Operational characterization of tokamak and stellarator type fusion power plants from an energy system perspective

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A B S T R A C T

Fusion power plants are not yet considered specifically in European long-term energy system studies. In order to include them in such studies a corresponding and valid parametrization of their operating performance has to be established despite the fact that fusion reactor design is still an ongoing effort.

The goal of the present paper is to specify and energetically represent the prospect of feasible operation and dynamics of tokamak and stellarator type fusion power plants from an energy system perspective. Special focus is given on time and operation mode dependent self-consumption. The basis of the parametrization is a one GW_{el} power output plant. As a result, we propose the representation of fusion power plants as a system with three main components (fusion reactor, thermal energy storage (TES) and power conversion system), followed by a set of parameters for both tokamak and stellarator type devices. Five different operating states are defined for a fusion plant, depending on the required and active auxiliary subsystems. The comparison between operational dynamics of conventional and fusion power plants showed no tremendous differences due to the TES utilization. However, fusion plants had a lower full-load operation efficiency due to higher self-consumption as well as extensive pre-production losses.

1. Introduction

The necessity of meeting a rising global energy demand and obtaining a sustainable and greenhouse gas emission-free energy system indicates the need for new energy supply technologies. In this sense, nuclear fusion can provide a significant contribution as an abundant and environmentally responsible local energy source [1]. The acceptance of fusion power could also be supported by the recent acknowledgement of nuclear fission power as an energy resource with a potential to substantially contribute to climate change mitigation by the corresponding Taxonomy Regulation of the European Commission [2]. This could further promote the attractiveness of private investments in fusion technologies. Although the European fusion research strategy aims at supplying the grid with fusion electricity by the middle of the 21th century [1], reports on the European energy long-term trends and development scenarios still do not specifically foresee the deployment of fusion power plants [3,4]. Currently, there are few studies published investigating fusion power plants in terms of their possible role in future energy systems [5,6] or their effects on the electricity grid [7]. For modeling fusion power plants in order to investigate their cost-optimal expansion as well as deployment in electricity systems, it is crucial that one is able to qualitatively and quantitatively describe their production behavior, taking into account technical restrictions and self-consumption requirements.

Systems code approaches are widely used to find optimal self-consistent fusion power plant design points incorporating performance expectations and system constraints [8–11]. This approach can hence be used to quantify possible power plant parameters. Since magnetic confinement fusion reactor design and development is an active area of R&D and an ongoing process, corresponding studies typically address specific device designs and their possible improvements. Tokamak type

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Nomenclature

η_{cha}	thermal energy storage (TES) charging efficiency
η_{dcha}	TES discharging efficiency
η_{PCS}	power conversion system (PCS) efficiency
Q_{cap}	TES thermal energy capacity
$\dot{Q}_{BB}$	thermal power from energy multiplication in the breeding blanket (BB)
$\dot{Q}_{cool}$	thermal power deposited in the primary coolant by pumps
$\dot{Q}_{ctrl}$	thermal power deposited in the plasma through the plasma and burn control system
$\dot{Q}_{fus}$	fusion power
$\dot{Q}_{HCD}$	thermal power deposited in the plasma through the heating and current drive (HCD) systems
$\dot{Q}_{tot}$	total thermal power
t_{CS}	duration of the central solenoid (CS) charging state
t_{prod}	duration of the heat production cycle
$t_{prod\ \ start}$	duration of the plasma start-up
$\dot{W}_{cryo}$	electricity consumption of cryogenic plant
$\dot{W}_{CS}$	electrical power for CS charging
$\dot{W}_{ctrl}$	total electrical power for plasma and burn control
$\dot{W}_{ctrl,\ T,add}$	electrical power for coils for plasma positioning
$\dot{W}_{HTS}$	electrical pumping power of heat transfer system (HTS)
$\dot{W}_{HTS,\ red}$	electrical pumping power of HTS in reduced operation
$\dot{W}_{loss,CS}$	electricity consumption in CS charging state
$\dot{W}_{loss,hot}$	electricity consumption in hot state
$\dot{W}_{loss,prod}$	electricity consumption in production state after production start
$\dot{W}_{loss,prod\ \ start}$	electricity consumption in production state during plasma start-up
$\dot{W}_{loss,warm}$	electricity consumption in warm state
$\dot{W}_{maint}$	electricity consumption of facilities for maintenance and monitoring
$\dot{W}_{MF}$	power for external magnetic fields
$\dot{W}_{net}$	net electrical power output of the plant
$\dot{W}_{net,start}$	net electrical power output of the plant during plasma start-up
$\dot{W}_{PCS}$	electrical power of PCS
$\dot{W}_{trit}$	tritium plant electricity consumption
$\dot{W}_{vac}$	vacuum system electricity consumption

Additional subscripts

S	stellarator
T	tokamak

reactors are currently considered as the best studied magnetic confinement fusion devices. That is the reason why the next-step device ITER as well as a possibly succeeding demonstration power plant (DEMO) – both devices aim at demonstrating the feasibility of fusion as a large-scale energy source – are being designed according to the tokamak principle [1]. Apart from that, the commissioning and operation of the Wendelstein 7-X stellarator points, together with the HELIAS power plant concept, towards the stellarator as a possible long-term alternative fusion power plant concept [8]. Preliminary electrical power requirements for DEMO auxiliary subsystems are for example identified in [12]. Nevertheless, a generally valid definition of possible operating states and their dynamics ranging from the start-up to the shut-down of a fusion power plant was not given in this study. Minucci et al. [13] describe the DEMO operation states between two dwell times from the detailed plant level perspective. Their study characterizes electric loads based on their steady-state and focusing on the sizing of the main electrical components also giving alternative configuration concepts when applicable [13]. However, the study thus does not directly elucidate the assignment of time-dependent loads of each of the active auxiliary systems to the described states. The indicated reactor power balance in the BLUEPRINT design code study [14] is exclusively intended to demonstrate the capability of the proposed design process. It is developed to reduce the design point definition time but does not propose specific reactor designs [14]. Integrated system codes like [14,15] generally tend to improve the calculation algorithms while being capable of comparing and optimizing concepts for a DEMO reactor. From the energy system engineering perspective, we thus identified a lack of a definition of operating states of a fusion power plant from a start-up to the shut-down accompanied with a concise summary of respective (presumed for future commercial power plants) power consumption and production behavior as well as underlying assumptions' set on the main system components.

