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**Assessment of the control and flexibility constraints on system components by the hybrid system simulator coupled with an optimizer**

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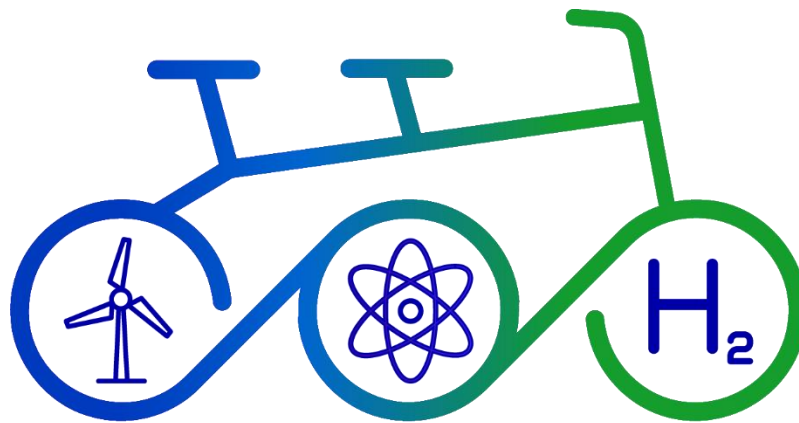
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## Summary

This document summarises the results obtained within the framework of Task 3.3 of the TANDEM project, which has the objective of evaluating the applicability of the techno-economic results in the definition of short-term operational strategies of Nuclear Hybrid Energy System (NHES) architectures. In particular, Task 3.3 investigates the potential coupling of the techno-economic optimisation models developed in the Work Package 3 activities with the dynamic simulators provided by Work Package 2, testing different levels of interaction between the two tools. The proposed methodological approach is applied to two case studies presented by Work Package 1: the Northern European case, featuring a hybrid system configuration powering a district heating network, and the Southern European case, focusing on two energy hub architectures.

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# TANDEM

## D3.4 - Assessment of the control and flexibility constraints on system components by the hybrid system simulator coupled with an optimizer

### WP3 - Task 3.3

31/05/2025 [M33]

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## Abbreviations and Acronyms

Acronym	Description
BOP	Balance Of Plant
CCGT	Combined Cycle Gas Turbine
DH	District Heating
DHC	District Heating and Cooling
E-SMR	European Small Modular Reactor
FMI	Functional Mock-up Interface
FMU	Functional Mock-up Unit
GAMS	General Algebraic Modelling System
HTSE	High-Temperature Steam Electrolysis
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
NHES	Nuclear Hybrid Energy System
NSSS	Nuclear Steam Supply System
NPP	Nuclear Power Plant
NPV	Net Present Value
OPEX	Operational EXpenditures
PV	PhotoVoltaic
SMR	Small Modular Reactor
SOC	State Of Charge
TES	Thermal Energy Storage
WP	Work Package

## Executive Summary

This document summarises the results obtained within the framework of Task 3.3 of the TANDEM project, which has the objective of evaluating the applicability of the techno-economic results in the definition of short-term operational strategies of Nuclear Hybrid Energy System (NHES) architectures. In particular, Task 3.3 investigates the potential coupling of the techno-economic optimisation models developed in the Work Package 3 activities with the dynamic simulators provided by Work Package 2, testing different levels of interaction between the two tools. The proposed methodological approach is applied to two case studies presented by Work Package 1: the Northern European case, featuring a hybrid system configuration powering a district heating network, and the Southern European case, focusing on two energy hub architectures.

The tight coupling among NHES components, which can exchange multiple energy carriers, such as electricity, heat, and hydrogen, translates into complex interconnection and potential non-linear dynamic effects that cannot be captured by conventional MILP optimisation tools. For this reason, the goal of this work is to present a methodological framework that integrates the dynamic simulator, being a more representative model to simulate the system's behaviour over time, and the techno-economic optimisation tools. In particular, two coupling strategies are investigated: soft-linking and hard-linking. In the former, the optimisation model parameters are updated to be consistent with the operational conditions observed in the dynamic simulator and the viability of a given optimal dispatch strategy is verified a posteriori by testing the optimised setpoints with the dynamic simulator. Conversely, the hard-linking approach allows accounting for the dynamics of the system within the optimisation phase itself, with the optimal setpoints being iteratively updated according to the feedback of the dynamic simulator.

The results show that the soft-linking approach, used in the Northern European case to couple VTT's Backbone optimisation framework with the district heating dynamic simulator, led to a good agreement between the tools, particularly because the thermal power flows were directly controlled in the simulator's control logic. In contrast, in the Southern European case, the thermal power flows were indirectly determined by other setpoints, resulting in a violation of the operational constraints when testing the setpoints with the dynamic simulator.

