Hydrogen Fusion and the Importance of Thermal Energy Storage Systems - Development of the DEMO Balance of Plant

Wasserstofffusion und die Notwendigkeit eines Wärmespeichersystems - Entwicklung der DEMO Anlagenperipherie

Sabrina Gil Pascual
Kraftanlagen Heidelberg GmbH
Im Breitspiel 7, 69126 Heidelberg, Germany
sabrina.gilpascual@kraftanlagen.com

Andreas Bender
Kraftanlagen Heidelberg GmbH
Im Breitspiel 7, 69126 Heidelberg, Germany
andreas.bender@kraftanlagen.com

ABSTRACT

The aim of ITER, the world's largest fusion experiment, is to prove that net energy can be produced from a fusion reaction. Demonstrating that net electricity can be produced from fusion will then be the next significant step. This is where a demonstration fusion power plant, the so-called DEMO, will come in. For the european DEMO, pre-conceptual studies have already taken place and its conceptual design phase (2021–2027) aims to demonstrate the technological and economic viability of fusion.

Kraftanlagen Heidelberg (KAH) has been collaborating with the Karlsruhe Institute of Technology (KIT) and contributes to this major milestone by delivering engineering services for the evaluation and optimization of the Balance of Plant (BoP) for DEMO.

The main goal of the BoP is the transfer of plasma thermal power from the breeding blanket to the power conversion system (PCS) and consequently to generate electricity. Since the European DEMO can only be operated in pulsed operation, the concept relies on a thermal energy storage system in order to ensure a reliable and continuous power output. Here comes along the importance of a thermal energy storage for a base-load capable Fusion Power Plant (FPP). With the integration of such kind of FPP to the future market, an added value to reliable power production is generated.

INTRODUCTION

According to ITER General Director Bernard Bigot, hydrogen fusion is the new synonym of nuclear fusion. One reason is that nuclear technology is experiencing a kind of renaissance in the light of climate change. Another reason is an impending energy crisis throughout Europe, unless society rethinks with regard to the acceptance of nuclear energy. An electricity-generating "hydrogen" fusion power plant still seems to be a far-off vision. Europe, however, is already on the verge of developing DEMO, the electricity-generating successor to ITER. KAH has a long-standing partnership with the KIT and with its strategic orientation to support the development of future carbon-free fusion power plants, the final piece of the puzzle for a sustainable power generation.

CHALLENGES OF HYDROGEN FUSION FOR ELECTRICITY PRODUCTION

In contrast to nuclear fission, nuclear fusion does not have to overcome the risks of an uncontrolled chain reaction; instead, maintaining the fusion reaction is the greatest challenge. Due to the Tokamak principle used in both ITER and the European DEMO, only pulsed operation is feasible. The reasons for this are numerous and mainly due to the magnetic confinement concept, which is easier to realise than the Stellarator principle. In the Stellarator, the twisting field is produced entirely by external non-axisymmetric coils, meaning that no central solenoid and consequently no pulsed operation is needed.

In the Tokamak, the rotational twist of a helical magnetic field is formed by a toroidal field generated by external coils together with a poloidal field generated by the plasma current. The required current is induced by the central solenoid shown in Figure 1 (left), which must be recharged after every pulse.

