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Small Modular Reactors and cogeneration: impact of steam extraction on power conversion performance

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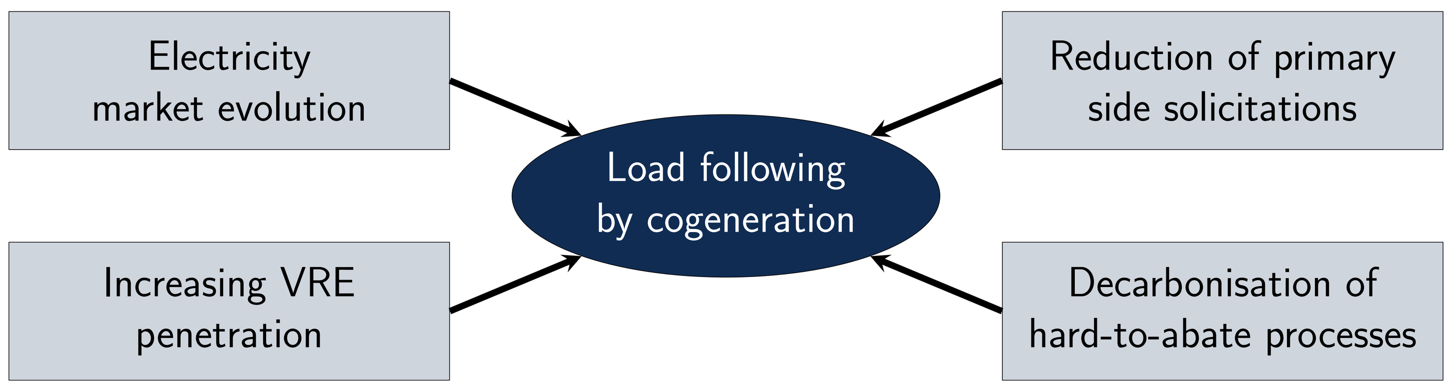
INTRODUCTION

Decarbonisation efforts are driving a radical transformation of the energy sector with a surge in **variable renewable energy (VRE) source penetration**. This shift is impacting both the operational requirements and the economic competitiveness of dispatchable generators, including nuclear power plants (NPPs). Consequently, there is a compelling need to **explore novel operational paradigms for nuclear reactors**.



In the **load following by cogeneration** mode, variable electrical load demands are met by dynamically allocating the **steady thermal power produced by the reactor** either for power conversion or to drive non-electric applications. This operational mode is facilitated in **nuclear hybrid energy systems (NHES)**, where the SMR is tightly coupled with storage devices and industrial processes, such as hydrogen production plants.

The **GOAL** of this study is to assess the impact various interconnection points between the balance of plant (BOP) of a PWR-type SMR and cogeneration systems on power conversion efficiency

REFERENCE ARCHITECTURE

The reference BOP architecture considered in this study, presented in Figure 1, is tailored to the operating conditions of the **European SMR (E-SMR)**, a conceptual design of a 540 MW_{th} reactor investigated in the Euratom ELSMOR project [2].

The simplified BOP architecture, which includes single feedwater preheaters and reheaters, proposed within the Euratom TANDEM project [4], was considered as the reference for this work. In the context of the project, the operational points of the architecture were determined using CEA's CYCLOP tool [1]. In this study, the operational points were instead defined using **EBSILON® Professional** software, providing consistent results [3].