Significant improvements were achieved by hard-linking the energy hub simulator with CEA's PERSEE optimisation model in the PEGASE co-simulation platform. This approach allowed for an adequate consistency between the tools and enabled the successful simulation of longer simulation horizons (up to one year), remaining within the allowed operational limits. Furthermore, various simulation setups were tested to assess the impact of the coupling parameters on the optimal dispatch strategy. Specifically, it is demonstrated that a more

frequent exchange of variables between the optimiser and dynamic model could improve the consistency between the codes, especially when it comes to NHES, where dynamic aspects significantly impact the operational conditions. However, the increased consistency achieved by updating the optimal setpoints with the dynamic simulator's feedback leads to a significantly higher computational effort compared to the stand-alone optimisation. Moreover, the optimal setpoint derived especially for short time-scale simulation leads to significant oscillations in the optimal profiles, which are more pronounced when hard-linking the two tools due to the continuous update of the optimisation initial conditions according to the simulator feedback. This aspect could be improved by adding additional constraints to the optimiser, valid also when transitioning from one optimisation cycle to the other in the coupled setup.

Overall, the work in Task 3.3 demonstrated the importance of accounting for the intricate dynamics of NHES within the optimisation phase in order to estimate a more physically representative optimal dispatch strategy. In particular, the hard-linking approach proved to be a valuable method to capture these phenomena, especially in the context of the energy dispatch optimisation in the short-term.

## Keywords

Nuclear hybrid energy systems, Small Modular Reactor, District heating, Energy hub, Hydrogen, Techno-economic optimisation, Dynamic simulator, Backbone, PERSEE, PEGASE, Modelica.

## 1 Introduction

The integration of nuclear reactors, particularly Small Modular Reactors (SMRs), into so-called Nuclear Hybrid Energy Systems (NHES) is seen as a promising solution in the context of the energy transition, as a tighter interaction between energy sources and final consumers is envisaged to increase flexibility, efficiency, and reliability, all of which are key pillars in decarbonisation strategies. The Euratom-funded TANDEM (Small Modular Reactor for a European safe and Decarbonized Energy Mix) project aims at investigating such systems from several standpoints, ranging from safety, techno-economic, environmental, education and training, as well as policy recommendations to facilitate the deployment of SMR-driven NHES in the European context. To support these assessments, several tools were developed in the framework of the project. For instance, Work Package (WP) 2 delivered an open-source Modelica library collecting dynamic models for NHES components (Simonini et al., 2024a), while WP3 focused on the techno-economic and environmental assessments of NHES with techno-economic optimisation tools. Three case studies were identified in the initial phase of the project by WP1, namely a Northern and Central European case, considering nuclear-driven district heating networks, and a Southern European case assuming an energy hub architecture with nuclear heat and electricity used to power several industrial processes, including hydrogen production (Värri et al., 2023).

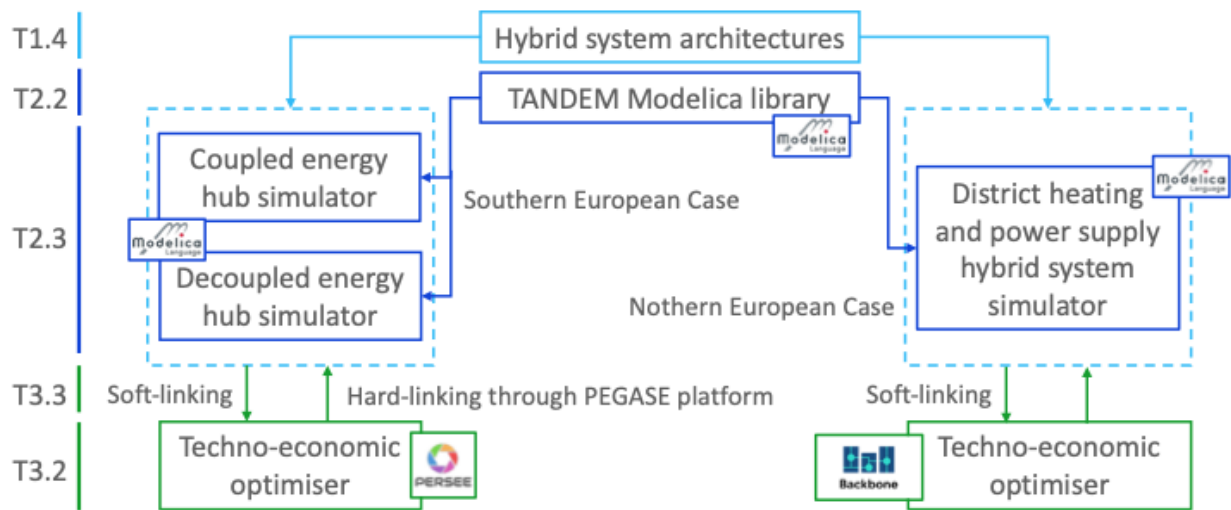
In WP3, the case studies were analysed employing two techno-economic optimisers, Backbone (Helistö et al., 2019) and PERSEE<sup>1</sup> (Ruby et al., 2024), developed by VTT and CEA, respectively. An extensive description of the tools and methodologies adopted in this WP is available in Deliverable 3.2 (Lavialle et al., 2024), including a presentation of the Key Performance Indicators (KPI) of the system, while in the subsequent deliverable (Ikonen et al., 2024), the impact of the main techno-economic assumptions has been assessed through a sensitivity analysis. The present deliverable summarises a part of the results obtained within the activities of Task 3.3, which aims at checking that the dispatch control strategy predicted by the techno-economic tools is applicable on a short timescale in compliance with the technical constraints of the system.