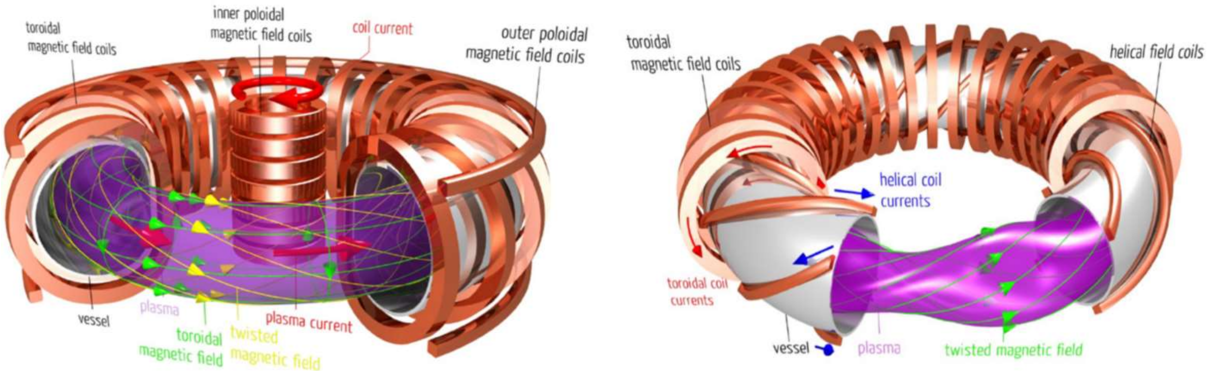

Figure 1: Main features of the Tokamak (left) and stellarator (right) device for magnetic confinement [1]

In the described tokamak scenario for DEMO, a pulse time of two hours is assumed with a subsequent dwell time of approx. 10 - 30 minutes. The greatest challenge to the BoP design and its components is the extreme gradient that occurs between the two operating modes, as the fusion reaction ends and begins abruptly. Another resulting challenge is to compensate for the power drop during the dwell time. To ensure that a future fusion power plant has a stable and flexible electricity output, it is essential to implement a thermal energy storage system. In summary, a future fusion power plant is dependent on a thermal energy storage system in order to ensure a reliable and continuous power output.

DEVELOPMENT OF A RELIABLE DEMO BALANCE OF PLANT FOR NUCLEAR FUSION

DEMO as a Tokamak fusion reactor operates in a pulsed mode due to solenoid loading and vacuum pump capacity. Consequently, the intermittent thermal power leads to a discontinuous electrical power output. In order to realise a steady and flexible DEMO electrical power output, a thermal energy storage based on heat transfer fluids such as molten salt which is widely used in Renewable Energy Power Plants, was included to the design. The so-called Intermediate Heat Transfer System (IHTS) is equipped with an Energy Storage and serves as an interface between the Primary Heat Transfer System (PHTS) and the Power Conversion System (PCS). The system was developed at KIT and Figure 2 shows the preliminary 3D layout of the DEMO Balance of Plant. In the Breeding Blankets (BB) the heat generated by hydrogen fusion is transferred to the helium coolant. Additionally, heat is removed from the Vacuum Vessel and Divertor via a water coolant, which is used to preheat the feed water of the PCS upstream the steam generator. The main goal is the transfer of plasma thermal power from the breeding blanket to the PCS and consequently generate electricity.

