A Time-Dependent Power Cycle developed for Multi-Timescale Systems Codes to study technology integration in advanced Fusion Power Plants

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Abstract

Systems Codes (SCs) are fundamental tools in Fusion Energy research that allow for parameter space exploration during conceptual design phases of Fusion Power Plants (FPPs). They may also be used to discover relevant dependencies through parametric studies, which are especially important to evaluate technology integration in reactors. However, current state-of-the-art SCs do not address this concern on a power plant level, in part due to the inherent difference in timescale in which each plant system predominantly operates. Thus, a novel Multi-Timescale SC approach is currently under study.

Preliminary assessments identify three timescales that must be prioritized: the Plasma Physics, the Reactor Pulse and the Lifetime of the FPP. To this end, new SC modules are being developed at the Karlsruhe Institute of Technology (KIT) to model the major systems that operate in these timescales. One module simulates Fuel Cycle (FC) scenarios, to study the consequences of design choices to the fuel balance of the plant in its Lifetime. Another module, the Power Cycle (PC), studies the consequences to the energy balance of the plant during a tokamak Pulse. Coupling both modules to a Plasma Transport solver will ensure the representation of the Plasma Physics timescale.

This work shows the implementation of the PC. In the chosen code architecture, the module is comprised of two models: a steady-state one (ss), used to collect design assumptions/requirements and characterize encompassing technologies; and a time-dependent one (tt), which uses this characterization to simulate their dynamics. The completed module was verified by building and running a Demonstration Power Plant (DEMO) PC model, and comparing its results to simulations from a commercial power plant design software. Future coupling of this module to a SC aims at determining inter-dependencies that can meaningfully affect the power balance, in particular the net power production.

Keywords: DEMO, Balance-of-Plant, Systems Codes, Nuclear Fusion Technology

Objectives

- **Challenge** – current major systems-codes only estimate net power production with steady-state 0D power balances, which do not take into account many plant design parameters (*e.g.* operational temperature ranges for materials) [1,2].
- **Goal** – develop a time-dependent thermodynamically-consistent systems-code module able to compute the net power production during a power plant pulse.
- **Strategy** – divide the Power Cycle into two sub-modules (Figure 1):
  - Balance-of-Plant (BoP), to compute gross power production (this work);
  - Electric Power Loads (EPL), to compute total power consumption.
- **Methodology** – develop simplified models that can reproduce results from commercial codes used in the design of the HCBP (indirect ESS) EU-DEMO 2017:
  - (flat-top & dwell phases) steady-state description of BoP: EBSILON [3];
  - (flat-2-dwell & dwell-2-flat phases) transient description of BoP: APROS [4].