An overview of how this Task is located in the frame of WP3 and, more generally, of the TANDEM project, is shown in Figure 1. As aforementioned, the study is based on the reference NHES architectures identified in WP1/Task 1.4. Components of the open-source TANDEM Modelica library were applied to assemble dynamic simulators of the architectures, specifically two for the energy hub case and one for the district heating case (Martos Nogales & Masotti, 2024). It is worth highlighting that, in the frame of the development of the hybrid system simulators in Task 2.3, only the Northern European scenario was considered for the district heating case. In Task

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<sup>1</sup>As part of an open source release, PERSEE that stood for “oPtimizER for System Energy management” was renamed to Cairn.

3.3, these models, together with the techno-economic optimisation tools of Task 3.2, were coupled with each other. For the energy hub case, PERSEE and Modelica were coupled through a hard-linking approach within CEA’s PEGASE co-simulation platform, accounting for the dynamics of the system directly in the dispatch optimisation phase. These results are compared with the optimisation outcomes obtained with a soft-linking approach. On the other hand, only a soft-linking approach has been considered in the district heating case, checking that the optimal dispatch strategy proposed by Backbone could be met by testing it with the dynamic model and updating the Backbone model considering the more physically representative operating conditions and constraints obtained from the NHES simulator.



**Figure 1. Contextualisation of Task 3.3 in the framework of the TANDEM project.**

The goal of having a tighter coupling between the dynamic models and the optimiser is to define a dispatch strategy that is consistent with the operation predicted by a physical model of the system, which in turn will provide a more reliable assessment of the economic performance of the considered NHES architecture. In particular, accounting for dynamic effects in the optimisation phase through the hard-linking approach could lead to a significantly different dispatch strategy compared to the one provided by optimisation tools based on Mixed-Integer Linear Programming (MILP) algorithms, such as PERSEE, e.g., due to the non-linearities arising from the dynamics of the system.

This deliverable is structured as follows: the first part focuses on the Northern European case, starting from a brief overview of the tools and a description of the soft-linking approach. Then, the consistency between the codes is verified by selecting illustrative weeks from the yearly optimisation. The Southern European case, with the two energy hub architectures, is discussed in Section 3. In this case, the results for several coupling setups (e.g., for different degrees of interaction between the optimiser and the dynamic model) are compared.

## 2 Northern European Case

The Northern European case focuses on the potential integration of an SMR used for combined heat and power production in the Finnish energy system. In the considered scenario, the thermal power extracted from the SMR is used to contribute to the decarbonisation of the district heating network of Helsinki's metropolitan area, interconnecting the heating systems of Helsinki, Espoo, and Vantaa (Värri et al., 2023). The reference nuclear technology considered in the TANDEM project is the European SMR (E-SMR), a 540 MW<sub>th</sub> pressurized-water type SMR conceptual design deployed in a two-module configuration. In the district heating architecture, intermediate pressure steam (at around 7.5 bar), extracted at the high-pressure turbine stage outlet, is used to supply heat to the district heating network (Martos Nogales & Masotti, 2024). This heat supply is coordinated with other heat sources, such as heat pumps, fossil-fuelled boilers, etc., and with heat storage devices to meet the district heating demand of each urban area. In this work, it has been assumed that the SMR is maintained at its rated conditions, leveraging the advantages of avoiding frequent core power variations (Jenkins et al., 2018), while allocating its thermal power either for electricity production or for district heating according to the end-user requirements.