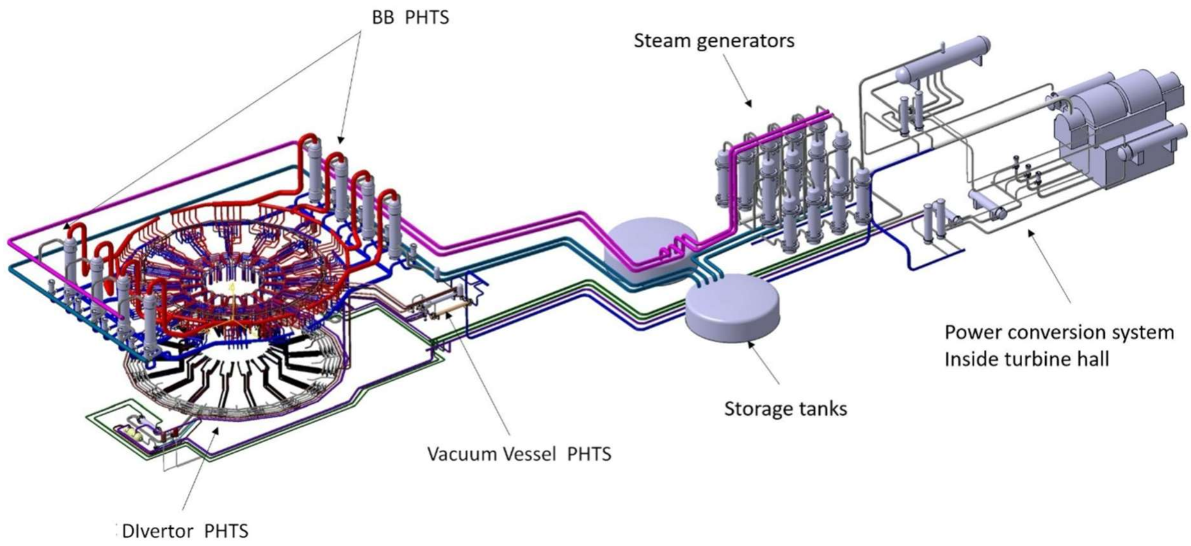

Figure 2: Preliminary Layout of DEMO BoP Design featuring all systems, PHTS, IHTS and PCS up to the Turbo-Generator [2]

The validation and readiness of the DEMO BoP design for the conceptual design has been verified by static and dynamic simulations. Figure 3 shows the simplified model of the DEMO ICD BoP design.

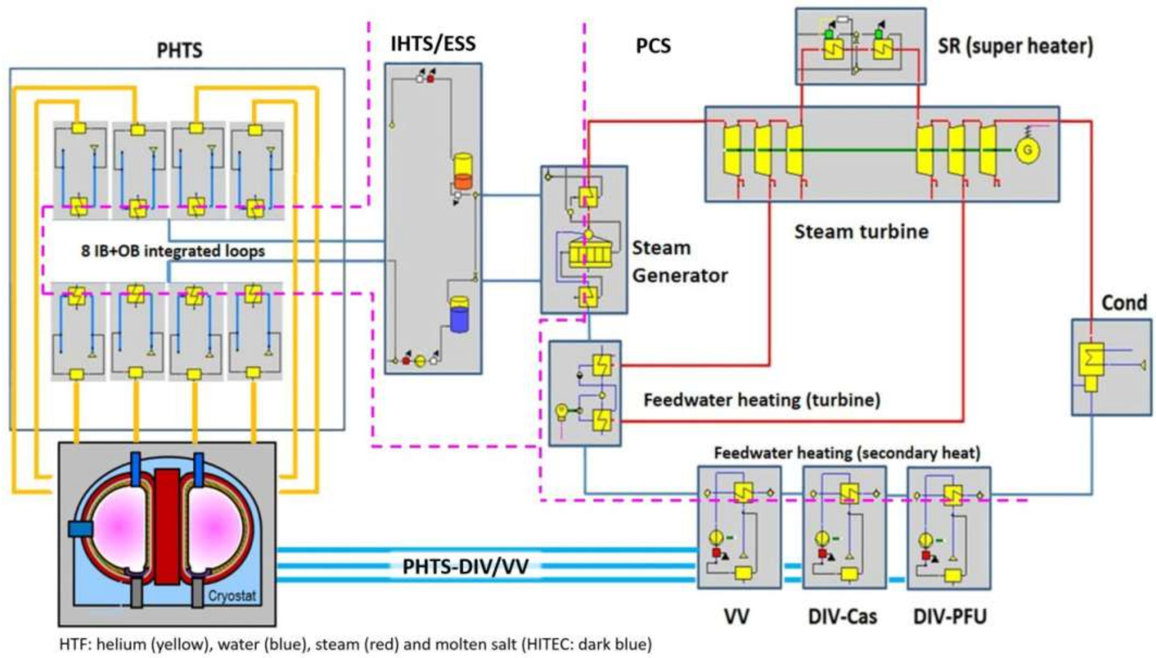

Figure 3: Overview of the DEMO Balance of Plant variant indicating the different Heat Transfer Fluids (HTF) and the interfaces (dashed lines) [3]

Currently, the temperature levels for the helium reactor coolant are limited to approx. 500 °C due to the usage of reduced activation steel. With the usage of more heat resistant reactor materials, the overall PCS efficiency could be increased by using liquid metal as storage medium and consequently raising the temperature levels to approx. 600 - 700 °C.