The aim of the present paper is to define operating states of a fusion power plant associated with their power consumption and production as well as to determine the overall plant dynamics in order to be able to model them in energy systems. Therefore, parameters needed for the modeling and operational planning are to be devised. Aiming to uniformly characterize them for further energy system analysis, the elaboration basis is a 1 GW_{el} net electrical power output plant. Special focus is given on time and operation mode dependent self-consumption. Comparison with conventional power plants should contrast their parametrization and advert particular requirements of fusion power plants when being implemented in an energy system. We investigate comparatively both tokamak and stellarator type reactors.

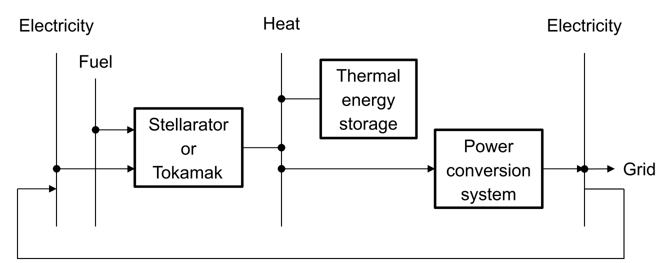

Fig. 1. Main fusion power plant components from an energy system perspective.

2. Modeling of fusion power plant operation

The modeling of fusion power plants is proposed with a system of three main components: reactor (tokamak or stellarator), thermal energy storage (TES) and power conversion system (PCS) (see Fig. 1). In doing so, auxiliary fusion power plant systems are associated with the reactor. Both tokamak and stellarator type reactors consume hydrogen isotopes, deuterium and tritium, as fuel as well as electricity which is needed by the auxiliary systems that enable fusion operation. Heat produced by the reactor can temporarily be stored in the TES or directly converted into electricity. Elaboration of the plant as a three-component system instead of one unit allows flexibility in power plant operation modeling and optimization, especially considering the pulsed heat production of tokamak devices.

The determination of fusion power plant operating states and their respective power requirements is based on the different auxiliary systems being active during the corresponding operation time. The thermal

Table 1
Operating states definition and transition duration.

State	*Transition*	Description
Cold		All systems are shut down, as e.g. during a prolonged downtime. There is no power production or consumption.
	Cold - to - warm	The transition duration between the cold and the warm state is mainly determined by the heating of the TES to its working temperature and the establishment of vacuum conditions in the plasma chamber. This transition is thus assumed to last several days to several weeks. Once its working temperature level is obtained, the TES can maintain it without being operated for multiple days without additional heating [16].
Warm		Magnetic fields are generated by superconducting coils which require the operation of a cryogenic plant for their cooling. In the plasma chamber, high vacuum conditions are maintained. Facilities for maintenance and monitoring of the plant are assumed to actively consume electricity.
	Warm - to - hot	The change between the warm and the hot state is assumed to last for about 15 min for both tokamak and stellarator type devices.
Hot		All subsystems from the warm state are energized. Additionally, the tritium plant is activated as well as the heat transfer system (HTS) in part load with a reduced power consumption.
	Hot - to - CS charging	The transitions between the hot and CS charging states are considered as immediate.
CS charging (Tokamak)		In case of the tokamak, the central solenoid (CS) for generation of the poloidal field component is being charged. All subsystems from the hot state are energized.
	CS charging - to - production	The transitions between the CS charging and production states are considered as immediate.
Production		The reactor generates thermal energy from the burning plasma. During the production state, plasma and burn control systems are active. The HTS is working with nominal load, all other subsystems from the hot state are energized. At the beginning of this state, heating and current drive systems (HCD) systems are operating with increased power demand for a few minutes during the plasma start-up.

inertia of these elements defines time constants for state changes and thus dynamics of plant operation.

2.1. Operating states

Fusion power plant operation can be divided into five main operating states described in Table 1 which furthermore gives explanations with respect to the transitions between the defined operating states.

Figs. 2 and 3 give a comparison between the operation of stellarator and tokamak type reactors, depicting qualitatively the different states with their associated power losses and duration times. Presently, it is assumed that the duration of the heat production cycle t_{prod} of a tokamak amounts to 2 h and the CS charging state duration t_{CS} to app. 10 min [10,17]. Plasma start-up at the beginning of the production state, which duration is denoted with $t_{prod\ start}$, is assumed to last 5 min for both reactor types [13,18].

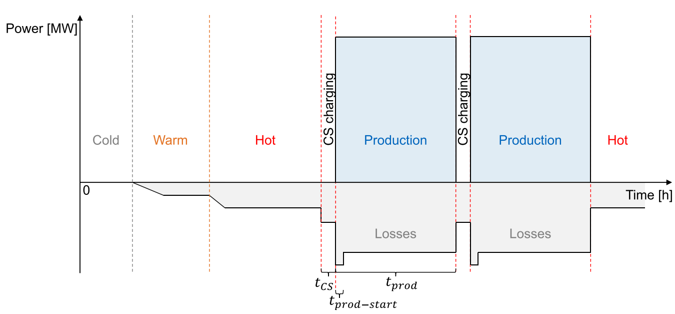

Fig. 2. Tokamak operating states and their transitions.

