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Pre-conceptual design of EU DEMO balance of plant systems: objectives and challenges

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The European Research Roadmap to the Realisation of Fusion Energy foresees that the DEMO reactor is going to succeed ITER in the pathway towards the exploitation of nuclear fusion, achieving long plasma operation time, demonstrating tritium self-sufficiency and producing net electric output on an industrial scale. Therefore, its design must be more oriented toward the Balance of Plant (BoP) than it is in ITER.
Since the early pre-conceptual phase of the DEMO project, emphasis has been addressed to identify the main requirements affecting the overall architecture of the BoP. For instance, specific efforts and proper solutions have been envisaged to cope with the pulsed nature of the heat source. Furthermore, the current development of two blanket concepts calls for two separate BoP options to be conceived.
This paper summarizes the main alternatives outlined at the end of DEMO pre-conceptual design phase for the BoP concepts based on both the Helium-Cooled Pebble Bed (HCPB) and Water-Cooled Lithium Lead (WCLL) Breeding Blanket (BB) technologies. Then, the assumed reference configurations of both the BoP concepts are described in detail highlighting the main features and the most relevant engineering aspects. Attention will be focussed on technological challenges, integration constrains and other open issues, highlighting pros and cons of the chosen BoP options to be further investigated in the next design phase.

Keywords: DEMO, Balance of Plant, HCPB, WCLL.

1. Introduction

The European Roadmap to Fusion Energy has foreseen the production of electric power from nuclear fusion by the middle of this century [1]. In this framework, the EUROfusion consortium is developing the project of a DEMOnstration Fusion Reactor (DEMO) which would follow ITER in the pathway towards the exploitation of fusion energy. Specifically, its main objectives are [2]:

1. conversion of heat into electric power (several hundred megawatts);
2. achievement of tritium self-sufficiency (breeding ratio > 1);
3. reasonable availability up to several full-power years;
4. minimization of radioactive wastes, without long-lived radioisotopes;
5. extrapolation to a commercial fusion power plant.

The general principles of the DEMO development strategy in Europe include [3]:

1. modest extrapolations from the ITER physics and technology basis to bound development risks;
2. robust design incorporating proven technologies as well as innovations validated through realistic R&D programs;
3. safety features and design licensability by integrating lessons learned from ITER licensing (and other existing nuclear facilities);
4. a 'success oriented' approach of DEMO design development taking place in parallel to ITER exploitation, but relying on design and physics validation prior to construction;
5. harnessing the industrial base established in bringing ITER to operation.

In the pre-conceptual design phase until 2020 the DEMO design development has been focused on eight Key Design Integration Issues (KDIIs) [4]. They have been selected for their impact on plasma physics and Tokamak architecture, safety, and maintainability.

Among them, a key role in the design and the licencing of the DEMO plant is played by the Balance of Plant (BoP), namely KDII #5. Indeed, considering the above-mentioned goals of the EU-DEMO, the plant design has to be more oriented toward the BoP than it is in ITER, where the heat power, available at a rather low temperature level and for much shorter pulses, will be

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wasted to the final heat sink. Moreover, being a nuclear facility, the DEMO BoP must meet many of those design criteria and safety requirements characterising the most common nuclear power stations and perform its function in a safe, reliable and efficient way [5]. This represents a culture change in the fusion community that was mainly focused on plasma performances and control and on the design of plasma facing components.

In conventional Nuclear Power Plants (NPPs) the main system of the BoP is the Power Conversion System (PCS) that converts the heat extracted from the plant heat source through the Primary Heat Transfer System (PHTS) into electric power. In DEMO, instead, BoP means the complex "chain" of systems devoted to the extraction of the pulsed thermal power generated by the plasma and deposited in the Breeding Blanket (BB) [6], Divertor (DIV) [7] and Vacuum Vessel (VV) and its conversion into electric power to be delivered to the external grid via the turbo-generator group [8, 9].

The aim of this paper is to provide an overview of design progresses of the DEMO BoP for the Helium Cooled Pebble Bed (HCPB) and the Water Cooled Lithium Lead (WCLL) BB options. The paper briefly outlines the investigated BoP alternatives. Then, the assumed reference configurations are described in detail highlighting the main features and the most relevant engineering aspects. Attention is focused on technological challenges, integration constrains [10] and other open issues [8] of the BoP options to be further investigated in the next project phase.

2. Challenges to the BoP design and strategy

The DEMO duty cycle foresees a continuous sequence of two main phases connected by two transitional phases. In particular, the plasma ramps-up within about 100 seconds bringing its power from zero to the maximum value. When the full power level is reached this condition is kept for 2 hours (pulse phase). Then, a ramp-down of around 100 seconds leads the system into the dwell phase which lasts 10 minutes and where almost no power is generated (the decay heat 1 s after shut-down is around 2% of the nominal power).

The pulsed operation is particularly demanding for DEMO systems such as the BoP, due to the "unconventional" time evolution of the plasma heat sources. Clearly, this boundary condition challenges the feasibility and the operations of the BoP which needs a robust design to cope with the loads caused by the very frequent transients while guaranteeing its safe and reliable operation.

The complexity of the BoP systems is another challenge for the feasibility of the plant, also due to the high DEMO thermal power, Tokamak size and different cooling temperatures required by the plasma facing components. It applies in particular to the high energy BB PHTS where best compromise choices have to be identified in the attempt to develop a design architecture fulfilling the often-contrasting requirements coming from safety, integration, maintenance and reliability.

In this context, the adopted strategy consists of an optioneering activity investigating different BoP concepts. In particular, the investigated alternatives can be functionally grouped in *Indirect Coupling Design* options and *Direct Coupling Design* options.