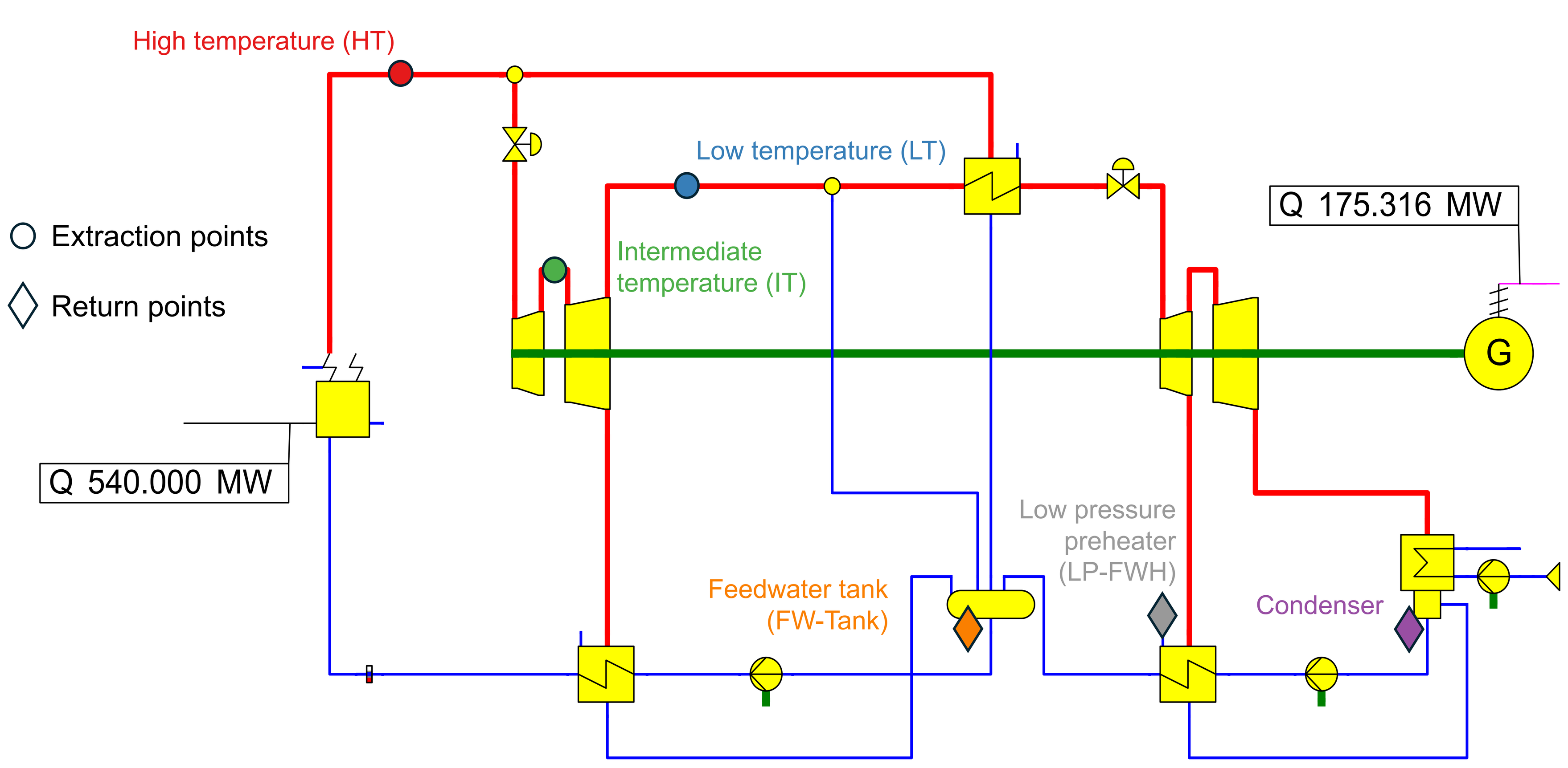


Figure 1. Reference BOP architecture, optimised for full power operation in EBSILON.

The following **OPTIMISATION** problem was set up in EBSILON to determine the operational points of the steam cycle:

- **Variables**: Pressure levels between turbine stages.
- **Objective**: Maximisation of the electrical power output, and consequently the cycle efficiency.
- **Method**: Genetic algorithm from the EbsOptimize module.

The optimisation resulted in a gross power output of **175.32 MW_e** and a cycle efficiency of **32.5%**, in line with the anticipated nominal power of 170 MW_e for the E-SMR reactor.

ARCHITECTURES IN COGENERATION MODE

The previous architecture has been modified to include different **steam extraction** and **condensate return** points, intended to represent the interface with the non-electric application, highlighted in Figure 1.

The steam cycle has been optimised, applying the same methodology, assuming to have the latter steam extractions at **nominal conditions**, without addressing the impact on the cycle performance in off-design conditions.