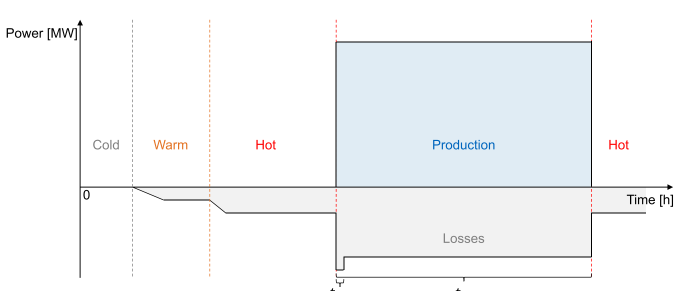

Fig. 3. Stellarator operating states and their transitions.

2.2. Power requirements

For derivation of the power requirements regarding each of the operating states, power consumptions for all considered subsystems are explored. With the aim of uniform characterization of tokamak and stellarator type reactors for further energy system analysis, the power consumptions are elaborated based on a 1 GW_{el} net nominal electrical power output plant. A helium-cooled breeding blanket (BB) system is considered. Symbols $\dot{W}$ and $\dot{Q}$ are used to denote electrical and thermal powers, respectively.

2.2.1. Self-consumption

The auxiliary subsystems mentioned in section 2.1 are grouped by operating state during which they are active, and their power consumptions are quantified below. A graphical ilustration of the operating states together with their corresponding summarized power requirements is given in Fig. 4. We focus exclusively on the active power consumption. Since fusion reactor design is still under development, as noted in section 1, the power consumptions of some of the components have a certain possible range and reasonable estimates have to be made.

Warm. In the warm state, external magnetic fields are generated, both in stellarator and tokamak type devices, for confining a high temperature plasma, which will be established in the production state and has to be kept away from the vessels walls, otherwise it would lose its thermal energy very quickly [19]. Such magnetic fields are assumed to be built up by the usage of superconducting coils. Therefore, the power for the build-up and sustainment of external magnetic fields $\dot{W}_{MF}$ is assumed not to be significant and is hence neglected [12,13].

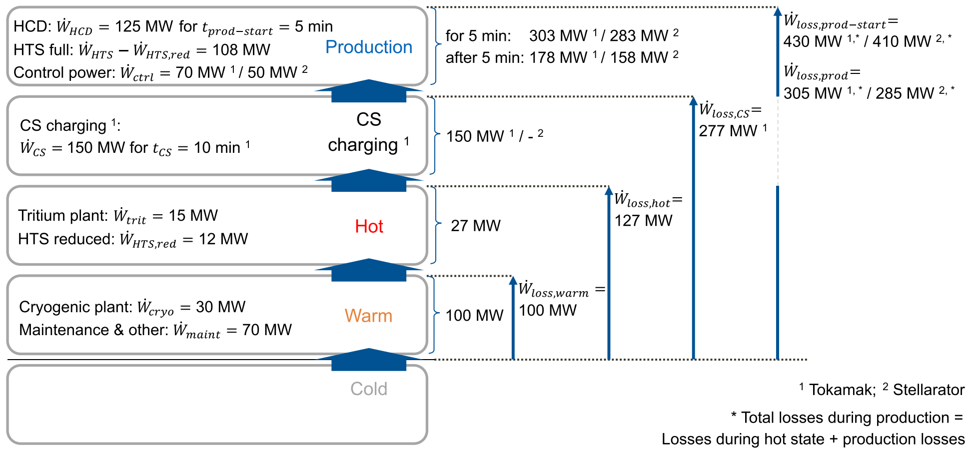

Fig. 4. Electrical power requirements of operating states.

However, for the low temperature operation of the superconducting coils a cryogenic plant is required to provide the cooling. The consumption of the cryogenic plant $\dot{W}_{cryo}$ is assumed to account for 30 MW_{el} for both reactor types [12,20]. The electricity consumption of the vacuum system $\dot{W}_{vac}$, that ensures high vacuum conditions inside the plasma chamber, is neglected since it is assumed that this system requires only around 1 MW_{el} [12]. In the warm state, facilities for maintenance and monitoring of the plant are engaged. They include building electrification, lightening as well as heating, ventilation and air conditioning, plasma diagnostics and control, radwaste treatment and storage, remote maintenance as well as further auxiliaries and site utilities. Based on literature evaluation for DEMO power plants [12,13] facilities for maintenance and monitoring are estimated to have a nominal power consumption $\dot{W}_{maint}$ of 70 MW_{el}.

Hot. In the hot state, the tritium plant is activated which can collect the tritium from the BB coolant and provide it to the fuel cycle of the power plant. It is assumed that tritium plants for both tokamak and stellarator type reactors consume a nominal power $\dot{W}_{trit}$ of 15 MW_{el} [12,13,20]. The HTS that ensures the coolant flow is activated in part load with a reduced power consumption since there is no fusion power production. Its nominal power consumption ranges for DEMO reactors from 90 MW_{el} in recent studies [21,22] to up to 300 MW_{el} [12,13,17,20] and for HELIAS stellarator reactor studies from 100 to 150 MW_{el} [8], depending on the device design. Based on recent DEMO studies and considering the nominal net power output of the plant presented in [22], nominal pumping power of the HTS $\dot{W}_{HTS}$ is assumed to amount to 120 MW_{el} electrically for a 1 GW_{el} power plant, or about 9%[1] of the electrical reactor power. When being in a reduced operation during the hot state, the HTS is assumed to require $\dot{W}_{HTS,\ red}$ of approximately 10% of its nominal power [13,17], or 12 MW_{el} for both types of fusion power plants.

CS charging. Prior to a production state, during the CS charging state, tokamak type devices require energy for creating a current in the plasma which is needed for the magnetic confinement during the production. Based on references regarding current DEMO design [10,12,17] the charging of the CS magnets has an assumed fixed predefined duration of 10 min. The power allocation for CS charging $\dot{W}_{CS}$ we assumed to account for 15% of the net electrical output power which corresponds to 150 MW_{el}.