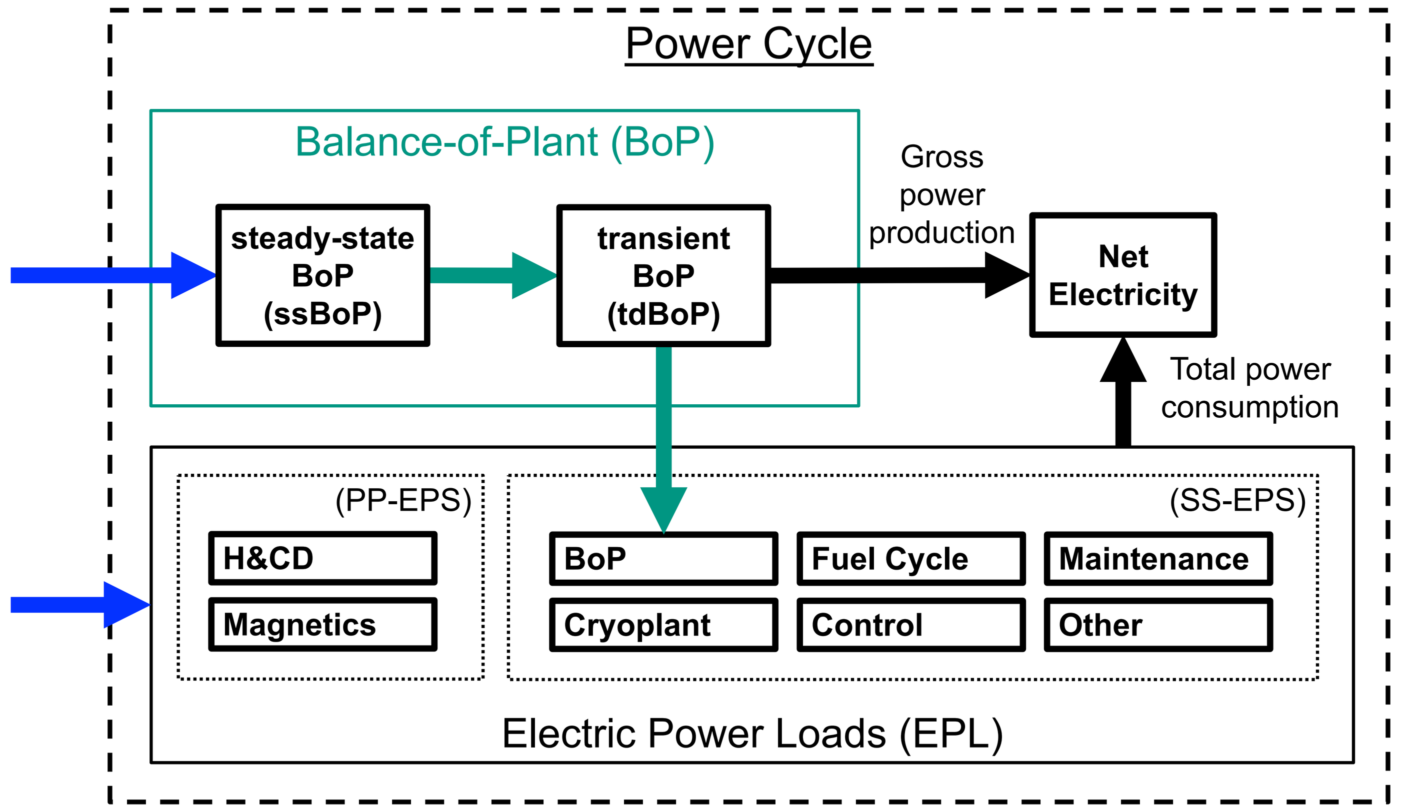


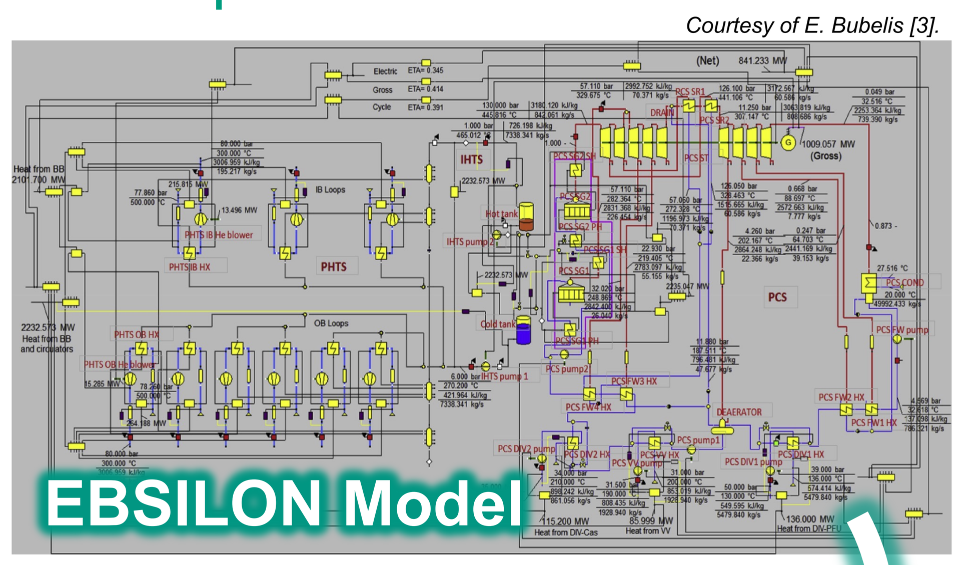
*Figure 1: Data transfer in Power Cycle module architecture. Initial characterization depends on assumptions and design parameters (**blue arrows**). Main results of the BoP sub-module are presented in this work (**green arrows**). The final output foreseen is a time-dependent curve of the net electrical power generated, computed from gross production and total consumption (**black arrows**).*

