPP.

2. DYNAMIC RATIONALE

The Spherical Tokamak (ST) offers a particularly attractive pathway to steady state operation. The bootstrap current, self-driven by the plasma, is optimised for the SPP [5]**,** greatly reducing the need for external current drive supplied either by the central solenoid or by (inefficient) non-inductive means. As a result, the SPP will not need to pulse on a frequent basis to recharge a central solenoid. This offers significant advantage in attempting to reach baseload power from fusion, as the ST can, in theory, run indefinitely producing thermal power without a defined pulse pattern. This would be similar to incumbent baseload power generating technologies.

Significant considerations for the SPP must be made with respect to the dynamics of the plasma ramp up and ramp down at the start and end of each operational period. Significant fusion power (P_{fus}) will only be generated from the period starting from the rapid density rise phase ("densification") towards the end of the plasma ramp, lasting ca. 100 seconds. From a power perspective this is an effective ramp of 2GWth generated from the tokamak, during this 100 second time frame. Prolonging this densification time frame is undesirable as then significantly more auxiliary power would be required – at this time the auxiliary power achievable is limited by microwave gyrotron capacity, as well as the power that can be drawn from the *National Grid*. For similar reasons a 100 sec period is also targeted for shut down, where the thermal energy generated by the tokamak drops from 2 GWth to almost 0. Managing this very rapid and sudden (relative to conventional power sources) ramp up and ramp down of tokamak heat is a difficult engineering feat. This challenge is further exacerbated when considering the prototypic nature of the SPP. Indeed, at this point in the project the actual pulse trajectories still carry some uncertainty as the design develops and modelling fidelity is increased. In addition, so far only the DT pulse has been modelled and a possible plasma commissioning phase without tritium may require additional capability from the power systems. Equally operations may be paused or even systems tripped while we learn how to operate the plant reliably.

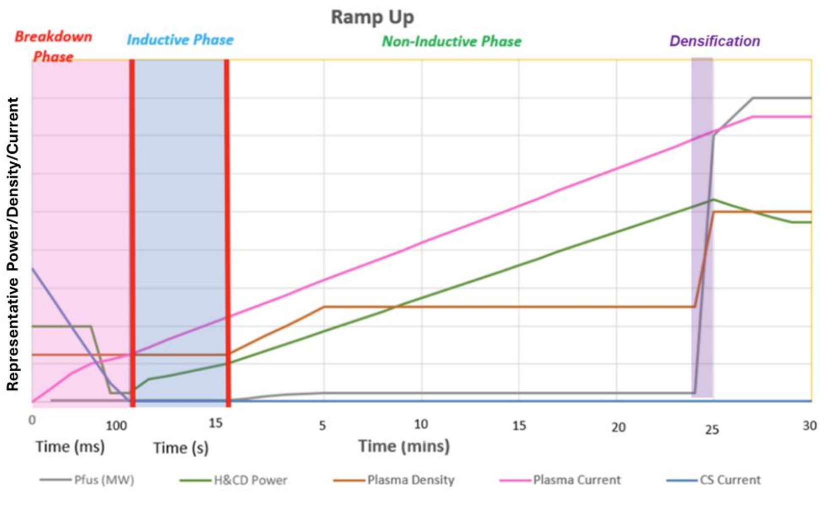

FIG. 2. STEP Estimated Plasma Ramp Up

3. P&C DYNAMIC MANAGEMENT

These kinds of time dynamics are atypical for many incumbent powerplants which will aim to have slow power ramp to match the required dynamics of traditional power cycle technologies, namely steam Rankine cycles. This is very much the cased for coal or fission based powerplants [6], which will typically ramp in hours.

More modern steam turbine within Combined Cycle Gas Turbines applications, will see much more dynamic responses, closer to 30-60 minutes typically (warm/hot start), however this often comes at a trade (cost, efficiency, life and scale limitations). Hence novel and unique P&C systems are required, holistically supporting the tokamak in its dynamic operations, while also ensuring the highest possible efficiencies.