The former ones imply the presence of an Intermediate Heat Transfer System (IHTS) equipped with an Energy Storage System (ESS) that might bridge the dwell time in order to ensure about 100% electricity delivery to the grid. On the other hand, the latter options foresee the presence of an additional energy source, which may be a small ESS or an auxiliary boiler, that might feed a minimum steam flow to the Steam Turbine (ST) so to keep synchronized the generator to the grid during dwell period. They are briefly illustrated in the next sections highlighting pro and cons and specific challenges for a feasible concept achievement.

3. Primary Heat Transfer Systems

DEMO presents four independent PHTSs. The largest one is devoted to remove the thermal power from the BB, two PHTSs are necessary to extract heat from the DIV while the last one is intended to cool the VV.

HCPB and WCLL rely on different BB PHTS layouts while DIV and VV PHTSs adopt the same arrangement for both concepts. However, it is worth to underline that small changes in the design of main heat exchangers coupling the PHTSs to the secondary circuit might occur according to the different BoP variants under investigation.

Tables 1 and 2 reports a summary of the PHTSs main design parameters for HCPB and WCLL, respectively. Further details may be found in [11, 12, 13].

Table 1. HCPB PHTSs Main Design Parameters.

Parameter	Value
Total reactor power (BB+VV+DIV) [MW]	2366.2
BB PHTS	
Power [MW]	2029
PHTS piping size hot/cold leg range	DN1100-1300
PHTS piping overall length [m]	6282
PHTS pumping power [MW]	92
PHTS overall coolant volume [m^3]	1735
DIV PHTS (PFU + CAS)	
Power [MW]	136 + 115.2
PHTS piping size hot/cold leg range	DN300-600
PHTS piping overall length [m]	2545 + 2787
PHTS pumping power [MW]	14.5 + 1.6
PHTS overall coolant volume [m^3]	114 + 130
VV PHTS	
Power [MW]	86
PHTS piping size hot/cold leg range	DN350
PHTS piping overall length [m]	2475
PHTS pumping power [MW]	2.63
PHTS overall coolant volume [m^3]	599

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Table 2. WCLL PHTSs Main Design Parameters.

Parameter	Value
Total fusion power (BB+VV+DIV) [MW]	2260.4
BB PHTS (FW + BZ)	
Power [MW]	1923.2
PHTS piping size hot/cold leg range	DN500-850
PHTS piping overall length [m]	3200 + 3700
PHTS Pumping power [MW]	16.52
PHTSs overall coolant volume [m^3]	563 + 159
DIV PHTS (PFU + CAS)	
Power [MW]	136 + 115.2
PHTS piping size hot/cold leg range	DN300-600
PHTS piping overall length [m]	2600 + 2800
PHTS Pumping power [MW]	12.0 + 1.6
PHTSs overall coolant volume [m^3]	128 + 142
VV PHTS	
Power [MW]	86
PHTS piping size hot/cold leg range	DN350
PHTS piping overall length [m]	1300
PHTS Pumping power [MW]	3.1
PHTSs overall coolant volume [m^3]	585

4. HCPB BoP

Transfer of plasma power to the electrical grid can be performed either using direct or indirect design concepts. During the pre-conceptual phase, several variants were investigated for the HCPB BoP assessing advantages, drawbacks and potential showstoppers. In particular, four main variants have been considered: three Direct Coupling Design (DCD) options and the reference HCPB DEMO layout, i.e. the Indirect Coupling Design (HCPB ICD BoP) [14, 15, 16].

The general architecture foresees the utilisation of all heat sources (BB, DIV and VV) to enhance efficiency and to reduce the cooling burden. The main power transfer occurs along the path that includes the BB PHTS, the Intermediate Heat Transfer System (IHTS) and the PCS. Three water-cooled systems complete the PHTS, two for Divertor, intended to cool the Divertor Plasma Facing Components and the Cassette Body (DIV-PFU PHTS, DIV-CAS PHTS), and one for the Vacuum Vessel (VV PHTS), transferring power to the PCS feedwater line through their integrated Heat eXchangers (HXs). Their design choice is invariant to the investigated alternatives of the chosen reference case. Figure 1 shows the developed heat transfer paths for the HCPB BoP reference solution.

