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

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**Abstract**

The evolving energy landscape requires a shift in the operational paradigm of nuclear power plants, traditionally employed as electric power generators, to meet the increasing need for grid flexibility and leverage dispatchable and low-carbon thermal power to decarbonise hard-to-abate processes.

These requirements can be met by extracting steam from the power conversion cycle to drive non-electric applications, such as high-temperature steam electrolysis for hydrogen production, which is the reference end-use considered in this study. In this work, the impact of different steam extraction and return points in terms of pressure, temperature, and mass flow rate on the performance of the balance of plant of a light-water cooled Small Modular Reactor (SMR) is investigated. The power conversion system of the SMR has been modelled and optimised, aiming to maximise cycle efficiency in response to different cogeneration requirements (up to 36 MWth), using the EBSILON Professional tool.

The results show that the steam extraction points upstream of the heat delivery to the end-user have the largest impact on the overall cycle performance. Such analysis offers a general overview of nuclear cogeneration opportunities, providing a quantitative evaluation of the impact of converting an SMR’s balance of plant to drive non-electric applications.

## INTRODUCTION

To address climate change mitigation objectives, the energy system is facing a radical transformation, transitioning from a heavy reliance on fossil fuels to low-carbon alternatives, including renewable sources and nuclear power. However, the surge of variable renewable sources, such as wind and solar power, has raised concerns about the stability of the power grid due to their intermittent nature. As a result, the increasingly fluctuating load demand requires the deployment of dispatchable generators like nuclear power plants. The latter have been traditionally operated as baseload power sources due to the technical and economic advantages of this operational mode [1]. However, the growing demand for flexible operations translates into a revaluation of the role of nuclear in the energy transition. An emerging application is the potential integration of nuclear reactors in a so-called nuclear hybrid energy system (NHES), where the reactor is strongly interconnected, for example, with energy storage devices and non-electric applications. In this context, Small Modular Reactors (SMR) are seen as particularly well suited for this kind of application, mainly due to their size compatibility with the industrial processes to be integrated within the NHES. A key advantage of such systems is the ability to meet variable load demands while operating the reactor at nominal conditions; specifically, the reactor power can be allocated either for electricity production or to drive non-electric applications according to external demands and market conditions [2].

A non-electric application that is drawing particular attention is hydrogen production via high temperature steam electrolysis (HTSE). This technology allows to produce hydrogen at higher efficiencies compared to conventional low-temperature electrolysers [3]. In this system, the water splitting process is performed with superheated steam at around 750°C rather than liquid water, which results in the need for a thermal energy source to ensure full evaporation of the process water and to bring the steam to the required conditions for the HTSE. The former heat can be supplied by extracting thermal power from the reactor’s balance of plant (BOP) and used to increase the process water temperature to up to around 150°C [4]. Ultimately, the electrolyser temperature requirements are met by increasing the fluid’s temperature through recuperation heat exchangers and electrical heaters. When integrated within a NHES, thermal and electrical power can be allocated for hydrogen production according to external load demands while keeping the reactor running at full power. In general, for a HTSE, the portion of electrical power needed to drive the electrolyser is significantly higher compared to the required thermal power input, resulting in the potential integration of megawatt-scale electrolysers requiring a small fraction of thermal power extracted from the BOP [4].

The aim of this study is to investigate the impact of different steam extraction and return points on the reactor’s balance of plant for different nominal thermal power extractions. A balance of plant architecture for a light-water cooled SMR is proposed and optimised for full power operation, following an adaptation of the plant to account for the steam extraction to drive the hydrogen production process. The objective is to provide a quantitative estimation of the advantages in terms of power conversion performances of extracting steam at one point with respect to another and, similarly, of returning the condensate after heat delivery to the non-electric application at a specific point.

##  The e-smr reactor

The reference nuclear reactor considered in this analysis is a light-water cooled, pressurised Small Modular Reactor (SMR). Specifically, the study is based on the design investigated in Euratom’s ELSMOR project [5], where a comprehensive description of the thermal-hydraulic characteristics of the conceptual European SMR (E-SMR) design has been conceived.

As an integral pressurised water reactor, all primary components, ranging from the core to the steam generator, are enclosed within the reactor pressure vessel. A module of the latter reactor is anticipated to have a rated thermal power of 540 MWth and an electrical power output of 170 MWe. A plant will be composed of two modules, each with its own turbogenerator. Given that the proposed analysis is limited to the reactor’s balance of plant, the only parameters that have been considered are those related to the steam generator’s secondary side, outlined in Table 1, which determine the steam conditions driving the power conversion cycle.