3.1. Need for pre-heat

In a cold start, turbomachinery, heat exchangers and associated pipework are in a "cold" state, close to ambient conditions. In these conditions slower ramps are required before achieving full load as increasing the temperature of the sub components must be slow and controlled; rapid warming will cause uncontrolled expansion often leading to significant damage of components (notably, heat exchangers and turbomachinery), especially if repeated over a short period. Warm or hot starts consider a pre-heat of the components to a certain temperature, up to the normal operating conditions (hot), prior to the start up process. It is clear that warm or hot starts will be preferred [6] hence some form of heating outside a pulse will be required possibly from an auxiliary heat – e.g. an electric heater, or from heat stored in previous pulses – e.g. stored in thermal storage.

3.2. Need for thermal energy storage

A minimum amount of thermal storage will be needed to manage the very immediate and sudden generation of heat from the tokamak, this in effect will increase the thermal inertia of the primary coolant loops, allowing for the power cycle to "catch up" and attain 100% load in a timely manner. This is because the power cycle will have significant load ramp time frames, which far exceed the ramp of fusion power, and hence also exceed the thermal power generation from the tokamak, as indicated in FIG. *2*. The ability for the power cycle to ramp rapidly, in short timescales will be important as this minimises the thermal storage.

Further, and potentially much more significant, thermal storage may be needed to enable partial operation of the power cycle from initial pre-heat to part load as previously established [6]. Previous analysis has shown significant thermal energy storage would be required for such operations.

3.3. Need for electrical energy storage

The electrical infrastructure must cope with highly rapid dynamics, and must sustain the fusion enabling systems – without internal power sources available (i.e. the turbines) – during the ramp up and ramp down periods when power generated from the turbine is not available. The power draw in this phase will primarily be from the grid, however the UK grid has limitations when compared with the ramp up or even ramp down requirements of the SPP. Hence a central energy storage system must be used to ensure operability and that the SPP adheres to the grid code while still enabling fusion.

Broadly, the Central Energy Storage System (CESS) is required to support operations of the SPP [3], notably to:

a) Provide active power where national grid limits are reached on how much power can be drawn.
b) Ensure compliance with the grid's power rate of change limits (known as "dP/dt"). Rapid demand of fusion power is expected from the fusion enabling systems, furthermore switching from 775MWe consumer of power to a 150MWe producer of power in a matter of 5-20 minutes will breach the allowable power demand changes on the national grid; hence CESS is required to support this by storing energy before dP/dt limits are reached, effectively acting as an energy buffer.
c) Provide reactive power support and regulate voltage levels. Fusion related loads, such as large inductive motors, or switched power supplies, will draw significant reactive power and produce high harmonic content – these are likely to exceed the reactive power available from the grid.
d) Provide emergency back-up power for protecting business critical assets ensuring safe shut down of the overall SPP and associated sub systems in the event of a loss of site power scenario.

A trade space between thermal energy storage and electrical energy storage exists, as thermal energy stored may be converted into electrical power during ramp up using the power cycle. The exact amount of thermal and electrical storage needed will therefore depend on the operations of the wider SPP, a number of potential operating scenarios have been previously established assessing the impact of these scenarios [6], ultimately trades can be made to optimise the amount of energy storage required.

3.4. Need for Auxiliary heat

In previous analysis [6], it is proposed that the pre heat and potential partial operation of the thermodynamic cycle is managed through thermal and electrical storage exclusively. An alternative proposal is preferred for the SPP which utilises auxiliary heat. In this context auxiliary heat is defined as a non-fusion related heat source. This heat source will not have a finite dynamic limitation unlike thermal storage. That is to say, the thermal storage is limited by its size and the energy associated to that size, hence will naturally stop enabling operations once its energy is depleted. Conversely, Auxiliary heat will keep enabling operations, to a defined power level, until it is no longer needed and switched off.