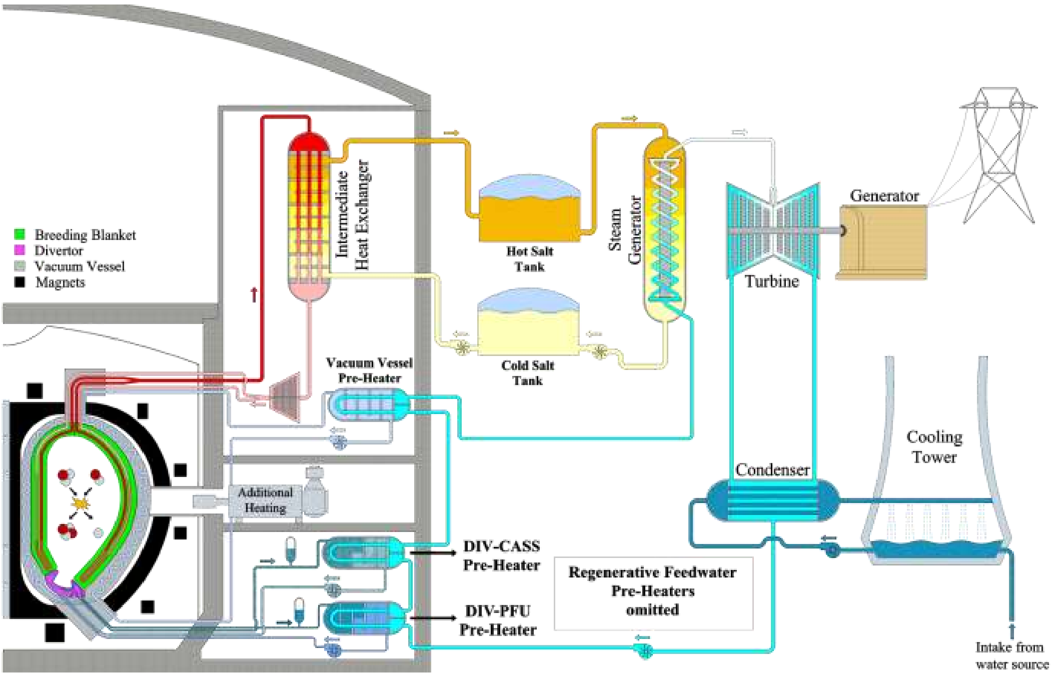

Fig. 1. Overview of the HCPB ICD BoP.

4.1. Investigated variants

The two main requirements considered in the variants' selection were:

1. to avoid disconnection from the grid for each pulse/dwell phase;
2. to reduce the impact of frequent temperature transients to structures.

Moreover, integration, performance, safety and cost are considered in the assessment of each variant.

In order to ease the reader's comprehension, a ranking map of the main HCPB BoP variants investigated is reported in Figure 2. It summarizes and compares the most relevant features of each variant highlighting high-level design choices and the identified critical issues together with the points to be further investigated during the DEMO conceptual design phase.

Variant		BB PHTS HX-SG/SH Pressure	Storage Molten Salt	Storage SS ESS	Auxiliary Heating system	Boiler Gas supply	Turbine load Flexibility	Critical components Type	Critical components #	Space for AHS/IHTS	System Feasible yes/no	Tolerant for frequent transients	Power output & plant supply	Safety function Barrier (T, ACP)	Critical issues
Importance -->		H	M	M	H	H	M		M	H					
DCD-l	large gas fired boiler	H_2O-H_2O high	-	-	Gas 220 MW	Large	Very low	Ext. Boiler, He-H_2O SGs	3	Large	TBI	TBI	+ gas	1	Boiler experiences temperature and pressure transients
DCD-s1	SS ESS	H_2O-H_2O high	-	Concrete	Gas 93 MW	Reasonable	Very low	SS ESS, He-H_2O SGs	4	Large	No	No	?	1	SS ESS has difficulties to release energy within the relative short times
DCD-s2	el. Heated boiler + small ESS	H_2O-H_2O high	2x400m³ HITEC	-	Electric 41.2 MWe	-	Very low	He-H_2O SGs, H_2O-HITEC IHXs, ST	4	Additional power supply for heater	TBI	TBI	+ electric power	1	Heating power difficult to be realized in HITEC
ICD	with 100% ESS	H_2O-HITEC low	2x3000m³ HITEC	-	Trace heating	-	Standard	H_2O-HITEC IHXs	4	Two large tanks	Yes	TBI	OK	2	Tritium behaviour in MS

Red: critical issue (size, feasibility, ...)
Orange: near or at present feasible and producible
Blue: producible but not in the shelf
Green: component from the shelf
TBI: To be investigate further
Importance: L = Low; M = Medium; H = High

Fig. 2. Ranking map of the HCPB BoP variants.

4.1.1. Indirect Coupling Design (ICD): intermediate storage loop

The first variant is the HCPB ICD BoP, which uses an IHTS equipped with an Energy Storage System (ESS) operating with molten salt (HITEC [17]) to decouple regular plasma strokes from the PCS. The IHTS design uses qualified technology coming from Concentrating Solar Power (CSP) plants [18] (150 MW_e and energy storage up to 1 GWh_{th}).

The analysis performed including design improvements by industry focused on different PHTS and the PCS (i.e. feedwater train optimization for pulse and dwell conditions) has allowed the BoP team to find reasonable answers for all challenges investigated so far. Therefore, the HCPB ICD BoP is the reference variant for the next step of DEMO development and will be described in more detail in §4.2.

4.1.2. Direct Coupling Design: Large auxiliary Boiler (AuxB)

In order to avoid the loss of synchronization during dwell time, a gas-fired boiler has been considered to provide steam flow to keep the power train in operation [19]. The size of the boiler depends on the minimum steam mass flow rate through the turbine. Different turbine concepts allow different levels of lowest operation power keeping the frequency constant. The main challenge is however to cope with the fast power transients, while keeping the turbine in a safe operational state. A second challenge is to keep the required power of the auxiliary boiler in the range of several hundreds of MW during dwell time. This requires an additional infrastructure, which consists of an Auxiliary Heater Section (AHS), comparable to a small gas-fired power station (around 200 MW_{th} if turbine would be driven at about 10% of its nominal power), requiring a sufficiently large gas pipeline. Main drawback is that during pulsed operation the boiler experiences temperature and pressure transients, which are difficult to manage.

The assessment of costs, requested size and heat transfer constraints has led to the decision to keep this option as potential back-up solution. Nevertheless, it should be remarked that the adoption of a relevant heating source from fossil fuel in support of a fusion plant might be questionable also for political reasons.

4.1.3. Direct Coupling Design: DCD-s1 small boiler plus solid state ESS

The second DCD variant collects fusion energy during pulse and stores it in a Solid State (SS) ESS. The collected thermal energy is then released to the PCS during the dwell period. This reduces boiler size so that this variant becomes more reasonable. A significant drawback here is the energy storage system realized as HT-concrete, which is not able to release the thermal energy within the relatively short dwell time.