Production. There is a main difference between stellarator and tokamak type devices regarding the heat production cycle. In stellarator devices, external magnetic fields are confining the plasma alone, and no electrical current in the plasma is needed. Hence, stellarators may be in production state continuously as long as fuel is fed into the plasma. The magnetic field cage of tokamak devices is partly built by the external magnetic fields and partly by the electrical current induced in the plasma by the CS. Thus, tokamaks work in a pulsed mode, having a limited length of production time during one production cycle. After finishing one production cycle, the tokamak may enter the CS charging state for a new cycle or enter the hot state and thus make a break in thermal power production. Since both tokamak and stellarator reactors are assumed to work under full load, flexibility of the electrical output is provided by the TES and the PCS. During the first few minutes of the production state, the HCD systems are operated with increased power demand for the plasma start-up [13,18]. The plasma ignition and the thermal power production start are assumed to occur concomitantly and instantaneously on the production state start. Power consumption of HCD systems at the beginning of the production state ranges in the literature from 50 to 150 MW_{th} auxiliary thermal power for DEMO tokamak [9,10,20], and from 50 to 100 MW_{th} for HELIAS stellarator reactor concept [8], with a HCD wall plug efficiency of 40 to 50% [20]. HCD nominal thermal power $\dot{Q}_{HCD}$ of 50 MW_{th} is assumed to apply for both tokamak and stellarator plants during the plasma start-up, resulting in an electrical power consumption $\dot{W}_{HCD}$ of 125 MW_{el}. HCD systems are operated also after the plasma start-up, but since we assume that the plant is operating close to the ignited state, HCD systems work then in a significantly reduced mode. Power required for the plasma heating during the whole production state is thus assumed to be contained in the plasma and burn control power. We assume that for plasma and burn control 20 MW_{th} thermal power $\dot{Q}_{ctrl}$, making 50 MW_{el} electrical power $\dot{W}_{ctrl,S}$, is required in average during production state in the case of a stellarator device. For tokamak, $\dot{Q}_{ctrl}$ of 20 MW_{th} thermal as well as 20 MW_{el} electrical power incurred for power supply for coils for plasma positioning $\dot{W}_{ctrl,\ T,add}$, make in total 70 MW_{el} electrical power required for plasma and burn control $\dot{W}_{ctrl,\ T}$. During production, HTS is operated with nominal full load, which adds 108 MW_{el} electrically ($\dot{W}_{HTS}$ $\dot{W}_{HTS,\ red}$) on top of the power demand of the reduced HTS operation from the hot state.

In Fig. 4 symbols $\dot{W}_{loss,warm}$, $\dot{W}_{loss,hot}$ and $\dot{W}_{loss,CS}$ represent total electrical power consumptions in states warm, hot and CS charging, respectively, whereas $\dot{W}_{loss,prod}$ and $\dot{W}_{loss,prod\ \ start}$ represent power consumptions during the production state after the production start and on its very beginning. We distinguish the values acossiated with tokamak and stellarator power plants.

[1] Percentual HTS power equals for tokamak $\frac{\dot{W}_{HTS}}{\dot{W}_{PCS,T}}$ $\frac{120\ MW_{el}}{1305\ MW_{el}} \approx 9\%$, and for stellarator devices $\frac{\dot{W}_{HTS}}{\dot{W}_{PCS,S}}$ $\frac{120\ MW_{el}}{1285\ MW_{el}} \approx 9\%$ see section 2.2.2.

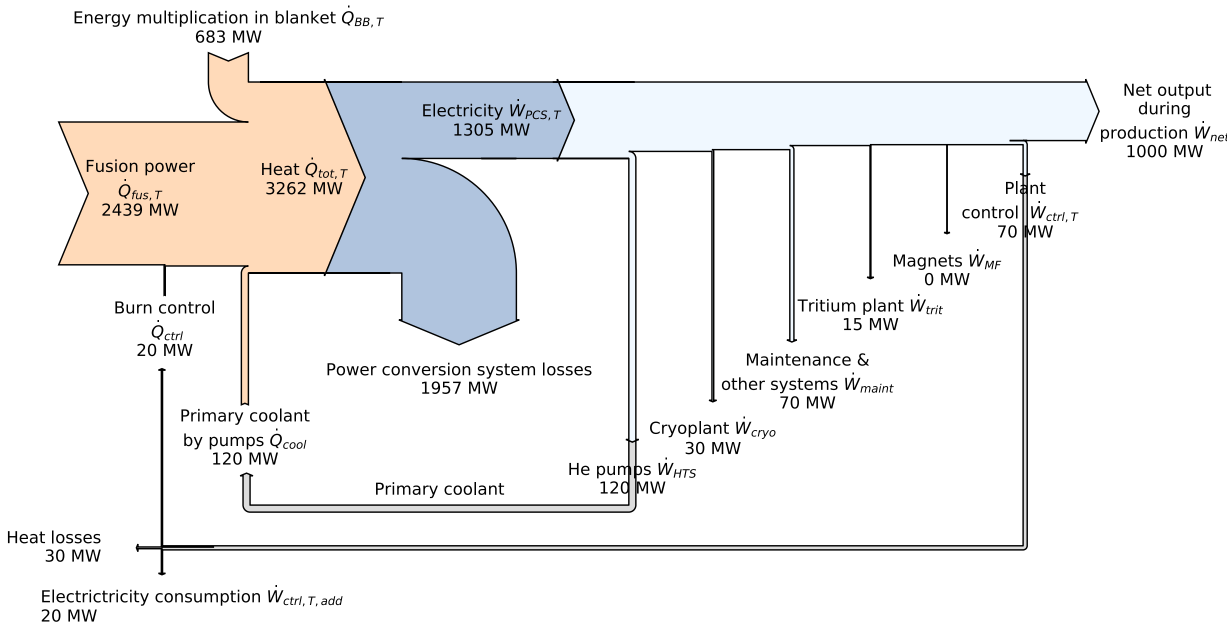

Fig. 5. Sankey diagram of a tokamak (T) device power balance during production.