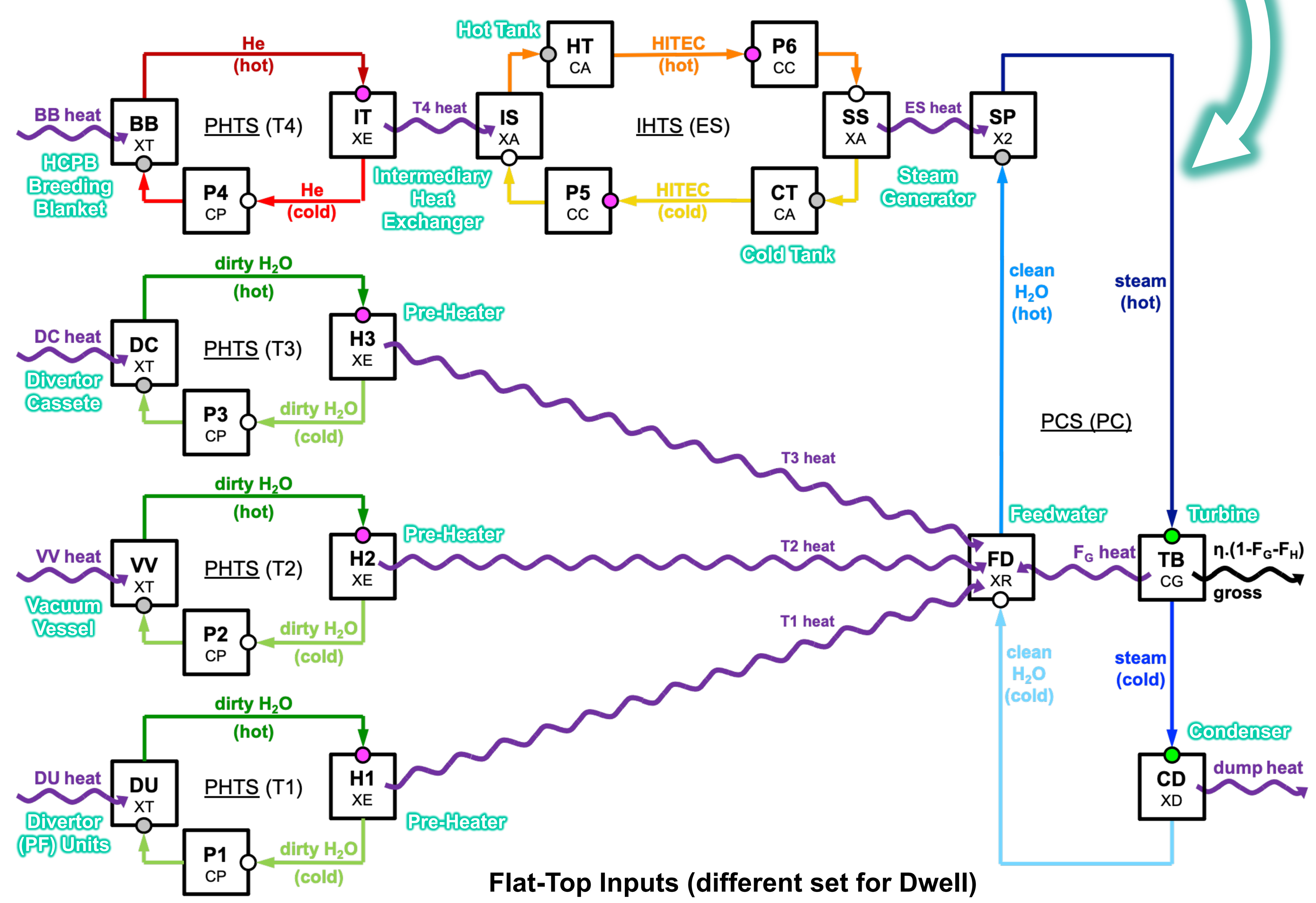
Model Description

Identified minimum set of inputs to completely characterize BoP in each phase (flat-top & dwell):

- ○ No Requirement
- Required Mass Flow
- Required Pressure
- Required Temperature
- Required Temperature / Pressure
- Required Temperature / Pressure / Mass Flow

Courtesy of E. Bubelis [3].





Flat-Top Inputs (different set for Dwell)

- BoP Model – Architecture, composed of:
  - Processes (**blocks**);
  - Subcycles (closed **loops** of blocks),
  - Couplings (**arrows**).
- Identified main BoP thermodynamical processes and developed associated simplified mathematical models.
- Multi-tiered (iterative) "**update**" due to data exchange (Figure 2) between:
  - Processes in a Subcycle, because of cyclical connections;
  - Subcycles in a phase, because of same-phase Couplings (*e.g.* heat from PHTS to IHTS);
  - phases, because of cross-phase Couplings (*e.g.* heat to PCS).
- **Output:** thermodynamical state tables (fully consistent), used as initial and final conditions for transients, which solve the model in multiple timesteps.