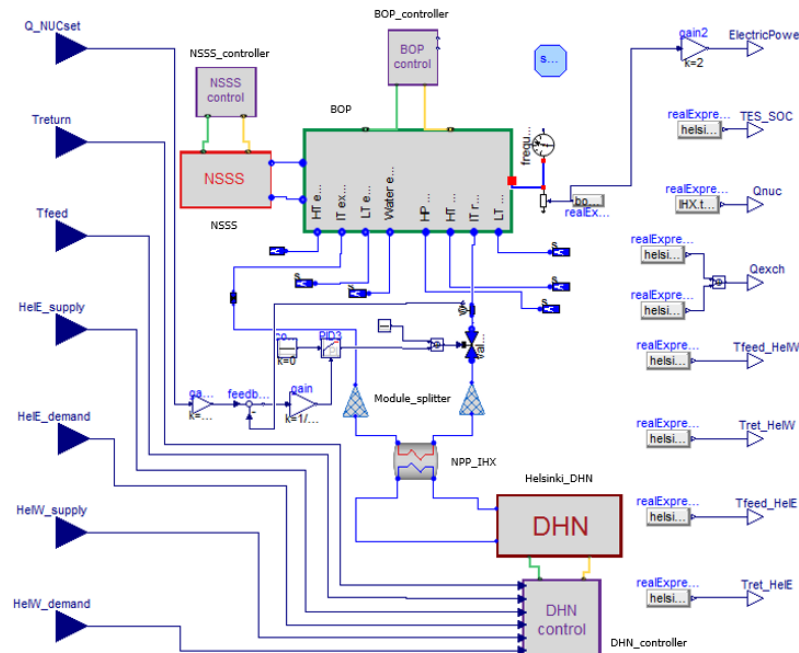
### 2.1 Overview of the tools

This section provides an overview of the tools adopted to predict and test the optimal dispatch strategy for the Northern European case. In particular, the Backbone optimisation framework is applied to estimate the optimal heat flows in the district heating network. The resulting profiles are then tested employing the dynamic simulator, verifying that the proposed power flows can also be met by considering delays due to the fluid travel time, inertial effects, and other phenomena that can hardly be represented by a linear optimisation tool. It is worth highlighting that the optimisation is performed on a yearly horizon, whereas the verification with the dynamic model is performed on a shorter timescale, i.e., selecting representative weeks from the yearly optimisation.

#### 2.1.1 Dynamic simulator

The dynamic simulator of the district heating architecture, shown in Figure 2, is described in Deliverable 2.5 (Martos Nogales & Masotti, 2024). It has been built with components from the Modelica TANDEM library (Simonini et al., 2024b), which in turn rely on components of the ThermoPower library (Casella & Leva, 2006). The model features several inputs and outputs, displayed on the left and right sides of Figure 2, respectively, to facilitate the connections and comparisons with the techno-economic optimisation. Specifically, the feed and return temperature setpoints are driven by outdoor temperature conditions. On the other hand, the Backbone optimisation provides the heat flows, namely the district heating demands for Helsinki

East and West, which also encompass those of Vantaa and Espoo, the heat supplied by the Nuclear Power Plant (NPP), and the heat supplied by other sources, lumped in single timeseries for each area (Simonini et al., 2024a).



**Figure 2. Dynamic simulator of the district heating architecture (Martos Nogales & Masotti, 2024).**

In this study, the integrated energy system is operated according to the following philosophy: a cogeneration valve is used to extract steam from the power conversion cycle for district heating purposes according to the thermal power defined by the input setpoint. Recalling the assumption of maintaining the reactor at its rated conditions, it will result that the whole power that is not supplied to the district heating network is converted into electricity and supplied to the power grid, independently of grid requirements.

### 2.1.2 Backbone optimisation model

Backbone is an adaptable energy systems modeling framework designed for studying the design and operation of energy systems, for both operational scheduling and investment planning. The framework has been developed as an open-source tool (Kiviluoma et al., 2018) using the General Algebraic Modeling System (GAMS). Backbone can model both high-level, large-scale systems and fully detailed, smaller-scale systems. The framework is based on mixed-integer programming, and it features unit commitment decisions for power plants and other energy conversion facilities. The formulations and equations that Backbone is built upon are described by (Helistö et al., 2019).

The structure of Backbone models is defined through parameter settings and input data, rather than hard-coded structures, allowing for the creation of various models for different purposes using the same data set. The Backbone model used in this work represents the Helsinki metropolitan area's district heating and cooling system. The model topology is composed of grids, nodes, units, and lines. These elements define the physical layout of the energy system model. Specific data relevant to the Helsinki metropolitan area, such as regional demand time series of district heating and district cooling, are implemented in the model. Documentation and validation of the Helsinki metropolitan area model can be seen from the source (Pursiheimo et al., 2022).