2.2.2. Nominal powers of main components

In order to ascertain nominal powers of the three main fusion power plant components (fusion reactor, TES and PCS) power and energy balances of the system are calculated. To obtain 1 GW_{el} net electrical output power, considering power losses and efficiency of the PCS, a total thermal power $\dot{Q}_{tot}$ of about 3.3 GW_{th} is necessary. The total produced thermal power is mainly composed of fusion power $\dot{Q}_{fus}$, additional power obtained by the energy multiplication in the BB $\dot{Q}_{BB}$, dissipated pumping power deposited in the primary coolant by pumps $\dot{Q}_{cool}$ and the power deposited in the plasma through the plasma and burn control system $\dot{Q}_{ctrl}$ as

$$\dot{Q}_{tot} = \dot{Q}_{fus} + \dot{Q}_{BB} + \dot{Q}_{cool} + \dot{Q}_{ctrl}. \tag{1}$$

The thermal power deposited in the primary coolant is approximated to be equal to the electrical power consumed by the pumps. The power obtained by the energy multiplication in the BB accounts for approximately additional 35% of fusion neutron power [23], which represents about 80% of the fusion power [24]. Presuming a fusion power generation in tokamak $\dot{Q}_{fus,T}$ of 2439 MW_{th}, additional thermal power $\dot{Q}_{BB,\ T}$ of 683 MW_{th} is gained from energy multiplication in the BB. For stellarator devices, fusion power $\dot{Q}_{fus,S}$ of 2400 MW_{th} is assumed, implying thermal power of energy multiplication $\dot{Q}_{BB,\ S}$ of additional 672 MW_{th}. Further 120 MW_{th} thermal power are deposited in the primary coolant and 20 MW_{th} thermal are deposited in the plasma through the plasma and burn control system. As a result, the nominal thermal powers $\dot{Q}_{tot,T}$ and $\dot{Q}_{tot,S}$ add up to 3262 MW_{th} and 3212 MW_{th} for tokamak and stellarator type devices, respectively.

Considering the production losses $\dot{W}_{loss,prod}$ (see Fig. 4) and the efficiency of the PCS η_{PCS} the net electrical power output of the plant $\dot{W}_{net}$ is calculated as

$$\dot{W}_{net} = \dot{W}_{PCS} \quad \dot{W}_{loss,prod} = \dot{Q}_{tot} \cdot \eta_{PCS} \quad \dot{W}_{loss,prod}. \tag{2}$$

If the efficiency of the PCS is assumed to be 40% [17,20], the nominal electrical power of the generator in PCS $\dot{W}_{PCS}$ is for tokamak $\dot{W}_{PCS,T}$ 1305 MW_{el} and for stellarator $\dot{W}_{PCS,S}$ 1,285 MW_{el}. Considering total production losses after the production start, net electrical outputs of both tokamak and stellarator power plants, $\dot{W}_{net,\ T}$ and $\dot{W}_{net,\ S}$, are obtained to be the desired 1 GW_{el}:

$$\dot{W}_{net,\ T} = 3,262\ MW_{th} \cdot 0.4 \frac{MW_{el}}{MW_{th}} \quad 305\ MW_{el} = 1,000\ MW_{el}, \tag{3}$$

$$\dot{W}_{net,\ S} = 3,212\ MW_{th} \cdot 0.4 \frac{MW_{el}}{MW_{th}} \quad 285\ MW_{el} = 1,000\ MW_{el}. \tag{4}$$

Figs. 5 and 6 visualize the thermal and electrical power flows for tokamak and stellarator reactor types during production, after the production start. At the production start, during the plasma start-up, reactors are operating with increased electrical power demand for HCD $\dot{W}_{HCD}$ for a few minutes and additional thermal power deposited in the plasma through the HCD systems $\dot{Q}_{HCD}$. For power balances during the plasma start-up see Figs. A.1 and A.2 in Appendix.

For generating an electrical output even during the CS charging state between two production intervals of a tokamak, a TES of sufficient capacity has to be installed. In order to provide energy for production of the net electrical output and coverage of the losses during the CS charging state, as well as to provide additional energy for the plasma start-up, considering TES charging and discharging efficiencies η_{cha} and η_{dcha} of 95% and 90%, respectively, the following TES thermal energy capacity Q_{cap} is needed[2]:

$$\begin{aligned} Q_{cap} &= \left(t_{CS} \cdot \left(\dot{W}_{net} + \dot{W}_{loss,\ CS}\right) + t_{prod-start} \cdot \dot{W}_{HCD}\right) \cdot \frac{1}{\eta_{PCS}} \cdot \frac{1}{\eta_{cha} \cdot \eta_{dcha}} \\ &= \left(\frac{10\ min}{60\ \frac{min}{h}} \cdot (1,000\ MW_{el} + 277\ MW_{el}) + \frac{5\ min}{60\ \frac{min}{h}} \cdot 125\ MW_{el}\right) \\ &\quad \cdot \frac{1\ MW_{th}}{0.4\ MW_{el}} \cdot \frac{1}{0.95 \cdot 0.9} \\ &= 653\ MWh_{th}. \end{aligned} \tag{5}$$

For tokamak devices the energy capacity of the TES should hence be in the order of 1 GWh_{th} [22]. For providing some grid flexibility, a TES should be installed for both power plant types whereby for stellarator

[2] Without consideration of additional energy for the plasma start-up, the TES thermal energy capacity would account for $Q_{cap} \quad t_{CS} \cdot (\dot{W}_{net} + \dot{W}_{loss,\ CS}) \cdot \frac{1}{\eta_{PCS}} \cdot \frac{1}{\eta_{cha} \cdot \eta_{dcha}} \quad 622\ MWh_{th}$.