TABLE 1. E-SMR STEAM GENERATOR SECONDARY SIDE MAIN PARAMETERS.

|  |  |  |
| --- | --- | --- |
| Parameter | Value | Unit |
| Exchanged power | 540 | MWth |
| Inlet temperature | 163.8 | °C |
| Outlet temperature | 300 | °C |
| Pressure | 45 | bar |

##  balance of plant architectures

This section provides an overview of the BOP layout considered as a reference, starting from the architecture optimised for full power operation before presenting the layout encompassing the steam extraction and return points considered in this analysis. The architectures were developed with the EBSILON® Professional tool, a commercial software for the simulation of power plants and other thermodynamic systems in both nominal and off-design conditions [6].

### BOP architecture for full power operation

The scope of the aforementioned ELSMOR project was mainly devoted to safety analyses of light-water cooled SMRs, resulting in a dataset centred on the nuclear steam supply system features rather than on the full plant architecture. For this reason, no reference BOP architecture has been proposed in the framework of this project. Nevertheless, a BOP architecture tailored to the E-SMR operating conditions, developed with the CYCLOP tool [7], a software developed by CEA for the optimisation of thermodynamic cycles, has been proposed in previous studies [8].

The BOP proposed in this work, shown in Fig. 1, has been built considering the architecture developed in the latter studies as a reference (for example, in terms of the number of feedwater preheaters), tailoring it to the scope of this analysis, i.e., in the spirit of having a framework to facilitate the analysis of several steam extraction and return points with minimal modifications to the reference architecture. The main components on which the proposed design is built are the following:

* A steam generator, whose operating conditions on the secondary side are provided in the E-SMR dataset. This component has been modelled with EBSILON’s *Steam Generator* component, imposing the required fluid conditions in terms of outlet temperature and pressure and the exchanged thermal power.
* A high-pressure (HP) and low-pressure (LP) turbine, both divided into two stages represented by the *Steam Turbine (SCC)* component, are used to convert the thermal energy of the fluid into mechanical energy. For each stage, a dry isentropic efficiency of 0.88 is assumed. Moreover, the component’s model allows for the specification of the number of steam ports at the outlet: in the full power architecture, additional ports are present both in the HP and LP stages to consider the steam bleeding to the HP and LP feedwater preheaters.
* The latter components, together with the reheater located between the two turbines, have been modelled using EBSILON’s *Feed Water Preheater / Heating Condenser* component, which imposes full condensation on the heat exchanger’s hot side, which translates into a saturated liquid outlet, and a user-defined upper terminal temperature difference, assumed to be 5°C for each heat exchanger.
* The *Control Valve* component has been selected to model the turbine admission valve for the HP and LP turbines. These components, which lead to a pressure drop of 1 bar for the fluid entering the turbines, play a fundamental role in terms of flexible operation: the electrical power output, or, in the case of an SMR operated in cogeneration mode, the thermal power delivered to the non-electric application, can be adjusted according to the demand with the support of these valves.
* The wet steam at the outlet of the HP turbine is dried in a moisture separator, simulated through the *Drain* component.
* A condenser, modelled with the *Steam Turbine Condenser* component, is located at the LP turbine stage outlet. This component is used to fix the condensation pressure at 0.07 bar and imposes saturated liquid conditions at the hot side outlet.
* The pressure in the feedwater line is increased from the condenser pressure up to the steam generator inlet pressure by a HP and LP pump, represented by EBSILON’s *Pump* component. These machines will absorb a portion of the electrical power produced by the plant, which has not been accounted for in the proposed analysis.
* Various streams, including the condensate at the HP preheater and reheater hot side outlet as well as the liquid drained in the moisture separator, are mixed with the main feedwater flow in a feedwater tank, simulated with the support of the *Water Tank* component.

The operational points in the thermodynamic cycle have been determined through an optimisation of the cycle, set up to maximise the electrical power output, and thus the efficiency, of the cycle. The selected optimisation variables were the pressure levels between two turbine stages, which will have a key role in the perspective of steam extraction for cogeneration purposes. A genetic algorithm optimisation, included in EBSILON’s EbsOptimize module, has been adopted to determine the optimal values of the latter variables. The optimisation resulted in a gross power output of 175.32 MWe and a cycle efficiency of 32.5%, in line with the anticipated nominal power of 170 MWe for the E-SMR reactor.