The implementation of the energy system model for the Helsinki metropolitan area District Heating and Cooling (DHC) system involves integrating the District Heating (DH) and district cooling production and storage structure into the Backbone model (Lindroos & Pursiheimo, 2022). The Backbone Helsinki metropolitan area model used is based on the year 2030, including existing production capacity modified with expected changes utility companies have planned up to that year. Division and interconnection of district heating grids between cities in the metropolitan area, Helsinki, Vantaa and Espoo, are included in the model. Furthermore, Helsinki is divided into two distinct DH grids. Moreover, the DHC system is interconnected with the national electricity grid, which enables both the supply of electricity to heat pumps and the sale of electricity generated by combined heat and power units to the Nordic electricity market. Timeseries data based on the year 2019 is used for modelling heat demand and electricity price in the DHC model. Ultimately, the optimisation identifies the combination of power sources – in terms of both installed capacities and operational strategies – that maximize the Net Present Value (NPV) of the overall district heating network. A more detailed description of the Backbone DHC model used in this work is available in Deliverable 3.2 (Lavialle et al., 2024).

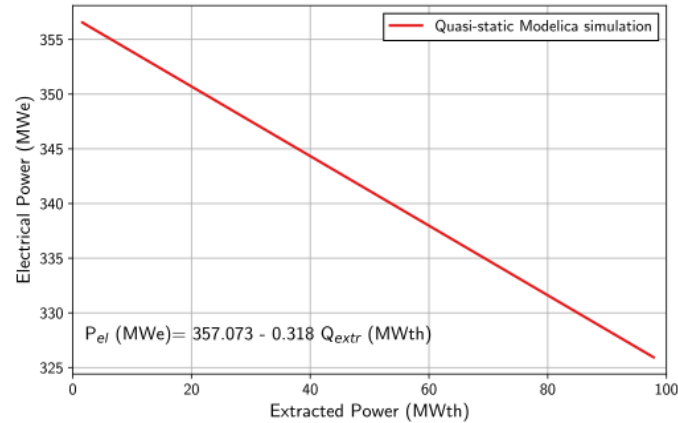
## 2.2 Methodology

For the Northern European case, the adopted coupling methodology is that of the soft-linking between the dynamic simulator and optimiser, meaning that there is no direct connection between the two tools. As a result, the optimisation is performed without having an inherent feedback from the dynamic model. In the proposed soft-linking approach, a more physically reliable optimal operational strategy is obtained by updating the Backbone model, considering operating conditions and constraints derived from the Modelica model of the system. In this regard, an iterative procedure is performed, with the objective to ensure a consistent behaviour between the optimised profiles and the transient behaviour predicted by Modelica. After updating the optimiser according to the feedback of the Modelica simulation, the new optimal profiles are tested with a dynamic simulation, which is used to identify further potential

inconsistencies and eventually to perform a new iteration in which the optimiser is further modified.

Specifically, with respect to the previous work performed to optimise the system through the Backbone framework (Laviolle et al., 2024), the following steps were performed in the frame of this work:

- The Backbone optimisation is repeated by considering the operational strategy implemented in Modelica, which consists of maintaining the reactor at its rated conditions and allocating a variable fraction of its thermal power for electricity generation or district heating. Conversely, in Deliverable 3.2, the reactor power was considered free to vary, allowing also its shutdown when energy demands are low. Due to this very different operational strategy, the results in terms of economic performance achieved with the updated Backbone model are not comparable with those of D3.2.
- In a subsequent step, the operational points of the system estimated by means of the dynamic model through a quasi-static simulation were implemented in the Backbone model. Specifically, the operational profile of the reactor is shown in Figure 3, considering the impact of heat extraction on electricity production, is used to modify the SMR characteristics in Backbone to ensure consistency with the simulator. The simulation results indicate a linear relationship between the extracted thermal power and the electrical power output. In other words, the slope of this relationship, known as the power loss factor, remains constant within the considered range of extracted heat.
- In a third step, further iterations between the tools are performed by simulating the optimal profiles with the dynamic model. In case of significant discrepancies, the operational constraints (e.g., ramping limits) observed from the dynamic simulation are translated into the Backbone optimisation framework. In particular, the transfer capacity between Helsinki East and Helsinki West district heating networks was modified from 140 MW<sub>th</sub> to 40 MW<sub>th</sub> and a ramping limit was introduced and set to 26 MW<sub>th</sub>/h. Also, for the E-SMR model, a ramping limit was introduced and set to 8.5 MW<sub>th</sub>/h. These constraints stem primarily from modelling assumptions and limitations, rather than from the actual operational limits of the real-world district heating network. For example, the reduction of the transmission capacity from 140 MW<sub>th</sub> to 40 MW<sub>th</sub> was due to the inability of the proposed architecture and control strategy to manage significant power flow reversals, which is a limitation that may not apply to a more realistic design and control approach. Nonetheless, from a methodological standpoint, the objective is to achieve consistency between the dynamic simulation and the optimisation results, regardless of the system's real-world fidelity at this stage of the analysis.