The presented BoP concept was widely investigated by KAH as the industrial partner for the KIT. Accordingly, adapted Readiness Level (RL) scales and definitions were elaborated. For the review, a definition of Technology Readiness Levels (TRL) alone is too generic and insufficiently detailed, which is necessary for accurate system-specific definitions. From KAH point of view, the introduced Integration

Readiness Level (IRL) is adequate for proven technologies that only need to be adapted to the system boundary conditions. The same applies to the overall HCPB BoP ICD concept where a System Readiness Level (SRL) definition is needed in order to assess the overall project progress.

Currently, the DEMO BoP design with an IHTS is assessed to fulfil the requirements to have an IRL and SRL of 4, meaning that for advancing to level 5, a pilot plant for the PHTS/IHTS interaction is needed. KAH is supporting the KIT with the upgrade of the Helium Loop Karlsruhe (HELOKA) facility with a thermal storage system. For that purpose, a regulation strategy is being developed for DEMO BoP which is then tested in this upgraded facility.

Since KAH was already involved in the planning and construction of German Nuclear Power Plants (NPP) and still carries out decommissioning projects at the sites today, there is a sound knowledge of the used power plant classification system called Kraftwerk-Kennzeichensystem KKS and its successor Reference Designation System for Power Plants RDS-PP. The KKS for German NPPs is in principle based on a coding system, which was developed for NPP new builts in the late 1960s. For the upcoming conceptual design of the DEMO systems, KAH proposed a coding system which is in principle based on German NPP coding systems but adapted to DEMO needs.

WHAT COULD THE ELECTRICITY GRID LOOK LIKE IN 2050 AND BEYOND?

Another important aspect for the utilisation of fusion energy by the middle of the century is the integration in the future electricity grid, which dramatically affects the DEMO plant design and operation. When checking the EU projection for the greenhouse gas emission reduction by 2050, renewable energy share will provide most of the electric energy. With the integration of FPPs to the future market, an added value to reliable power production is generated, especially for balancing the steadily increasing share of Variable Renewable Energy Sources (VRES) by load following operation and sector coupling. This means that FPPs dependent on a thermal storage system will be very attractive for supporting grid stability. Today, this concept is considered in advanced nuclear power plants, where innovative reactor designs (e.g. Integral Molten Salt Reactor) provide energy storage systems to handle the dynamics of the electrical grid.

The integration of a future FPP into a multi-modal energy system must respect several aspects that need to be addressed:

- Analysis of characteristic data of a future FPP (extrapolation from DEMO)
- Development of FPP grid embedding strategies (considering internal/ external energy storage solutions)
- Including sector coupling power-to-heat (P2H) and vice versa via inbuilt PCS
- Consideration of required start-up performance on assessment of grid stability

The fusion road map as shown in Figure 4 indicates the steps needed for reaching a future commercial FPP.