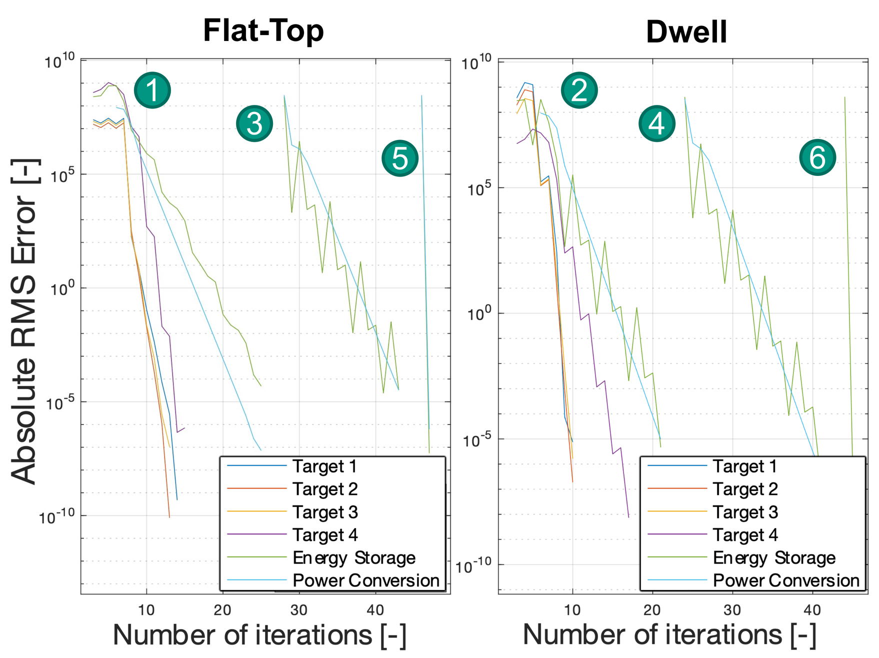


*Figure 2: Visualization of the multi-tiered iterative computation of the BoP model, until total absolute RMS error is below a certain threshold. Each curve shows the error reduction from updating a single Subcycle; error reduction is non-monotonic because of Coupling between Subcycles in a single phase. Coupling between phases implies each phase must be updated multiple times (**green numbers** indicate order of update).*

Steady-State BoP (ssBoP) Results

- **Requirements** from design of the Primary Heat Transfer System (PHTS) determine coolant mass flows (*e.g.* temperature window, inlet pressure, total heat, …).
- Coolant **pump powers** are computed for each Subcycle pressure drop, estimated with Darcy(-like) factors.
- HITEC® mass flows in the Intermediary Heat Transfer System (IHTS) depend on the heat transfers to the PCS (direct & indirect) in both phases and phase durations.
- **Turbine** model (Rankine) estimates fractions of steam flow for regenerative and reheat processes.
- State tables can produce simplified thermodynamical cycle **diagrams** (Figure 3).