**Figure 3. Operational map showing the impact of low temperature steam extraction on the E-SMR electrical power output.**

## 2.3 Results

In the following sections, the simulation outcomes are presented, highlighting the modifications applied from one iteration to the other to enhance the consistency between the optimisation tool and the more physically representative simulator of the system, with the objective of achieving a more representative operational strategy and economic performance of the system.

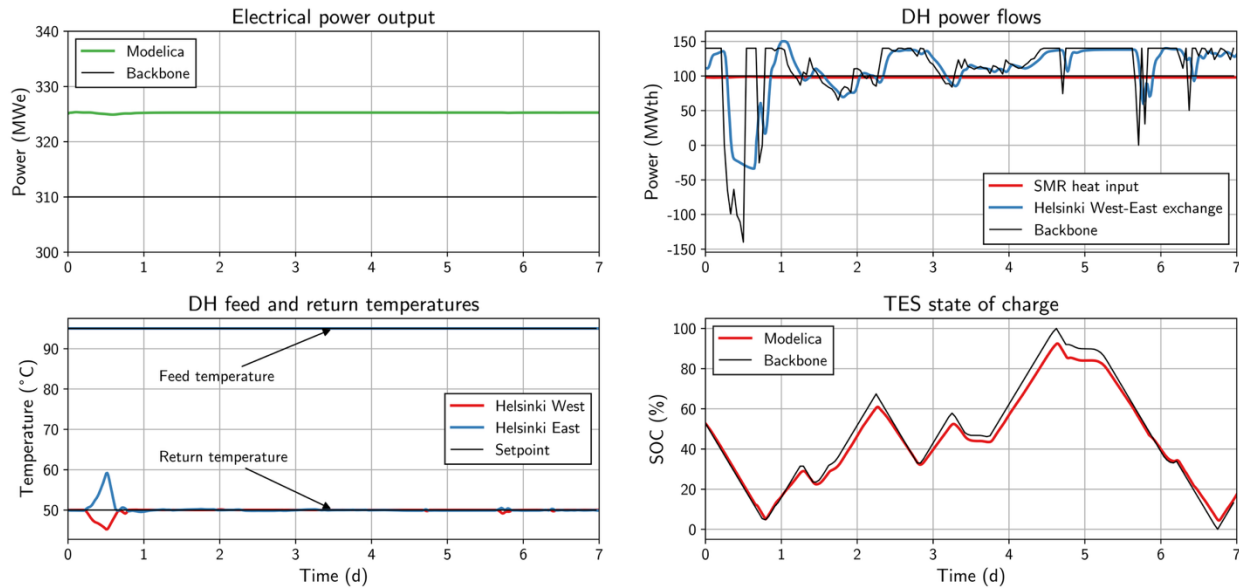
Two examples are selected to showcase the soft-linking approach in the Northern European context. Specifically, two illustrative weekly profiles were selected from the yearly optimisation, one representative for a week in the winter and another one for the summer. The rationale behind selecting two weeks lies in the significant seasonal variability of district heating requirements, both in terms of heat demand and temperature requirements. In particular, the last week of January was considered for the winter conditions, whereas the first week of June was chosen for the summer scenario. These weeks were selected to ensure the reactor's optimal operation is compatible with the dynamic model's capabilities. On the other hand, case studies that included situations like a complete reactor shutdown were not included in the analysis since the dynamic model is not able to adequately simulate such events.

### 2.3.1 Winter week

The results obtained by testing the system imposing the setpoints obtained from the first Backbone optimisation, adopting the modelling setup of previous analyses (Lavialle et al., 2024), are shown in Figure 4. Conversely, the results obtained at the end of the iterations performed to update the Backbone model according to the simulator's feedback, both in terms of SMR operational strategy and additional constraints, are presented in Figure 5.