Due to the uncertainty of the prototypic SPP operations, relying on thermal storage to manage injection of heat is both non pragmatic, and unviable. Larger thermal storage, up to 100s MWh will require long periods to ramp up and heat the thermodynamic cycle, it will add long time constants between pulse. Furthermore, should plasmas take longer to ramp than expected, an indefinite ability to operate the power cycle is preferable, to ensure it is ready to receive power. Thermal storage also has limited capability in ensuring safe shut down in unplanned shut down events or the ability to mitigate lack of heat from a fusion heat source during operations.

In this sense, an auxiliary heat source is advantageous to manage:

a) Availability of the power cycle
- Ensures start-up/shut down independence between power generation and tokamak systems – thus creating a power generation system that can receive fusion heat, which is favorable when such fusion heat is unpredictable
- Improves availability of total plant infrastructure for start-up (less reliance on grid and electrical or thermal energy storage, including less charge time for the energy storage systems; and therefore less dwell/recharge time between pulses)

b) Independence of the power cycle
- Ensures a safe shutdown of power generation system when tokamak trips
- Significantly increases the likelihood of recovery in the event of a disruption

c) Variation handling - Auxiliary heat can supplement tokamak heat
- Ensures ability to handle excessively low temperature from tokamak
- Ensures ability to handle excessively low power from tokamak
- Ensures ability to handle temp/power operational variability throughout a pulse while still achieving constant power out needed for operational purposes

For these reasons auxiliary heat, *in addition* to thermal and electrical energy storage, is preferred on the SPP.

3.5. Need for cryogenic storage

The main cryogenic user is the magnets, and this has a number of significant dynamic scenarios to consider, namely around plasma breakdown phase. Cryobuffers are proposed to manage these dynamic scenarios where significantly more cryogenic cooling will be required temporarily. During the plasma ramp this is caused by the use of the central solenoid during the breakdown phase, this will create added heat into the centre column, including heating of superconducting magnets, additional cryogenic cooling is therefore required, temporarily.

3.6. Holistic approach

A summary of how all these systems must work together, during steady and transient conditions can be seen in both *FIG. 3* and *FIG. 4.*

It is therefore clear that additional elements within the existing systems of the SPP are required to enable the rapid dynamics of the plasma and the associated fusion enabling systems. Each system can now be described in detail highlighting how they address the simultaneous challenge of enabling fusion operations while still ensuring high efficiencies.