### BOP architectures in cogeneration mode

The architecture presented in Fig. 1 has been modified to include different steam extraction points, intended to represent the interface with the non-electric application. The goal of the analysis is to analyse the impact of these extraction points, combined with different return points, for different cogeneration requirements in terms of extracted power on the steam cycle, evaluating the influences on the operating conditions and performances with respect to the architecture optimised for full power operation. The steam cycle has been optimised assuming to have the latter steam extractions at nominal conditions, without addressing the impact on the cycle performance in off-design conditions.



*FIG. 1. BOP architecture in full power mode, with steam extraction and return points.*

Different end-user requirements are analysed, both in terms of thermal power demand and steam temperature. In particular, five extracted power levels are considered, up to 36 MWth. The analysis has been limited to this amount to be consistent with the reference non-electric application of this study, hydrogen production via HTSE. This industrial process requires a significantly larger portion of electrical power with respect to thermal power, and in the case of power extractions beyond 36 MWth, the net electrical power output of the BOP would be hardly able to meet the electricity requirements of the hydrogen production plant.

Moreover, three different steam extraction and return points are accounted for. The steam extraction points are highlighted by a circular shape in Fig. 1. They are subdivided according to the temperature level of the steam at the corresponding point of the cycle. Assuming a temperature requirement for the HTSE of at least 150°C, the following extraction points have been identified:

* A high temperature (HT) extraction point is located at the steam generator outlet. The fluid conditions at this point are dictated by the E-SMR operational data and are reported in Table 1.
* Steam extraction at the outlet of the first HP turbine stage is labelled as an intermediate temperature (IT) extraction point, as it occurs around 230°C and 25 bar.
* Lastly, low temperature (LT) extraction is performed at the second HP turbine stage outlet, with a temperature of around 168°C, corresponding to a pressure level of 7.7 bar.

As a result, according to the extraction point, the steam might be in superheated or two-phase conditions. In general, the extracted heat quality is dictated by the temperature requirements of non-electric applications [9]. High and intermediate temperature steam conditions might be suitable to power industrial processes such as pulp and paper manufacturing and oil refining. For instance, steam at 220°C is delivered from the Gösgen nuclear power plant in Switzerland to a nearby cardboard factory [9]. Low temperature applications, usually below 150°C, include district heating and seawater desalination. As a result, it would be possible to drive the latter processes, as well as HTSE, by exploiting steam at the HP turbine outlet. Other steam extraction points, e.g., between the two LP turbine stages or at the LP turbine outlet, were discarded due to the low temperature levels, which would not be compatible with the HTSE requirements.

Similarly, three return points are considered for the reinjection of the fluid downstream of the heat delivery to the end-user, identified by a diamond shape in Fig. 1:

* A low pressure return point at the condenser, with the extracted fluid being reinjected in the condenser shell together with the turbine discharge.
* Secondly, reinjection in the low-pressure feedwater preheater (LP-FWH) is evaluated.
* Steam return in the feedwater tank (FW-Tank) is then considered.

In each case study, the return points are at a lower pressure with respect to the steam extraction. Consequently, it is assumed that the heat transfer to the end-user occurs at the extraction pressure, after which the flow is throttled to match the pressure at the return point.

Fig. 2 shows an illustration of the modified steam cycle to account for the thermal power extraction for cogeneration purposes. In the proposed example, steam is extracted downstream of the HP turbine, flows to EBSILON’s *Heat Consumer* component, representing the thermal power extraction, and is then reinjected in the feedwater tank. An analogous approach has been adopted to analyse the other steam extraction and return points. The *Heat Consumer* component is used to impose full condensation of the steam, and the extracted flow rate is controlled to meet the thermal power requirements (in the example in Fig. 2, 36 MWth).



*FIG. 2. BOP architecture in cogeneration mode, with LT steam extraction and FW-Tank return.*

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## RESULTS

In this section, the results obtained by optimising the BOP configurations described above are presented. The figure of merit adopted for the comparison is the gross electrical power output, which is strongly correlated to the system’s efficiencies. Two efficiencies have been considered for the analysis: the electrical efficiency, defined as the ratio between electrical power generation and thermal power supplied by the nuclear reactor, and the overall efficiency, which accounts for the extracted thermal power as a valuable commodity.