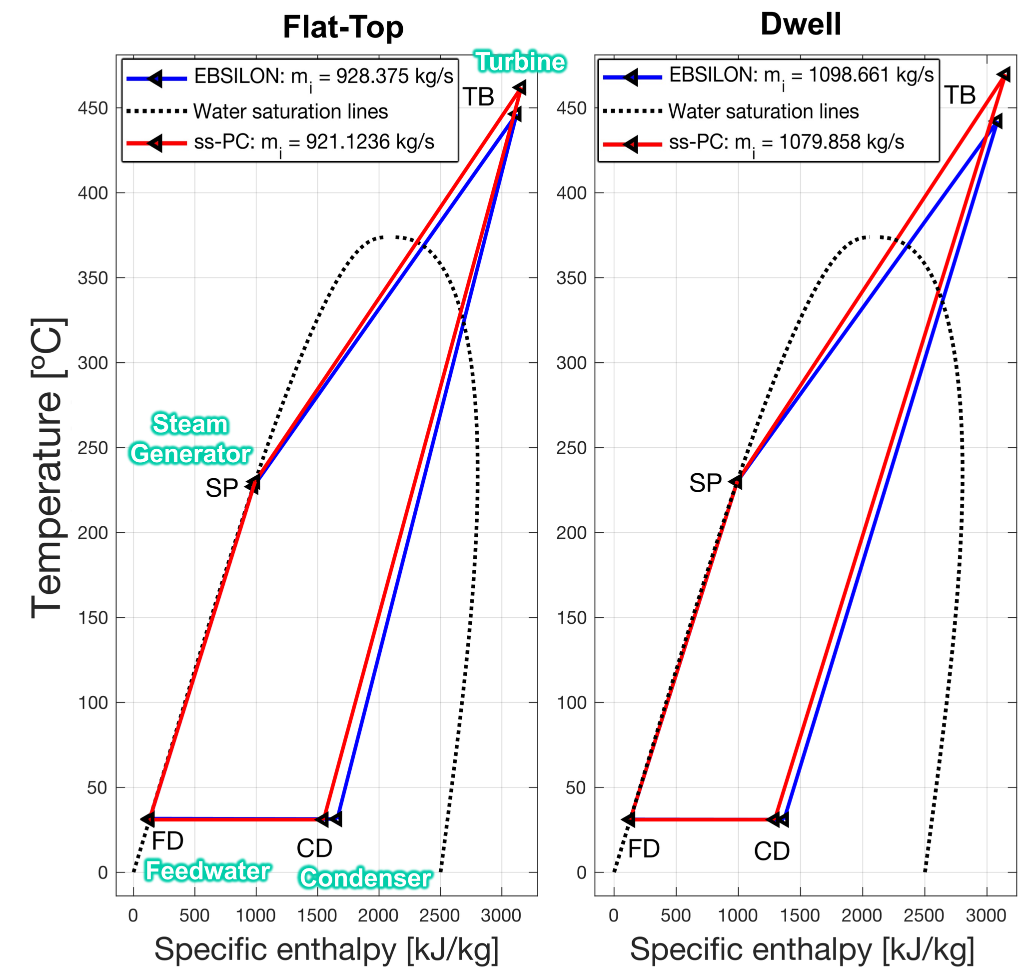


Figure 3: Simplified thermodynamical cycle diagrams for the Power Conversion System (PCS) Subcycle, with points indicating mass-averaged inlet values of properties for heat transfer fluid (water). Connecting lines are only representative: evaporation has fixed temperature in steam generator and turbine presents multiple outlets, both taken into account by the model.

Table 1: Comparison between representative results of the ssBoP model and the EBSILON code.

Flat-Top Property	EBSILON	ssBoP	Rel. Dif. (%)
HCPB He Flow [kg/s]	1841.774	1838.248	0.19
HCPB Pump Power Consumption [MW]	87.954	87.111	0.96
PCS Water Flow [kg/s]	928.375	921.124	0.78
Gross Electrical Power Production [MW]	892.511	871.721	2.33

(Preliminary) Transient (ttBoP) Results

- **Initial and final conditions** (steady-state phases) are connected by running the model multiple times.
- Most **inputs** for each time step are interpolated between values from ssBoP state tables; some have other dependencies (*e.g.* Darcy-like factor $f_p \propto \dot{m}^{-2}$).
- Preliminary results: implementation of **heat capacity** for each Process is ongoing (Figure 4).

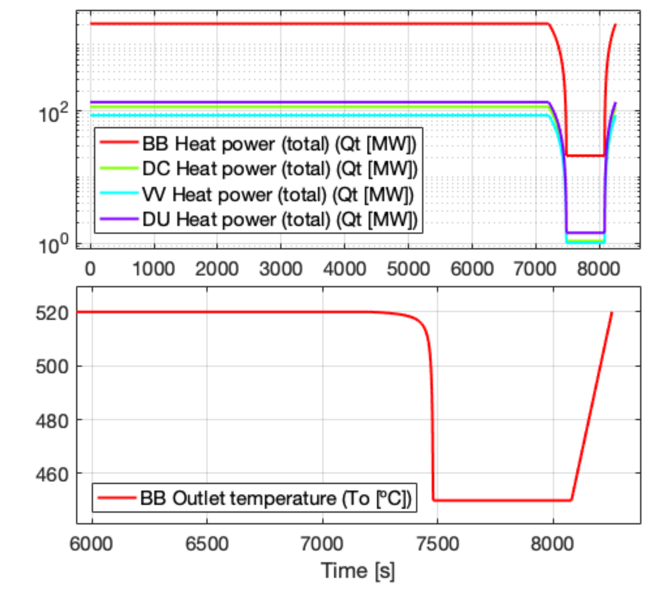


Figure 4: Preliminary results of the ttBoP model.

Outlook

- **Next models** foreseen for implementation (priority order):
  1. Processes heat capacity, from structural design (to simulate impact in transients);
  2. different power curve functions in transients (to represent L-H transition);
  3. First Wall temperature profile (for systems-code coupling);
  4. Couplings between Subcycles with technology parameters (for design ranges).

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