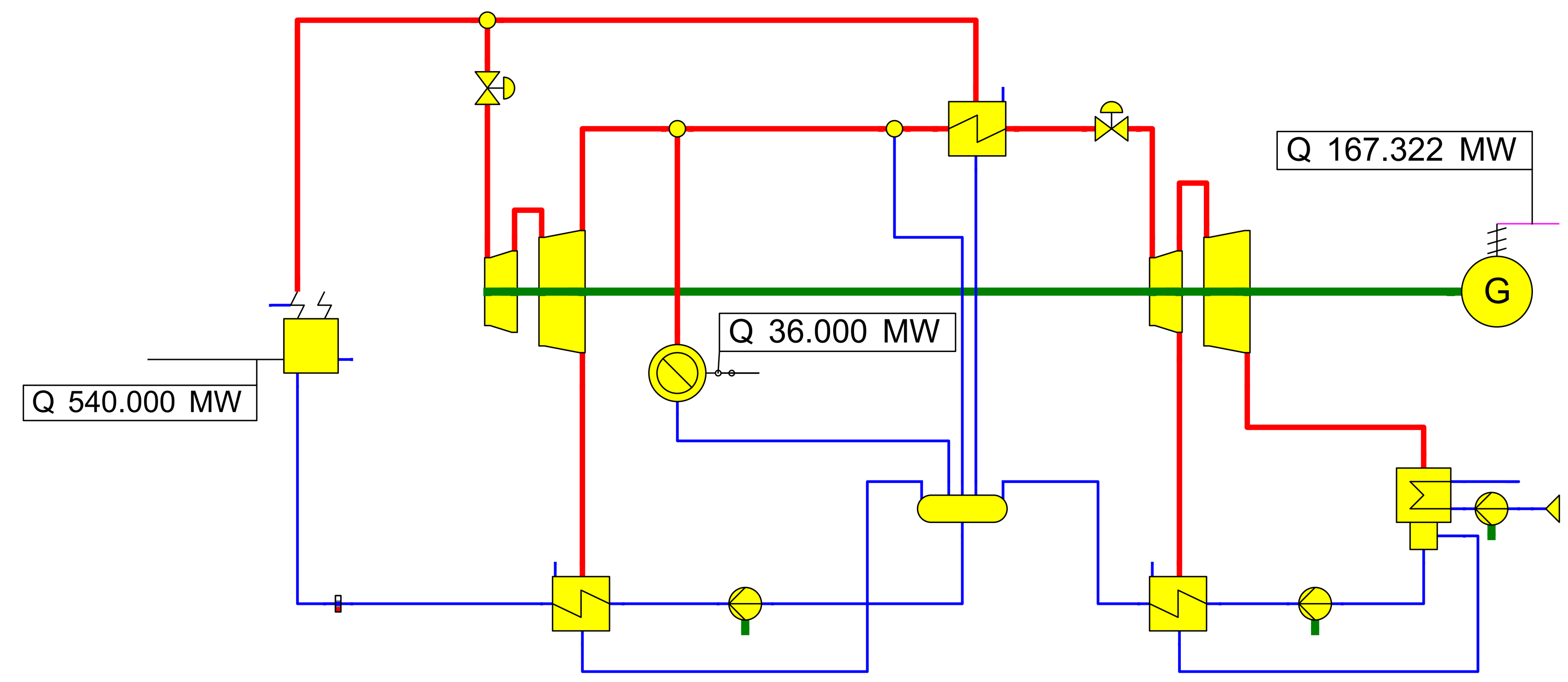


Figure 2. Example of the modified architecture featuring low temperature steam extraction and feedwater tank return.

Different end-user requirements were analysed, both in terms of **temperature requirements** (reflected in the choice of the steam extraction points) and **extracted thermal power** levels. In this study, thermal power extractions up to 36 MW_{th} were considered. Figure 2 illustrates the BOP layout in cogeneration mode, with steam extracted at low temperature and returned to the feedwater tank after exchanging thermal power with the cogeneration system.

IMPACT OF COGENERATION ON CYCLE PERFORMANCE

The comparison between steam extraction points is performed in terms of loss of **electrical power output** and power conversion **efficiency**. The results in Figure 3 demonstrate that the higher the enthalpy of the extracted steam, the higher the impact on power conversion efficiency. Moreover, the performance degradation is more pronounced in cases of high thermal power extraction. Condensate return points also have an impact on power conversion efficiency, as they determine the amount of condensate energy recovered for power conversion.