Furthermore, the piping and control system becomes very complicated and, most important, the solid ESS works as a HX; heat is stored from PHTS-Helium on one side and PCS-water/steam removes the heat during dwell. Since the PHTS safety function could not be maintained due to spatial request of the ESS, further investigations have been postponed to the Conceptual phase as a remote back-up solution.

4.1.4. Direct Coupling Design: DCD-s2 small ESS plus electrical boiler

A third variant developed by industry uses HITEC molten salt (400 m^3) and a 41 MW_e electrical heater. This is done in order to maximize electrical power production of the PCS during pulse and to maintain synchronized the electrical generator to the grid during dwell period while operating the steam turbine at a minimum operational load of 10%. Preliminary architecture has been drafted and some initial assessments on dynamic behaviour of the main BoP systems have been made. Results highlight that, among the three different direct coupling options investigated, the third appears to be the one with the lowest integration and feasibility risks, allowing to adopt control strategies that might minimize the impact of thermal-hydraulic transients on main equipment. Further studies, focussed on creep assessment and start-up evaluation are needed to confirm that this solution can be considered as first back-up choice in case the ICD option would present some design integration challenges.

4.2. Reference HCPB BoP configuration

The latest design of the HCPB ICD BoP is shown in Figure 3.

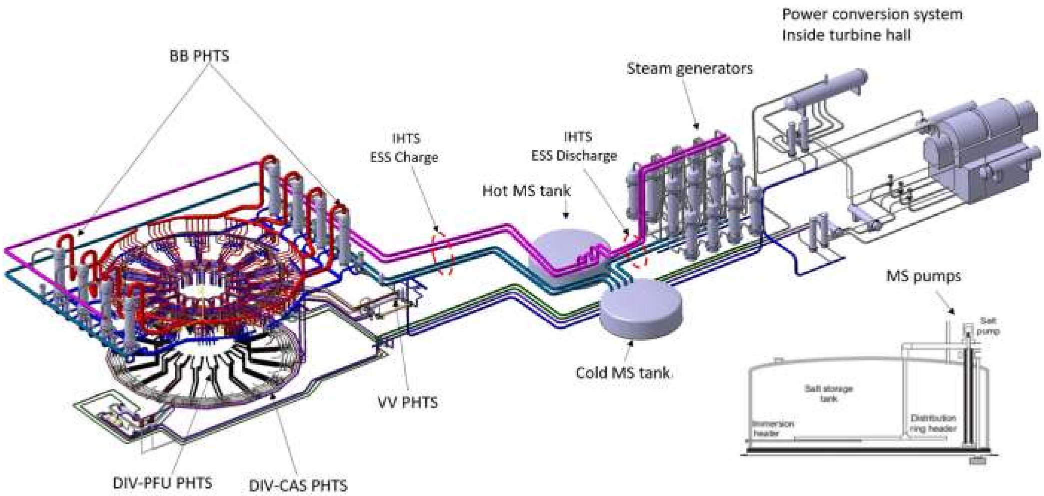

Fig. 3. HCPB ICD BoP layout.

During pulse, 90% of the power is delivered to supply the grid while 10% is stored in the ESS. During dwell time, ESS releases energy to the PCS supplying 104% of the pulse electrical output (~890 MW_e) to facility and grid. IHTS and PCS designs of the HCPB ICD BoP variant profited from industrial CSP experience. Furthermore, the base design has been strongly supported by industry.

4.2.1. IHTS

The IHTS collects energy from the BB PHTS in the ESS during pulse, controls BB inlet temperature via HX secondary side inlet temperature and then transfers thermal energy to the steam generator/superheater as requested by the PCS. During dwell, the HITEC mass flow rate is finely tuned in order to guarantee the decay heat removal from the BB on the left side (Figure 1) using a dedicated small pump. On the right side, during both pulse and dwell time, the IHTS follows the requests of the PCS. To achieve such a decoupling function, the presence of 2-3 HITEC pumps operating independently from each other is foreseen. For RAMI reasons, twin pumps are required to guarantee redundancy.

The main design and operating parameters of the HCPB ICD BoP IHTS are summarized in Table 3.

Table 3. HCPB ICD BoP IHTS Main Parameters.

Parameter	Value
ESS capacity [MWh]	426
ESS hot/cold tank number	1/1
ESS tank molten salt volume [m^3]	2600

Currently, the ESS is realized as a classical two-tank solution. On-going research (in CSP domain) focusses on the more compact single tank solution, which has the advantage to avoid the costly high temperature HITEC pump and to reduce space for the IHTS.

4.2.2. PCS

During the pre-conceptual phase, the PCS (Figure 1, right side) has been optimized based on the different variants and the available energy sources. The detailed design proposed by an industrial partner gave a breakthrough because of the optimization of the turbine-feedwater train.

In particular, the steam turbine configuration consists of a steam turbine with two steam re-heaters that use steam from steam extractions of the high/intermediate pressure steam turbine. The main idea is that all hot molten salt should be used for steam generation, all the steam should go through the steam turbine before being used anywhere else for steam re-heating or feedwater pre-heating. In the DEMO PCS, there are also two low pressure feedwater preheaters and two high pressure feedwater preheaters that use steam from different steam extractions of the steam turbine. A special steam extraction of the steam turbine is also connected to the deaerator.

Steam generator of the proposed DEMO BoP configuration is a two-stage Steam Generator (SG). During pulse time, first stage SG generates steam at ~291 °C and ~59 bar while the second stage SG generates steam at ~446 °C and ~121 bar. During dwell time steam parameters are slightly different. First stage SG generates steam at ~293 °C and ~60 bar while the second stage SG generates steam at ~442 °C and ~134 bar. Steam parameters leaving the first stage of SG are nearly constant during the whole DEMO operation so to keep the temperature of the cold molten salt returning to the cold tank at ~270 °C.