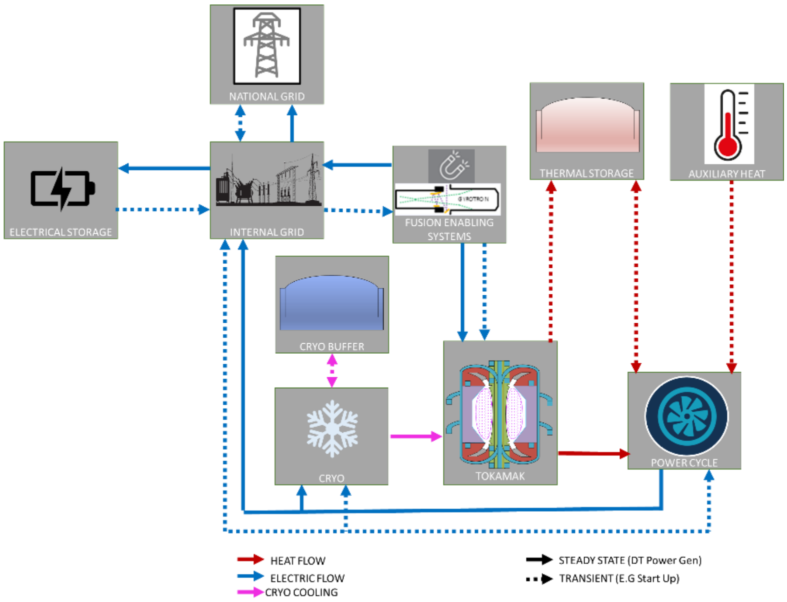

FIG. 3. P&C System dynamic dependencies

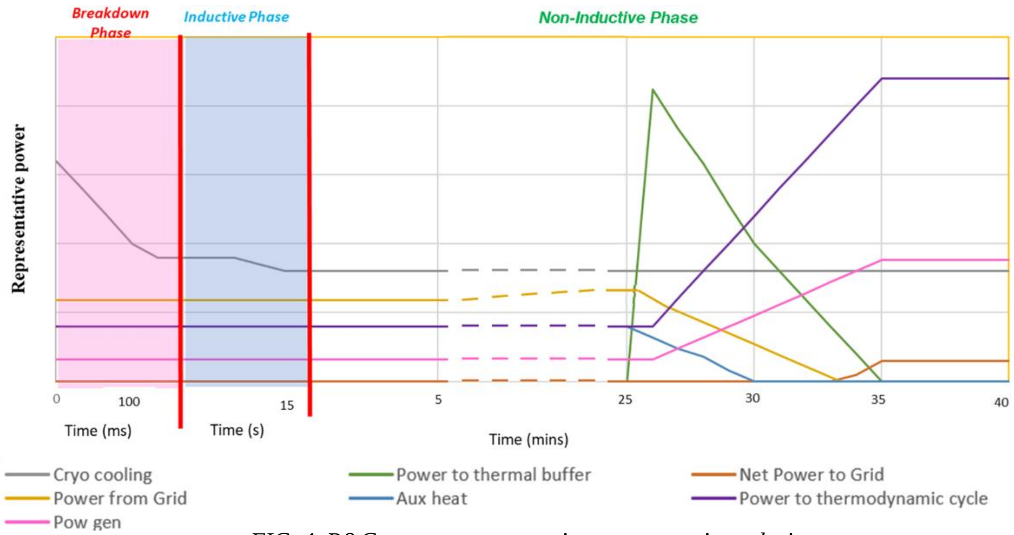

FIG. 4. P&C system representative powers vs times during ramp up

4. THERMAL POWER TRANSFER SYSTEM

The thermal power transfer system ensures sufficient coolant is supplied to the tokamak at all stages of operations while simultaneously also ensuring sufficient heat is transferred to the working fluid and power generation system. The thermal power transfer system must efficiently remove heat from the tokamak while also enabling tokamak operations through tailored dynamic responses.

A mix of (light and heavy) water and gas (helium) coolants have been selected as the *primary coolants* for the SPP [3]. The selection of water on the inboard ensures the tokamak functions around shielding for the centre column. Gas on the outboard is needed for neutron transparency purposes enabling sufficient tritium breeding in the blanket. The selection and conditions (temperature and pressure) of these coolants has been carefully tailored to maximise net power (through heat integration into the thermodynamic cycle), while adhering to the other STEP objectives (notably TBR and availability) [3]. The choice of gas coolants will require significant technology development, especially due to the large pressures and pressure losses in the loop – the conditions are more severe than incumbent technologies such as Advanced Gas-cooled Reactor (AGR) circulators. High pressures are required in the first place to minimise, as far as practicable, impacts on power for the compressor. The high-pressure coolants also ensure a dense fluid enabling the removal of heat in high heat flux conditions. Due to the compact nature of the spherical tokamak these pressure losses are significant. These circulators will need to include part load control, ensuring the ability to ramp the flowrate of coolant as required during various ramping scenarios, for these reasons it is likely that variable drives will be attached – despite efficiency losses.

Printed circuit heat exchangers (PCHE) have been selected as the prime candidate for the majority of the heat transfer into the thermodynamic cycle. This choice of heat exchanger is enabled by an sCO2 thermodynamic cycle. The PCHE allows for a compact and efficient solution - high heat transfer area for a given area and pressure loss, relative to incumbent technology such as shell and tube. PCHE technology for this particular application at scale will require some technology development.