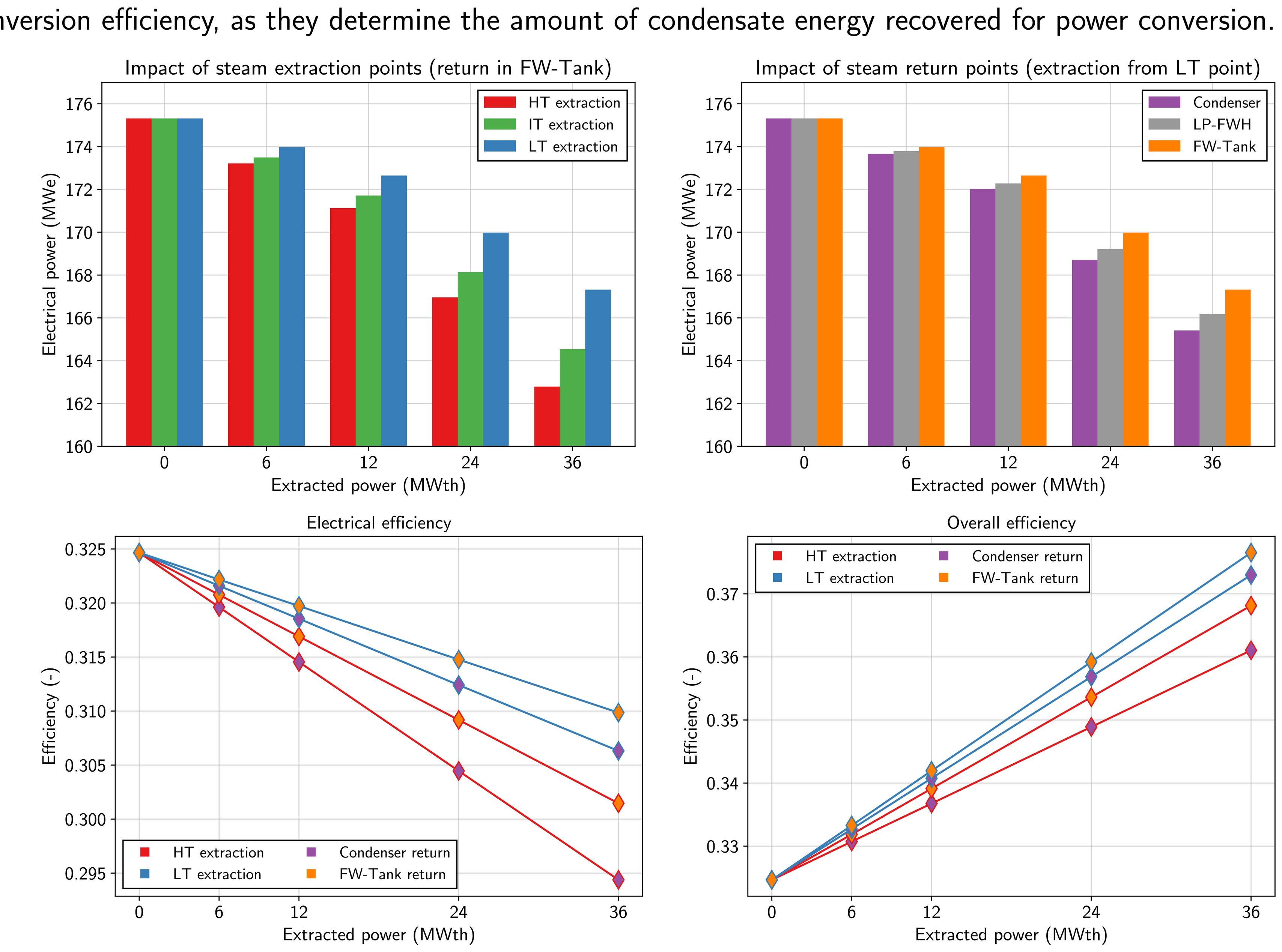


Figure 3. Impact of cogeneration on power production and efficiency.

CONCLUSIONS

The results emphasised the significant **impact of the steam extraction point** in determining the overall performance of the steam cycle with respect to the condensate return point, with the **low temperature steam** extraction point attaining the higher efficiencies. Moreover, the analysis of the condensate return points emphasised the importance of **recovering the energy** of the flow driving the non-electric application to achieve higher system efficiencies. In future, the analysis should be extended to **off-design operation** to address the increasing flexibility requirements of the grid and to higher thermal power extraction levels.

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