Table 4 reports the main parameters of the HCPB

ICD BoP PCS.

In this respect, it may be underlined that the cycle efficiency (η_{CY}) for both the pulse and the dwell phases has been calculated as:

$$\eta_{CY} = \frac{W_{Gross} - W_{Pumps}^{PCS}}{Q^{IHTS} + Q^{DIV\ PFU} + Q^{DIV\ CAS} + Q^{VV}} \quad (1)$$

where W_{Gross} is the gross cycle output, W_{Pumps}^{PCS} is the power required by the PCS pumps while Q^{IHTS}, $Q^{DIV\ PFU}$, $Q^{DIV\ CAS}$ and Q^{VV} are the heat inputs from the IHTS, the DIV PFU PHTS, the DIV CAS PHTS and the VV PHTS, respectively. On the other hand, the overall plant efficiency (η_o) has been calculated as:

$$\eta_o = \frac{\int_0^T (W_{Gross} - W^{BoP})\,dt}{\int_0^T (Q^{BB} + Q^{DIV\ PFU} + Q^{DIV\ CAS} + Q^{VV})\,dt} \quad (2)$$

where T is the period of a typical demo duty cycle, W^{BoP} are the BoP electrical loads while Q^{BB} is the heat input from the BB. In this regard, it must be highlighted that the other DEMO plant electrical loads have not been considered in the calculation because they have not been defined yet.

Table 4. HCPB ICD BoP PCS Main Parameters.

Parameter	Value
Gross Output (pulse/dwell) [MW]	882.5/930.0
Cycle efficiency (pulse/dwell)	37.6%/43.8%
Overall efficiency	34.1%
Steam turbine type	SST5-6000

The flexibility of the reference HCPB BoP variant allows adapting DEMO to the needs when design requirements are finalised.

5. WCLL BoP

The following section reports a brief description of the three concepts proposed for the WCLL BoP. In particular, three main variants have been conceived:

- one Indirect Coupling Design (ICD), consisting in an indirect configuration with an Intermediate Heat Transfer System and an Energy Storage System (IHTS+ESS);
- two Direct Coupling Designs (DCD), consisting in a direct configuration with a small ESS and a direct configuration with an AUXiliary Boiler (AUXB).

5.1. Investigated variants

Each variant presents advantages and drawbacks that must be taken into account in the analysis for the definition of the reference configuration for the DEMO plant. The main requirements for the design of each variant are to avoid disconnection from the grid for each pulse/dwell phase and to limit the impact of frequent temperature transients to structures while considering the feasibility of the solutions proposed, as well as performance, safety and cost aspects.

The design activity has aimed to attain a comprehensive design development to allow the selection of a single WCLL variant, minimizing the risks of the still pending uncertainties.

In order to ease the reader's comprehension, a ranking map of the main WCLL BoP variants investigated is reported in Figure 4. It summarizes and compares the most relevant features of each variant highlighting high-level design choices and the identified critical issues together with the points to be further investigated during the DEMO conceptual design phase.

Variant		BB PHTS HX-SG-SH Pressure	Storage Molten Salt	Storage ESS-Concrete	Auxiliary Heating system	Boiler Gas-supply	Turbine load Flexibility	Critical components Type	Critical components #	Space for AHS/IHTS	System Feasible yes/no	Tolerant to frequent transients	Power output & plant supply	Safety function Barrier (T, ACP)	Critical issues
Importance -->		H	M	M	H	H	M		M	H					
DCD	with small ESS	H_2O-H_2O high	2x1500m³ HITEC	-	Electric 41.2 MWe	-	Low	H_2O-H_2O SGs;	4	small ESS	yes	TBI	+ electric Power	1 TBI	Check SGs stability & Turb. load variations
DCD AUXB	gas fired boiler	H_2O-H_2O high	-	-	Gas 250 MW	Large	Low	Ext. Boiler, H_2O-H_2O SGs;	5	Large	TBI	TBI	+ Gas	1 TBI	As DCD + Boiler T/H transients
ICD	with 100% ESS	H_2O-H_2O high H_2O-HITEC high	2x11000m³ HITEC	-	Trace heating	-	Standard	ESS tanks, H_2O-H_2O SGs; H_2O-HITEC IHXs	6	Two large tanks	yes	TBI	OK	1-2 TBI	Size of ESS; Tritium behaviour in MS
Additional variants suggested during WPBOP Design Review (only a few studies and/or considerations in support)															
DCD NO STORAGE	no auxiliary system	H_2O-H_2O	-	-	-	-	Very Low	H_2O-H_2O SGs; Turbine	5	slightly larger Deaerator in PCS	TBI	TBI	OK	1 TBI	As DCD + Turbine-to-Alternator coupling elements
ICD low load	with ≈10% ESS (prelim.)	H_2O-HITEC	2x1500m³ HITEC (prelimin.)	-	Trace heating	-	Low to moderate	H_2O-HITEC IHXs	4	small-to-medium ESS	TBI	TBI	OK	1-2 TBI	Tritium behaviour in MS; Turb. load variations

Red: critical issue (size, feasibility, ...) Blue: producible but not in the shelf TBI: To be investigate further Importance: L = Low; M = Medium; H = High
Orange: now or at present feasible and producible Green: component from the shelf

Fig. 4. Ranking map of the WCLL BoP variants.