5. CRYOGENICS SYSTEM

The Cryoplant is of significant scale (cryo-load equivalent to around 100 kW at 4.5 K – similar scale as CERN and ITER) with multiple user temperatures at 15°K, 50°K and 80°K [7] – in this virtue alone it is a unique and novel system. Furthermore, associated cryo-distribution systems must cater to multiple users at multiple locations around the tokamak and the wider powerplant. To ensure efficiency, while supporting multiple users at different temperatures, the Cryoplant will need to be focussed on heat integration. Moreover cryobuffers and rapidly adaptable sub systems will be needed to manage magnet and other user dynamic requirements. Naturally, elements of the cryogenics systems will require technology development to meet dynamic and efficiency requirements.

6. WORKING FLUID AND POWER GENERATION SYSTEM

The working fluid and power generation system mainly consists of the thermodyanamic power cycle which converts heat from the primary coolant to electrical power. An efficient thermodynamic cycle is key to a successful fusion powerplant, regardless of other performance parameters [8]. Supercritical CO_2 is the preferred cycle for STEP as it lends itself well to the both the dynamic requirements [9] and the efficiency needs [3] of the SPP.

Heat is generated primarily from 6 major heat sources in the tokamak. For the purposes of thermodynamic cycle architecture and modelling, including heat integration, these can be summarised as 3 heat sources, where [3]:

- Ca. 65% of the heat is from is from the blanket and outboard first wall – this is the HT heat source, (400-600°C)
- Ca. 20% of the heat is from the in-board build (inboard first wall and inboard shield) and divertor plasma facing component - for simplicity, and because the temperatures of the component coolants are so similar, this is combined as a LT heat source in the thermodynamic model (200-213°C),
- Ca.15% of the heat, from the outboard limiter (250-450°C), and from the divertor cassette (350-500°C) delivered as the MT heat source

FIG. 5 illustrates the supercritical CO2 cycle proposed for the SPP with the 3 key heat integration points – matching the major heat sources of the tokamak [10].

The cycle integrates heat at all stages while still ensuring high efficiencies, this is a factor of cycle parameters and cycle configuration. Previous analysis [10] has indicated that a Transcritical sCO2 cycle, with no working fluid blends, is preferred with parameters shown in *FIG. 5*. This configuration indicates the highest performance, which can match or even in some circumstances outperform a Steam Rankine incumbent technology [10].

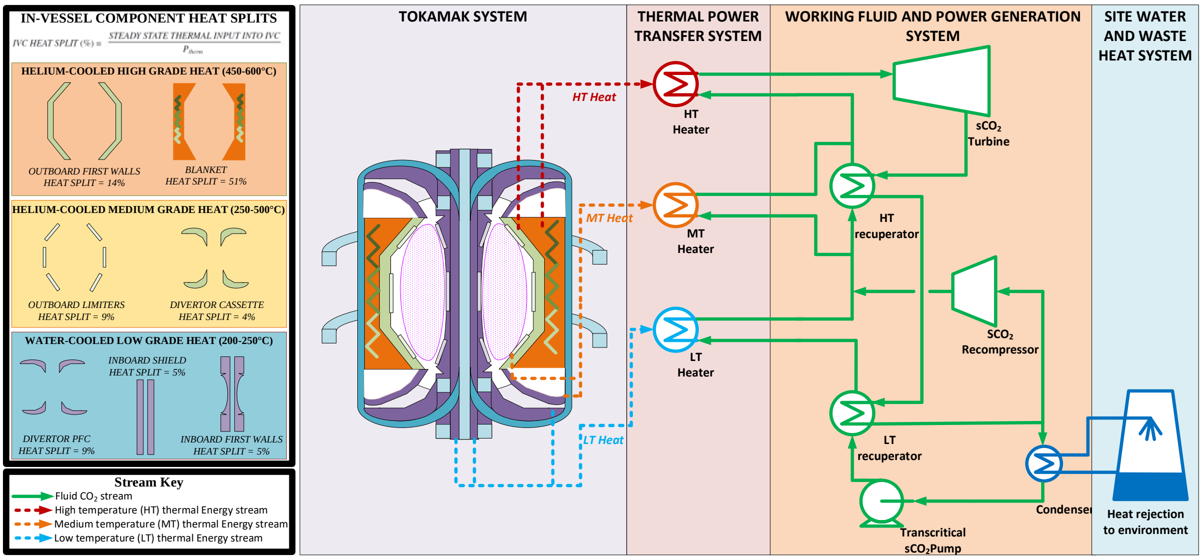

FIG. 5. STEP Transcritical sCO2 power cycle (no blends)