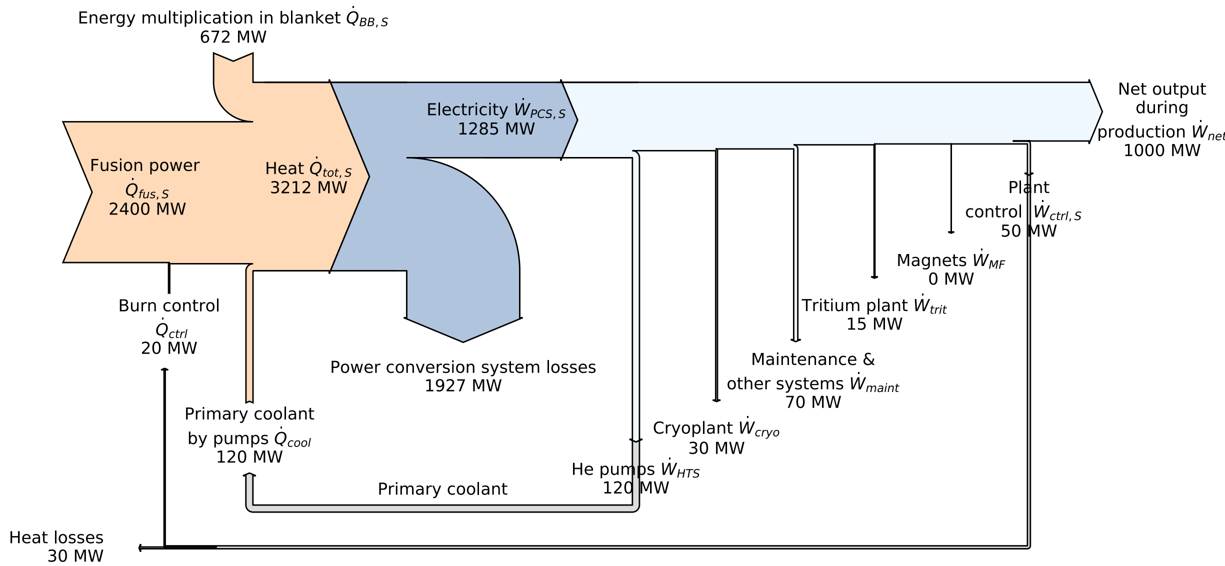

Fig. 6. Sankey diagram of a stellarator (S) device power balance during production.

the TES could also be smaller sized.

3. Comparison with conventional power plant operation

For identification of particularities when modeling and planning energy systems with fusion power plants, a comparison with conventional fossil fired and nuclear fission plants is conducted in the following.

Both fusion and conventional thermal power plants produce electricity in two steps, first converting energy stored in the fuel into heat and secondly converting heat into electrical energy. The technology of heat conversion into electricity has the same basis for fusion and conventional power plants. Whereas the heat released in fossil fired power plants (gas, oil, biomass etc.) originates from the energy stored in chemical bonds of the fuel molecules, in nuclear fission and fusion power plants energy is released due to nuclear reactions that imply changes in the binding energy of the involved atomic nuclei. Operating states for fusion power plants we have defined in the present paper are based on the heat production process.

In contrast to the tokamak, the production state length is in principle not limited for conventional power plants. The period during which the power plant has to be out of operation once it is turned off, is rather an economical and not a physical limitation for conventional plants [25]. Part load operation of conventional power plants is mainly achieved by varying the intensity of the fuel combustion or nuclear fission chain reaction reduction. In the future, operational scenarios which enable part load operation of fusion reactors might be possible. Currently, we assume, however, no part load behavior for fusion reactors. Nevertheless, part load behavior of a fusion power plant could also be realized through a corresponding operation of the TES and PCS, aligning thus fusion and conventional power plants in this regard.

For power plant extension and operation planning, power plants are usually modelled as one unit, described by equivalent parameters and dynamics for the whole system [26]. Thus, to compare dynamics and subsequently flexibility of tokamak and stellarator power plants with conventional ones, elaborated data for fusion power plant components have to be aggregated. Comparison of operational dynamics of fusion and state-of-the-art open cycle gas turbine (OCGT), combined cycle gas turbine (CCGT), hard coal-fired, lignite-fired and nuclear fission power plants is given in Table 2. The adaptions of parameter definitions in comparison to conventional plants, necessary for applying them to fusion power plants, follow below.

Power plant start-ups, defined for conventional plants as time between the standstill and minimal part load production, are divided depending on how long the power plant was out of operation. According to [25,27] hot, warm and cold start-up follow after a production break of less than 8 h, between 8 and 48 h, and for more than 48 h, respectively. The hot start-up for fusion power plants we thus define as the duration between the hot and the production state of the reactor (10 min for CS charging for tokamak and instantaneous for stellarator reactor concept) with addition of the start-up time of the PCS, which we assumed to be the same as for fission power plants (20 min). For the cold start-up of fusion power plants we consider the time duration between the cold and production state, assuming it to be the same as for nuclear fission, presuming that the vacuum conditions in the torus are still maintained and that the TES is still warm. Otherwise, the vacuum establishment and heating up of the TES could take multiple days to weeks. Minimal part load for conventional power plants is defined as the lowest net power output which a power plant can deliver while maintaining a stable operation [27]. Minimal part load of fusion power plants, assuming no part load behavior for fusion reactors, depends only on the PCS and TES. Since production of thermal energy in a fusion reactor starting from the CS charging state for tokamak and from the hot state for stellarator device types is considered instantaneous, the load ramp rate corresponds to the ramp rate of the PCS. Consumption of the power plant when supplying only auxiliary subsystems and transferring no electricity to the grid is referred to as self-consumption. In coal fired power plants, main auxiliary consumers are conveyor systems for coal transport, grinder for bruising coal for combustion, pumps for water compression and condensation, air and flue gas fans as well as flue gas cleaning systems [30]. Self-consumption of gas fired power plants bases on air compressors, eventually water pumps, air and flue gas fans [27]. Main auxiliary power consumer for a CCGT is the heat rejection system for cooling waste heat to a targeted temperature level [33]. For self-consumption of fusion plants, power requirements of the hot state in comparison with the gross electricity production is considered in Table 2. Equivalent full load efficiency of fusion power plants is based on electricity net energy output in contrast to the total produced heat energy, considering enhanced energy consumption at the beginning of the production cycle as well, in case of tokamak, the CS charging energy. It depends to some extent on the production duration due to the plasma start-up losses at the beginning of the production state.