5.1.1. Indirect Coupling Design (ICD)

The DEMO plant configuration relevant to the

Indirect Coupling Design (WCLL ICD BoP) option foresees the use of an IHTS+ESS operated with molten salt (HITEC) to decouple the regular operational transients of the Tokamak from the PCS operation.

The energy recovered from the Breeding Zone (BZ) is delivered to the PCS while the First Wall (FW) power is delivered to the IHTS, then to the PCS. The power from BZ and FW is used to produce the main steam at condition suitable to feed steam turbine. The cold sources, i.e. DIV and VV, are used as feedwater heaters, in order to improve efficiency. The ESS is designed to deliver 100% of the nominal power during the dwell time, assuring continuously the nominal power to the turbines for steam generation.

The main advantage of this configuration is the design requirement of continuous and nearly constant electrical power delivered to the grid in both pulse and dwell. The primary to intermediate system heat exchanger (water/HITEC) is simple and it can be operated in conditions involving low thermal and mechanical stresses. Furthermore, the IHTS design can use qualified technology coming from the experience on solar power plants applications.

The large dimensions of the energy storage tanks (around 11000 m^3 each) is a significant disadvantage. In fact, because of the requirement of constant electrical power supply during dwell (i.e. ~100%), the amount of molten salt stored, and thus the dimensions of the storage tanks, are designed considering such power scenario.

5.1.2. Direct Coupling Design with small ESS (DCD)

The DEMO plant configuration with Direct Coupling Design BoP (WCLL DCD BoP) is based on the direct cycle, in which the BZ and FW Once through Steam Generators (OTSGs) are directly connected to the steam turbine of the PCS. The heat from DIV PHTS and VV PHTS is used to preheat the PCS feedwater to increase the cycle efficiency.

The system foresees the adoption of a small ESS (with two tanks of 1500 m^3 each) operated with molten salt (HITEC) and heated with electrical heaters. It can feed the steam turbine during the dwell with a steam flow rate of about 10% of its nominal value, maintaining the connection with the electrical grid with a minimum production of electric power (enough for the PHTSs and BoP auxiliaries).

The BoP architecture has been studied with a detailed transient analysis and stress assessment highlighting the effectiveness of the solution. The adoption of the small ESS simplifies the control of the system. Therefore, the WCLL DCD BoP is considered as the reference variant for the next step of DEMO development and it is described in more detail in §5.2. Figure 5 shows a block scheme of the WCLL BoP reference solution.

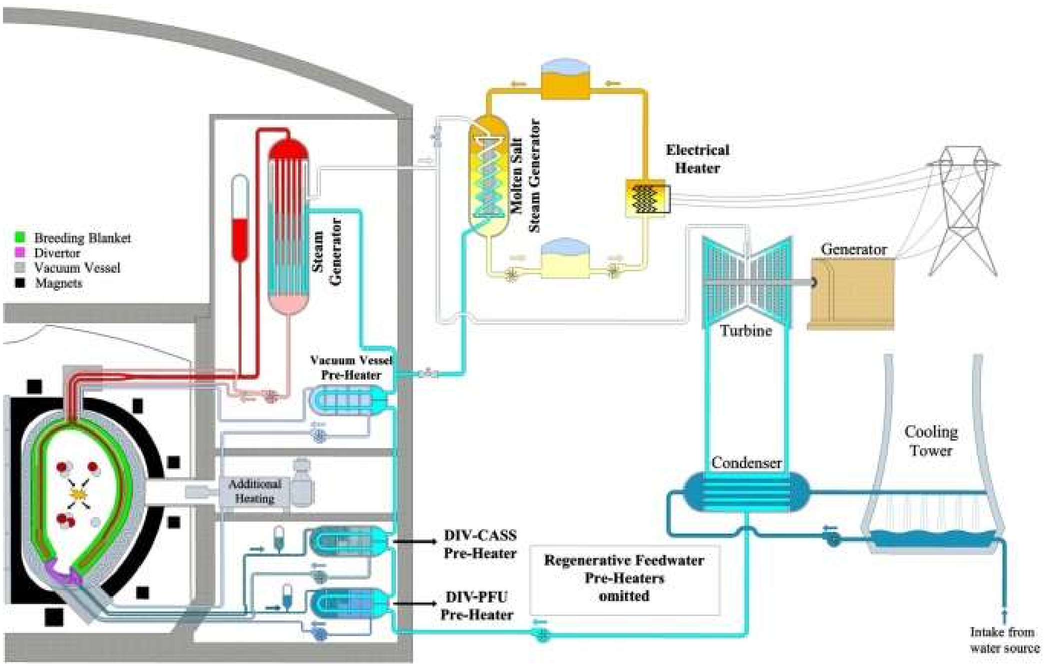

Fig. 5. Overview of the WCLL DCD BoP.

5.1.3. Direct Coupling Design with Auxiliary Boiler (DCD AUXB)

A second solution has been conceived for the DEMO plant configuration with Direct Coupling BoP, with the adoption of an Auxiliary Boiler (WCLL DCD AUXB BoP). In this configuration, the BZ and FW PHTSs are directly coupled with the PCS through two OTSGs. The energy recovered from the DIV and VV is used to heat the PCS feedwater. The steam flow rate during dwell is assured by the auxiliary boiler, which consists of gas-fired boiler, designed to be directly connected to the turbine and sized to provide the minimum steam flow rate of 10% of the nominal value. The component works during both pulse and dwell time, providing 250 MW of power, thus the turbine works during dwell time at 10% of nominal power.

The design features of the main components are comparable with existing ones from nuclear and conventional industry. This implies no challenge for the design, the manufacturing, the operation and the inspection of all the main components but the steam turbine, whose feasibility should be assessed. Nevertheless, the main drawback of this solution is the large power of the auxiliary boiler required to have an external source for operating the BoP at minimum load in dwell, which makes this solution non-convenient with respect to other proposals.