The sCO2 cycle allows for a much shorter ramp (from part load to full load) than incumbent technology, nonetheless two considerations must be made:

a) There is still a dynamic gap, whereby the densification heat will occur over 100 seconds, and the thermodynamic cycle full ramp can only occur in as short a period as 5-20 minutes. Hence heat must be stored or removed from the primary loops over this period enabling full operations of the thermodynamic cycle and heat transfer to that thermodynamic cycle. This heat storage or removal must be managed through the increase of thermal inertia to the primary loop (as discussed in section 3). Thermal storage, such as a molten salt heat store, is an attractive option to increase this thermal inertia.

b) The thermodynamic cycle must, at a minimum be pre-heated and ideally operating at part load prior to the densification phase. As discussed in section 3, This will require an auxiliary heat source, that is not fusion based, to ensure such operations. Auxiliary heat sources can be considered such as:
   - Combustion sources, natural gas (with built in carbon capture), hydrogen or green ammonia
   - Electrical sources, namely an electric heater

Clear advantages around efficiency and dynamic performance are presented for the Transcritical CO2 cycle proposed, nonetheless it is recognised that the maturity of such a cycle is less than the incumbent technology, the steam Rankine Cycle, which still remains a pivot options for STEP [11]. As a result of the low technical maturity of the sCO_2 cycle, a technology development programme is planned to derisk the cycle itself and its integration with a tokamak and supporting operational sub systems (namely auxiliary heat and thermal storage).

7. ELECTRICAL INFRASTRUCTURE

The electrical infrastructure will need to manage both the ability to import power before the densification phase, throughout the ramp up of the plasma, and then ensure the ability to export power to the grid after the turbine ramp up to 100% (5-20 mins after the densification phase starts) – as shown in FIG. *4*. A strong and reliable connection to the national grid is required, namely to enable electrical supply for the plasma start up period up to densification. Significant power is needed during this phase (up to 775 MWe) from the grid, furthermore a rapid switch to generation, which is connected to a 400kV grid, is required. As such there are multiple 400kV High Voltage connections required to simultaneously ensure the large power demand is met prior to the densification phase, while also enabling power generation from the prototype after densification. Other independent connections are proposed for "non pulsed" loads, that is to say loads which are not linked to the pulsed operations of the tokamak.

The Electrical Infrastructure architecture shown in *FIG. 6* has been designed to be AC (Alternating Current) which uses conventional components while still ensuring a sufficiently efficient system. A DC system has also been considered but the added TRL development challenges was considered excessive for potentially mediocre gains on performance. *FIG. 6*, illustrates the location of the CESS within the Electrical Infrastructure, which addresses the requirements discussed in section 3. A CESS predicated on batteries is judged to be the most suitable technology within the current landscape for electrical energy storage, as it largely matches the dynamic timescales (minutes to hours). Additional electrical storage technologies may also be used to support unique requirements which battery technologies are not optimised for.