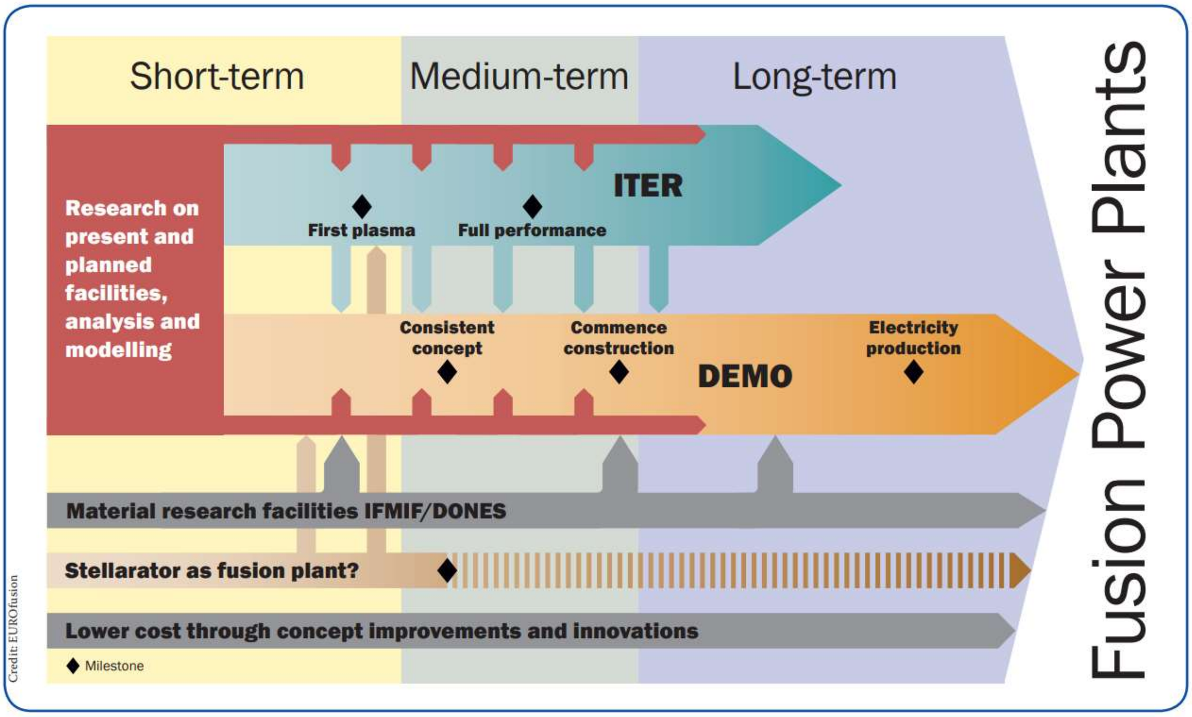

Figure 4: Hydrogen Fusion Road Map towards a future FPP [4]

THE IMPORTANCE OF ENERGY STORAGE FOR FUSION AS A RENEWABLE ENERGY SOURCE

As already described in the DEMO BoP concept, a heat storage concept suitable for the application plays a key role in the integration into future electricity grids.

The main purpose of the IHTS is to dampen or even to eliminate the negative effects of the pulsed operation of DEMO (2 h pulse and 10 – 30 min dwell time). KAH investigated together with potential suppliers the feasibility of DEMO BoP without an IHTS. Having no IHTS integrated, the operational boundary conditions of the PCS will change periodically, leading to undesired load cycles that eventually lead to:

- Unstable el. power output, with even a negative balance in dwell time where nearly no el. power is generated
- High revision costs due to shortened revision intervals
- Fatigue for the pressure parts of the steam generator, especially when alternating stresses are present
- The necessity to provide at least 10 to 20 % of live steam to the turbo machine is only feasible with additional heat sources in a scenario with zero fusion power

The necessity of decoupling heat and power generation is already evident in various technologies, as the seasonal discrepancy between power generation and power demand is drifting further and further apart. Even modern conventional coal-fired power plants are becoming increasingly uneconomical to operate, despite their high efficiency.

This is mainly due to the boundary conditions of the market, since at present all electricity generation has to be subordinated to renewable energies. Consequently, it is so important to anchor reliable highly flexible low carbon power plants in the German and European market to stabilise the grid for a safe and secure energy supply in the long-term. In addition, nuclear fusion as a predictable energy source can drive emission reduction technologies.

SYNERGIES OF FUSION POWER THERMAL STORAGE SYSTEMS TO OTHER POWER PLANT TYPES

Fusion has to master extreme challenges in any field providing various spin-off effects to the German Industry like the ones described here. Additionally, effects to the development of industrial grade high temperature superconductors applicable from power lines to manned space flight radiation protection. Thus, a close follow-up or even participation in fusion research can develop new business fields in the short-term, which are important in the European or international competition.

CONCLUSION

Hydrogen fusion is going to play a major role in the future energy supply of the world, not only because the world's energy hunger is constantly growing, but also because natural resources are limited. In fact, fusion does have the potential to serve as an independent renewable energy source whose fuel is almost limitless and widely available. Its ability to flexibly provide large amounts of energy based on the fusion of hydrogen isotopes in combination with large-scale thermal storage systems is another advantage of this future technology. As nuclear fission used to be an innovative technology of its time, so will hydrogen fusion be the next logical step towards an advanced and prosperous future for humankind.

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