5.1.4. Preliminary Work on additional variant

A very preliminary study, useful to both confirm the feasibility and provide an optimization of DCD BoP has been recently started. It adopts basically the same architecture of DCD with small ESS, minimizing the energy storage while ensuring a safe operation of the steam turbine in dwell. For the latter, an innovative connection of the High Pressure (HP) section to the Low Pressure (LP) one is also postulated (HP ST connected to the LP stage through a clutch) [20, 21]. This configuration, called "WCLL DCD NO STORAGE", will be further investigated in the next DEMO conceptual design phase. It could represent an interesting optimization of the DCD itself after demonstration of the availability of the adopted technologies (i.e. high-power clutches) and the feasibility of the concept (ST operation at very low steam load).

A recent focus has been addressed to an additional BoP ICD option with small storage system. The idea is to introduce an intermediate loop with a small ESS to limit the large operational duty variation of the steam generator units so that to avoid regulation and stability issues. The ESS would be much smaller than that presented in §5.1.1. and sized so to operate the steam turbine at low load during dwell.

5.2. Reference WCLL BoP configuration

The reference variant of the DEMO WCLL is the Direct Coupling Design (WCLL DCD BoP) with small ESS. In this configuration, energy transferred from the BB PHTS (BZ and FW) to the PCS through steam generators is used to produce the main steam in conditions suitable to feed the turbine. The energy transferred from the DIV and VV PHTSs is used to preheat the PCS feedwater thanks to the integration of DIV and VV heat exchangers in the feedwater train of heaters in order to improve the overall plant efficiency.

The WCLL DCD BoP is designed to maximize electric power production during pulse and to maintain synchronized the generator to the grid during dwell period. This is realized implementing a small molten salt ESS (about 200 GJ of thermal energy stored in a hot tank of about 1500 m^3 with molten salt inventory of about 2700 tons) that is necessary to produce sufficient steam flow to drive the steam turbine and to keep hot the main PCS components. The power compensation system chosen for the WCLL DCD BoP during dwell is downstream the SG. This configuration has been selected in order to limit complexity (and hence safety and integration challenges) of BB PHTS. The latest design of the WCLL DCD BoP is shown in Figure 6.

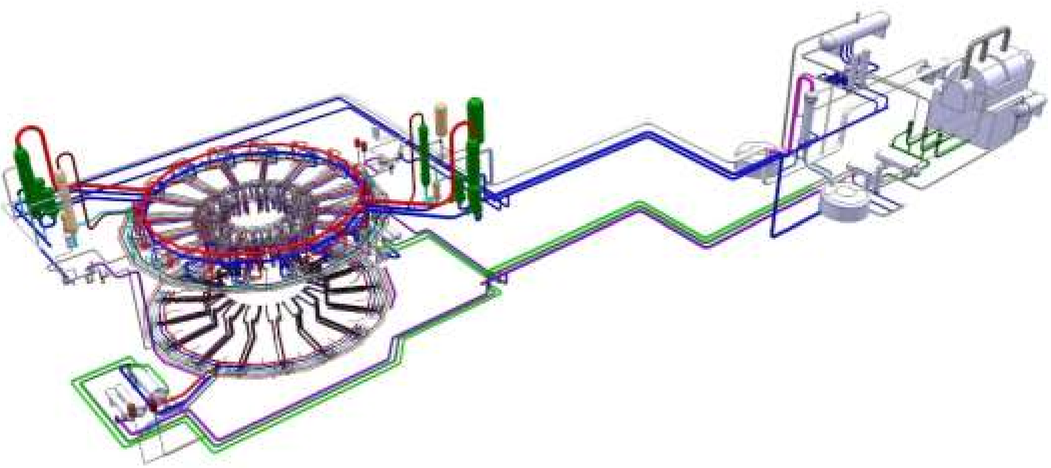

Fig. 6. WCLL DCD BoP layout.

5.2.1. PCS and ESS

The WCLL PCS is composed of one loop. The main heat sources are the BB PHTSs. It is also connected to VV, DIV-PFU and DIV-CAS PHTSs, which act as preheaters. It is mainly placed in the turbine building. Only few piping connections are located within the Tokamak building (linked to DIV-PFU, DIV-CAS and VV HXs). The reference thermodynamic cycle is based on superheated steam at 6.41 MPa and 299 °C.

The PCS is mainly composed of steam turbine with condenser, low-pressure and high-pressure feedwater heaters, deaerator, condensate extraction pump, feedwater pump, forwarding pump, condensing cooling water pump and connecting pipes between these components.

The Small ESS loop is composed of molten salt pumps and tanks, electrical heaters, steam generator and the connecting piping between these components. The tanks have a volume of 1500 m^3, containing an inventory of about 2700 tons of molten salt. The total thermal energy stored is about 200 GJ. The small ESS loop feeds the steam turbine during the dwell at about 10% of the nominal steam flow rate, maintaining the connection to the electrical grid with a residual production of the electricity (enough for the PHTSs and PCS auxiliaries).

The thermal power needed to heat the HITEC comes from an electrical heater operated during pulse.

The main design and operating parameters of the WCLL DCD BoP PCS are summarized in Table 5. The cycle efficiency and the overall efficiency have been calculated through the equations reported in §4.2.2 where Q^{IHTS} is replaced by Q^{BB}.

Table 5. WCLL DCD BoP PCS Main Parameters.