Table 2
Comparison of operational dynamics of nuclear fusion and conventional power plants.

Feature	Fusion	OCGT	CCGT	Coal	Lignite	Fission
Hot start-up [min]	20–30[3]	5–10 [27]	30–40 [27]	80–150 [27]	75–240 [27]	20 [28,29]
Cold start-up [h]	24–50[4]	0.1–0.2 [27]	2–3 [27]	3–6 [27]	5–8 [27]	24–50 [28]
Minimal part load [% P_{nom}]	40[5]	15–50 [25,27]	20–40 [27]	25–40 [27]	35–50 [27]	40–50 [28]
Ramp rate [%P_{nom}/min]	10[6]	10–20 [25,27]	4–10 [27]	3–6 [27]	2–6 [27]	2–10 [25,28]
Self-consumption [%P_{nom}]	9.7–9.9[7]	1.6–1.9 [25]	2.0–2.2 [25]	4.3 [25]	5.0–5.5 [30]	5.0 [31]
Efficiency in full load operation [%]	29.8–31.1[8]	39.7 [27]	60.0 [27]	46.0 [27]	43.0 [27]	38.0–40.3 [32]

Equivalent full load efficiency for stellarator devices based on proposed parameters resembles with net efficiency calculation from the literature [34]. For tokamak devices, the calculation of the full load efficiency in the literature is rather simplified. It does not consider the increased power consumption directly before and at the beginning of the production cycle [15], or it relies on the PCS efficiency considering the ratio of the production and the dwell time duration [17,35].

Summarizing the comparison, key differences between conventional and fusion power plants are following:

- In contrast to conventional plants, the heat production duration of tokamak fusion devices is limited. For conventional plants, the production state length is in principle not restricted and as well as the minimum down time after a shut-down, it is rather a consequence of economical and not physical constraints.
- Minimal part load behavior of fusion power plants, assuming no part load behavior for the fusion reactors itself, depends only on the PCS and TES. In the aspect of minimal part load fusion power plants thus have very similar operational characteristics as conventional plants.
- Fusion plants are characterized by high self-consumption losses during the hot state of about 10% of nominal gross electrical output in comparison to about 2 to 6% self-consumption of conventional plants. Furthermore, during the production state, the self-consumption of fusion power plants increases to about 20% of nominal gross electrical output. However, tritium is partly produced during the production state due to the interaction of fusion neutrons escaping the plasma with lithium contained in the BB of the fusion reactor [36]. Fusion power balance includes thus the fuel production cycle which significantly limits the comparison with conventional plants.
- In contrast to conventional plants, fusion power plants have a rather extensive electricity consumption for HCD systems on the very beginning of the production, as well as, in the case of tokamak, for CS charging shortly before the production starts. Thus, for representation of fusion power plants in energy systems their electricity consumption prior to the production state has to be explicitly modeled.

[3] Tokamak concept requires 10 min more than stellarator due to the CS charging.
[4] Since similar to nuclear fission, it should last one to two days.
[5] Assumption on minimal part load of the PCS based on [27].
[6] Assumption on ramp rate of the PCS based on [27] for state-of-the-art plants.
[7] For tokamak: $\dot{W}_{loss,hot}/\dot{W}_{PCS,T} \quad 127MW_{el}/1305MW_{el} \quad 9.7\%$, and for stellarator power plant type $\dot{W}_{loss,hot}/\dot{W}_{PCS,S} \quad 127MW_{el}/1285MW_{el} \quad 9.9\%$
[8] For tokamak assuming 2h production cycle, 10 min CS charging duration and 5 min plasma start-up at the beginning of the production state as well as power balance at the production start (see Fig. A.1):

$$\left(\dot{W}_{net,\ T}\cdot\left(t_{prod}-t_{prod-start}\right)+\dot{W}_{net,\ \ start}\cdot t_{prod-start}-\dot{W}_{loss,CS}\cdot\tau_{CS}\right)/\left(\dot{Q}_{tot,T}\cdot t_{prod}\right)$$
$$(1000MW_{el}\cdot 115min+895MW_{el}\cdot 5min$$
$$-277MW_{el}\cdot 10min)/(3262MW_{th}\cdot 120min)$$
$$29.8\%$$

For stellarator, assuming continuous (infinite) production length: $\dot{W}_{net,S}/\dot{Q}_{tot,S} = 1000MW_{el}/3212MW_{th} = 31.1\%$

4. Conclusion and outlook

In the present paper, tokamak and stellarator type power plants are investigated to characterize the operation of fusion power plants from an energy system perspective. For representation of fusion power plants in energy system modeling we proposed a system of three main components: fusion reactor, thermal energy storage and power conversion system. For all main components, a preliminary set of parameters for tokamak and stellarator type power plants is introduced, having a 1 GW_{el} net electrical power output plant as the basis of the parametrization. Five operating states are defined, based on the fusion reactor operation and the different auxiliary subsystems which are active during the time. The comparison between conventional and fusion power plants in terms of operational dynamics shows no tremendous differences in time constants or overall part load behavior due to the utilization of a thermal energy storage. Main difference exists in the extensive electricity consumption of fusion plants prior to the production and on its very beginning as well as, especially for tokamak, in heat production duration limitations.