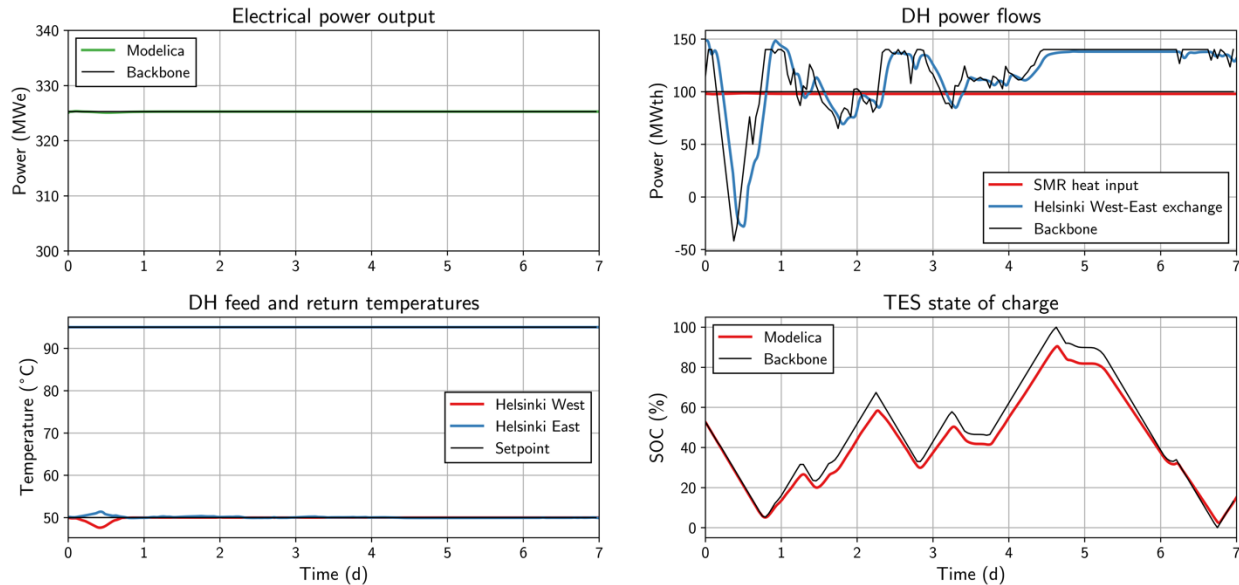
As far as the first iteration is concerned, a comparison of the reactor's electrical power output computed by the dynamic simulator and the Backbone profile is displayed in the first plot of Figure 4. The value predicted by the Modelica simulation is consistently higher than the Backbone value since the power conversion efficiency of the dynamic simulator is significantly higher compared to the one assumed in Backbone. It is worth highlighting that Modelica's profile refers to the gross electricity generation, but accounting for the auxiliary consumptions would decrease the generated power by 2-4 MW<sub>e</sub>, resulting in a power output that would still be higher compared to the one in Backbone. In the following iterations, the relation between extracted thermal power and electrical output presented in Figure 3 was implemented in Backbone, ensuring a consistent operational map to describe the SMR operation. In this regard, the difference in the electrical outputs is related also to the considered operational strategy: in the Modelica model, the controlled variable is the heat supplied to the district heating network, which, as shown in the top right figure, remains constant at the maximal extraction level of 100 MW<sub>th</sub> throughout the whole transient. The heat extraction level determines the electrical power output of the system, coherently with the operational map reported in Figure 3. Furthermore, the power exchanged between the Helsinki West and East distribution networks is represented by the solid blue line in the same plot. It is fairly in line with the profile obtained with the Backbone optimisation, despite significantly smoother variations due to dynamic and inertial effects that mitigate the rapid power variations resulting from the optimal operation. Nevertheless, notable inconsistencies are visible at the beginning of the transient, where the exchanged power reaches almost 150 MW<sub>th</sub> delivered from Helsinki East to West, according to Backbone. The dynamic model is not able to handle such a violent inversion in exchanged power, considering that the exchanged power will be driven by the control performed on dedicated control valves actuated to meet the feed and return temperature requirements of the system. Moreover, the evolution of the latter variables will also entail the dynamics of the system, such as the fluid travel times, as well as non-linearities arising from phenomena like the heat transfer in the heat exchangers connecting the two urban areas. The mismatch between the power flows computed utilizing the simulator with respect to the setpoint leads to a deviation of the distribution networks' return temperatures from their setpoint, as displayed on the bottom left-hand side of Figure 4. In particular, the lower thermal power delivered from Helsinki East to West leads to a decrease in the return temperature for the latter urban area, whereas the higher energy available in Helsinki East translates into a heating up of the water in the distribution network of almost 10°C. The Thermal Energy Storage (TES) system, assumed to be connected to the Helsinki West network and lumping the contributions of each storage system in the actual district heating network (Martos Nogales & Masotti, 2024), is operated to meet the temperature requirements of the Helsinki network up to its charging and discharging limits. As a result, it can only limit the return temperature reduction in the latter network due to the discharging power limitations, which will determine the rate at which the State-Of-Charge (SOC) of the TES is

decreasing at the beginning of the transient. In general, the profile of the SOC predicted by the dynamic model is consistent with the one resulting from the Backbone optimisation, despite a notable underestimation at high storage levels.