Parameter	Value
Small ESS power [MW]	41.2
Small ESS hot/cold tank number	1/1
Small ESS molten salt volume [m^3]	1500
Gross Output (pulse/dwell) [MW]	791.6/62.9
Cycle efficiency (pulse only)	34.1 %
Overall efficiency	31.3 %
Steam turbine type (HP+2LP)	1500rpm

6. Synopsis

The paper aims to provide an overview of design progresses of the DEMO BoP for the HCPB and the WCLL BB options. It briefly outlines the most promising BoP configurations. Then, the assumed reference configurations are described in detail highlighting the main features and the most relevant engineering aspects. Attention has been mainly focused on technological challenges, integration constrains and other open issues, highlighting pros and cons of the BoP options to be further investigated in the next DEMO project phase [3] to attain a feasible concept design according to the program objectives.

Concerning the HCPB BoP, the DEMO HCPB ICD variant appears the most promising concept among the BoP variants investigated and it appears the most suitable to meet the DEMO BoP requirements. The adoption of the IHTS equipped with an ESS allows easily connecting the PCS to the grid and enabling DEMO to work as baseload power plant.

Helium thermal cycle allows to keep the ESS size within reasonable values. The two storage tanks would be around 3000 m^3 each, a size which is well below the current tank dimension employed in CSP plants (≈10000 m^3 each), as well as the installed overall capacity of them (≈130000 m^3).

The feasibility of this configuration is ensured, since the manufacturing of main equipment seems possible, with limited extrapolation for some components (e.g. circulators) with respect to state-of-art technologies. However, it must be emphasized that helium technology may suffer the lack of vendors available to supply nuclear components, such as the circulators, with specifications outside industrial application which could be hardly attractive for the market; this might imply in turn, at least, a higher cost for manufacturing.

To limit this risk, actions are on-going to strengthen research on the market so that to enlarge the contacts with manufacturers having well-proven experience in nuclear components technologies with the aim to invite them to contribute to the design development of the HCPB BB PHTS equipment.

In particular, during the next Conceptual Design phase, first priority will be given to helium circulators, which appears to be the most critical components to be developed and qualified to fulfil the strict PHTS requirements (high efficiency, excellent reliability, maximum leak tightness etc).

A preliminary study of reliability gave a yearly operational availability greater than the preliminary target taken as reference (30%).

Additional studies will also address abnormal and accidental transients, tritium related issues, and size optimization of the largest components to minimize integration and safety challenges as well as reduce the costs of the BoP systems.

In addition to the promising ICD variant, the DCD-s2 variant (electrically heated molten salt storage) has revealed some potential. It is expected a certain effort to continue the development and validation of this solution as it could represent an optimized, simplified and hopefully cheaper, back-up option of ICD BoP.

Regarding the WCLL BoP, the DEMO WCLL DCD with small ESS configuration appears to be the most promising concept among the BoP options investigated and it has been taken as reference variant to be further investigated during the forthcoming DEMO conceptual design phase for design and technology choices, verification and validation. It allows supplying the turbine with a modest amount of steam (around 10% of nominal) necessary to avoid high thermal transients in the main equipment and keep the stresses below the acceptable limits with reasonable safety margins. Furthermore, this option manages to maintain the turbo-generator at the nominal speed (and then synchronized with the grid) because a reasonable amount of steam is continuously provided to the turbine also in dwell.

This configuration has been selected in order to limit complexity and hence safety and integration challenges of the whole BoP architecture. On the other hand, a pure direct cycle (without any kind of storage system and postulating a steam turbine "ON/OFF" operation in pulse/dwell) seems not viable at the current status of the studies due to the adverse impact on qualified life of some equipment, especially the steam turbine.

As stated, in order to minimize the required storage for dwell operation and optimize the configuration, a comprehensive assessment (including a suitable R&D) to verify the safe and reliable operation of the steam turbine at low load will be addressed in WPBoP conceptual design phase.

The feasibility of WCLL DCD option can also take advantage from the use of commercial components (PWR experience), even though some of them might operate under unconventional working conditions. For these reasons, further efforts (both analyses and R&D campaigns) are necessary to validate completely this promising option and cover the remaining technical uncertainties.

Therefore, particular attention will be devoted to test the performance and the stability of the operations of steam generators also at low load. Additional studies to be carried out in the next years, in synergy with other work packages, will address abnormal and accidental transients and tritium related issues to minimize integration and safety challenges of the BoP systems.

A preliminary study of reliability gave a yearly operational availability greater than the preliminary target taken as reference (30%).

Considering the challenges of the WCLL DCD with small ESS, mainly related to the regulation and stability of the steam generators, an interesting back-up solution for the WCLL BoP might be an ICD option with a small ESS that, in fact, has been introduced in the work program of DEMO BoP concept design development.

7. Outlook

In addition to what already mentioned and considering the main outcomes of the Preconceptual Design phase, the main R&D and design activity of the DEMO Balance of Plant to be carried out during the forthcoming Conceptual design phase will be devoted to:

- provide a concept design of the PHTSs of breeding blanket, vacuum vessel, divertor and limiters, of the IHTS (in case of Indirect Coupling options) and PCS for a DEMO concept equipped with a driver and an advanced blanket to be selected between the WCLL and the HCPB concepts [22];
- provide a concept design of the Decay Heat Removal System (DHRS) dealing with the removal of the decay power after accident;
- provide a concept design for auxiliaries such as Chemical Volume and Control System (CVCS), Chilled Water System (CWS) and Component Cooling Water System (CCWS);
- perform the required R&D plan, which includes manufacturing feasibility & performance verification of He blowers, main He-molten salt Heat Exchangers, main H_2O-molten salt heat exchangers/steam generators, divertor and vacuum vessel heat exchangers, steam turbine rotor and blades.

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