The differences for the several extraction and return points are displayed in Fig. 3. The impact of the steam extraction points for the same return point, i.e., FW-Tank, is shown on the left-hand side of the figure. In general, the lower the pressure and temperature of the steam extraction point, the higher the power generated by the steam cycle and, consequently, the efficiencies of the system. Moreover, the impact of the extraction point on the cycle’s performance becomes more significant at higher thermal power extractions. For low powers delivered to the non-electric application, e.g., 6 MWth, the difference between the HT and LT extraction configuration is less than 1 MWe, whereas it increases to about 4.5 MWe in the case of a 36 MWth extraction.

The steam extraction point showing the best performance, i.e., LT extraction, has been considered as a reference to evaluate the impact of the potential return point on the steam cycle’s power output. It is worth noting that the viability of extracting a large amount of thermal power at this temperature is strongly related to the industrial process temperature levels, since the difference between the two should be sufficiently high to enable a thermal power flow and meet the desired intermediate heat exchanger cold side outlet temperature conditions. The results, reported on the right-hand side of Fig. 3, show that the highest power output is achieved by reinjecting the condensate resulting from the thermal power extraction into the feedwater tank, while the performances worsen when considering the condenser as the return point. However, the difference for the various return points is not as significant as for the extraction points, since the power generation difference between the FW-tank and Condenser return is 0.3 MWe and 1.9 MWe for 6 MWth and 36 MWth, respectively. This trend can be explained by the potential recovery of the residual energy of the condensate return in the steam cycle. Considering the fluid’s return to the condenser, its residual energy is discharged to the environment without contributing to the overall economy of the steam cycle. On the other hand, by returning the condensate in a later stage of the feedwater line, its energy can reduce the recuperation requirements of the cycle to meet the steam generator inlet temperature conditions, e.g., by reducing the bleeding requirements for the feedwater preheating, thus increasing the electrical power generation and the cycle’s efficiency.



*FIG. 3. Impact of extraction and return points on the power generated by the cycle for different thermal power extractions.*

The impact of thermal power extraction in the different configurations has direct implications for the steam cycle efficiencies, as shown in Fig. 4. The graphic illustrates the efficiency variation for the most and least performant interfaces with the non-electric user, namely LT and HT extraction levels and, for the return points, the feedwater tank, and the condenser, respectively. The electrical efficiency of the system, shown in the lower part of the figure, is linearly decreasing with the extracted thermal power due to the resulting decrease in electrical power output. The extraction and return points have a direct impact on the gradient of this trend, with the most performant configuration, i.e., LT extraction and FW-Tank return, showing the lowest efficiency degradation with extracted thermal power. The same outcomes in terms of impact of steam extraction and return points are valid also for the overall efficiency, which accounts for the power delivered to the non-electric application as a valuable output of the system. The improvement in terms of efficiency for the 36 MWth in the most performant configuration with respect to the less effective combination with HT extraction and condenser return is about 1.6%, and, according to this trend, it is poised to increase for higher extracted thermal power levels.



*FIG. 4. Variation of electric and overall efficiency for different configurations and thermal power extractions.*

## CONCLUSIONS

This work focused on the impact of thermal power extraction interfaces on a light-water cooled SMR balance of plant performances, with specific attention given to the context of hydrogen production via HTSE. Consequently, the analysis is limited to thermal outputs up to 36 MWth and an extracted heat temperature higher than 150°C. A reference BOP layout has been optimised for full power operation with the EBSILON Professional software, and then it has been adapted and optimised to account for different steam extraction and return points.

The results underscored the significant impact of the steam extraction point in determining the overall performance of the steam cycle with respect to the condensate return point. Notably, a linear decrease in generated power with increasing extracted thermal powers is obtained, with HT extraction exhibiting a more pronounced effect compared to LT extractions. On the other hand, 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.

The proposed analysis is limited to nominal steam cycle conditions without considering off-design operations. The latter is particularly important in the context of growing flexibility needs for dispatchable generators such as nuclear power plants coupled to non-electric applications, which are required to dynamically allocate power for electricity generation and cogeneration purposes according to market demands. Moreover, since the boundaries set in this study have been set to the SMR’s balance of plant, the gained insights can be extended to a wide range of non-electric applications. For the latter, it might be worth increasing the extracted power levels considered in this study, which have been limited to 36 MWth due to the peculiar power requirements of HTSE.

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