Since fusion power plants are still in a conceptual state, design points of future commercial power plants are not definite. The results we elaborated give a possible parameter set for their modeling and investigation from the power system operator's point of view. The highest influence on modeling results can have deviating self-consumption and the CS charging state duration since they change the power and energy balances and thus the energy system parametrization. It stays for the future elaboration to model fusion power plants in energy systems and investigate the use cases which support their expansion and utilization as well as the possible contribution to the grid flexibility.

CRediT authorship contribution statement

Anđelka Kerekeš: Investigation, Methodology, Data curation, Writing – original draft. **Larissa Breuning:** Investigation, Methodology, Data curation, Writing – review & editing. **Alexander von Müller:** Validation, Methodology, Data curation, Writing – review & editing. **Julia Gawlick:** Data curation. **Felix Warmer:** Data curation. **Sina Fietz:** Data curation. **Richard Kembleton:** Data curation. **Sergio Ciattaglia:** Data curation, Writing – review & editing. **Wolfgang Hering:** Data curation, Writing – review & editing. **Hartmut Zohm:** Conceptualization, Supervision. **Thomas Hamacher:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix

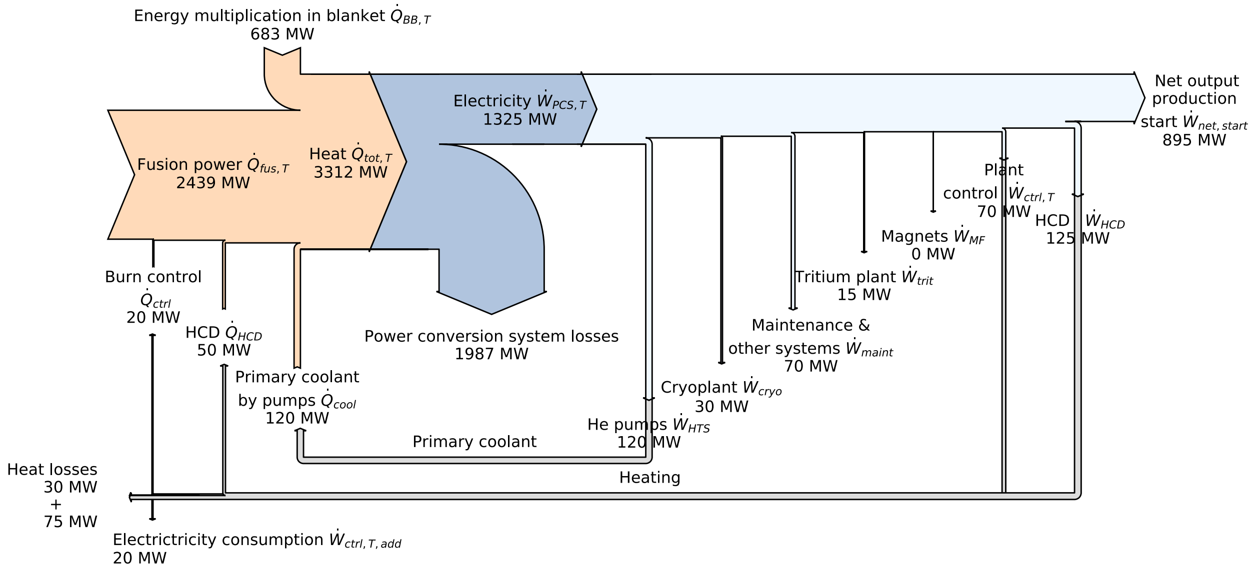

Fig. A.1. Sankey diagram of a tokamak (T) device power balance at the production start.

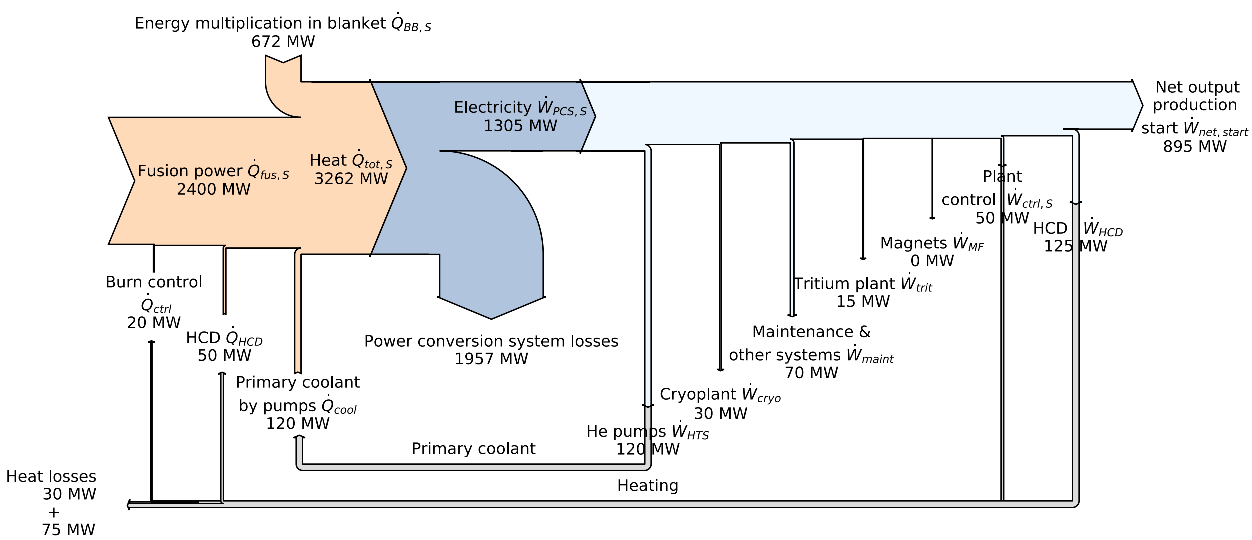

Fig. A.2. Sankey diagram of a stellarator (S) device power balance at the production start.

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