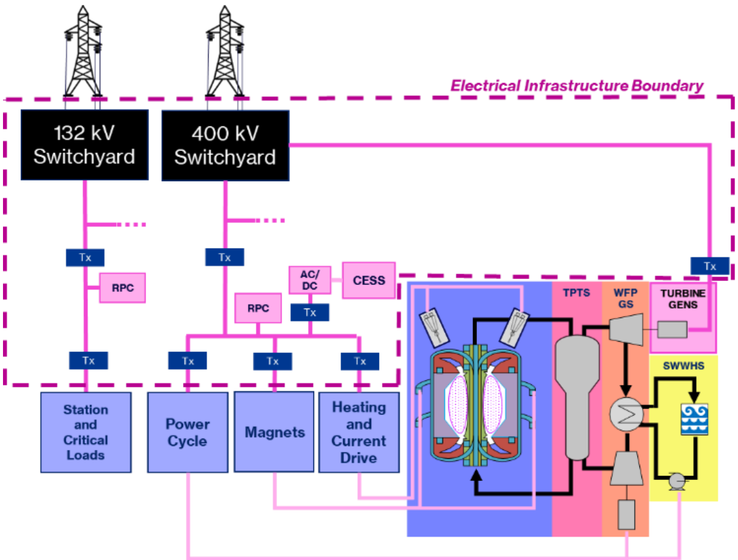

FIG. 6. Electrical Infrastructure illustration

The dynamic response and control of the overall site electrical power flows is of clear significance. The SPP will use a dedicated Power and Energy Management System (PEMS) to control very large power flows and ensure power system stability. PEMS will be, initially, developed through adequate modelling and simulation, testing incumbent and available technology to understand the feasibility and viability of the overall Electricity Distribution Network and the associated components. Particular control and power system features of the design will probably need hardware-in-the-loop testing for performance verification

8. CONCLUSION

A number of systems and sub systems, as well as the associated technologies, have been presented, and summarised in FIG 7. These systems allow the SPP to operate in both an efficient and flexible manner, enabling the highly dynamic plasma operations within the tokamak.

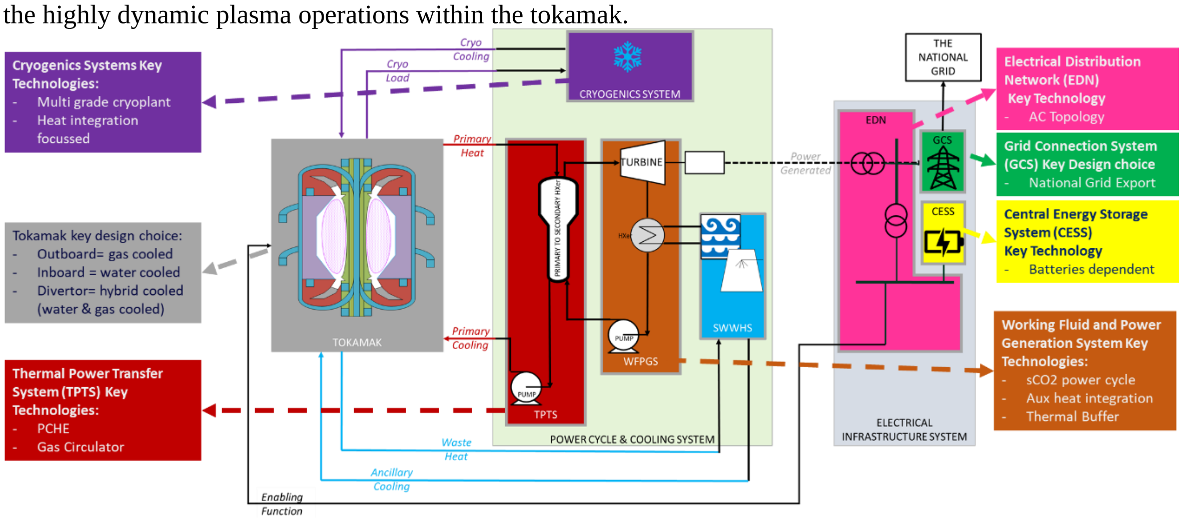

FIG 7. STEP Power & Cooling System breakdown with key technologies

The overall technology of the P&C systems are predicated largely on incumbent technologies which are readily available, albeit with certain unique requirements incurring more bespoke componentry for select systems. Nonetheless a number of novel technologies, and novel applications, are discussed. As a result selective research and development is required to derisk these technologies in a timeline compatible with the SPP. Several technologies development programmes must therefore be started imminently to ensure project success. STEP is seeking partners and suppliers to support these programmes ultimately enabling project success.

ACKNOWLEDGEMENTS

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