**Figure 4. Comparison between optimal profiles and dynamic simulation for the winter scenario (first iteration).**

The results obtained by updating the Backbone model according to the feedback from the dynamic simulator are shown in Figure 5. In particular, the parameters governing the Backbone optimisation were adjusted with the objective of minimising the discrepancies with the Modelica model to converge on an optimal operational strategy that is verified by a more physically representative model. For this reason, the NPP’s operational map presented before was implemented, together with additional constraints on the power exchange between Helsinki East and West, in terms of both ramps and magnitudes. In this case, the power generation between the models is consistent, potentially providing a more accurate estimation of the revenues from the electricity market. In addition, the evolution of the power exchanged between urban areas aligns well with the prediction of the dynamic model, despite a considerable delay due to the fluid travel time in the transmission lines, as seen in the previous case as well. The improved consistency between the power profiles leads to a significantly lower deviation of the return temperature from its setpoint, although a variation of a few degrees is still present in the initial phase of the transient. Lastly, no significant reductions in the difference of the TES SOC between the two models are achieved, mainly because the operation in the critical part of the transient remains the same from one iteration to the other, i.e., at maximum discharging power.



**Figure 5. Comparison between optimal profiles and dynamic simulation for the winter scenario (final iteration).**

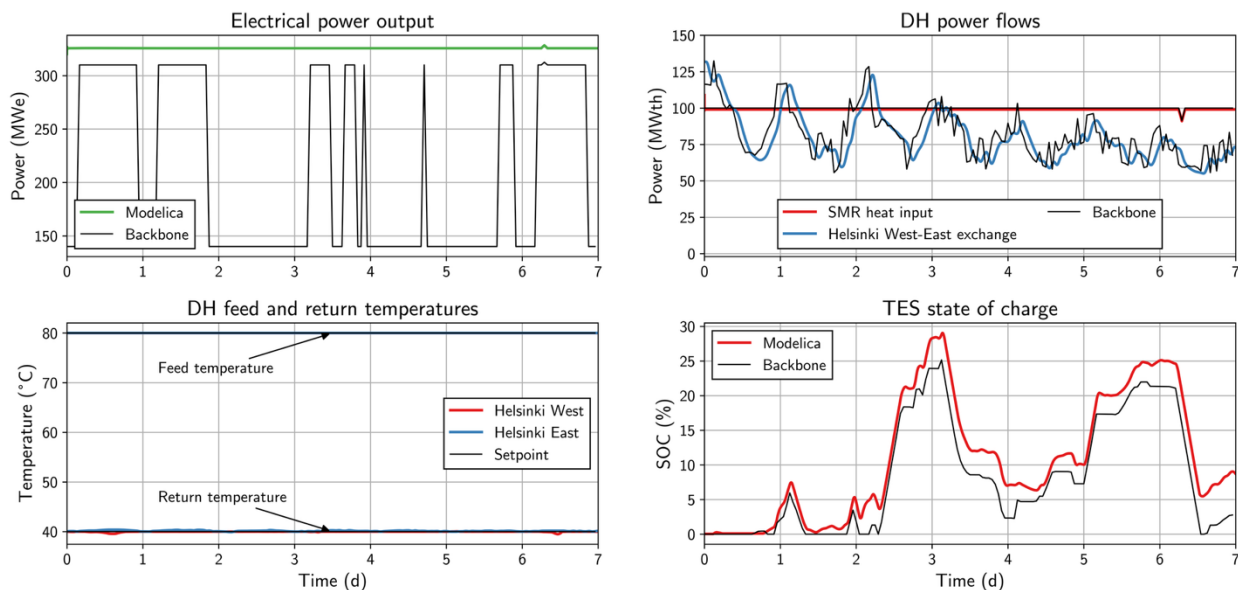
It is worth mentioning that both in the first and final iterations, the control system is able to meet the setpoint for the heat supplied to the district heating network, which remains constant throughout the whole transient. As a result, also the balance of plant and primary loop operation are stable and not subject to perturbations arising from the coupling with the cogeneration system.

In conclusion, updating the Backbone model accounting for the operational conditions and constraints estimated by means of the dynamic simulator, allows for achieving consistent results between the tools, leading to the definition of an optimal operational strategy that is viable also accounting for the significant delays in heat transmission and non-linearities characterising such a strongly thermally interconnected architecture. Specifically, reducing the heat that can be delivered from Helsinki East to West allows achieving a better agreement between the models. This is mainly related to the dynamic model’s assumptions since the system components are sized to deliver a certain amount of power from the western part of the city to the eastern part, and a significant inversion in the power flow direction can only hardly be met with the heat exchanger disposition modelled in the simulator (Martos Nogales & Masotti, 2024). However, it could be possible to get over this limitation by improving the representativeness of the dynamic model of the real-world district heating network.

### 2.3.2 Summer week

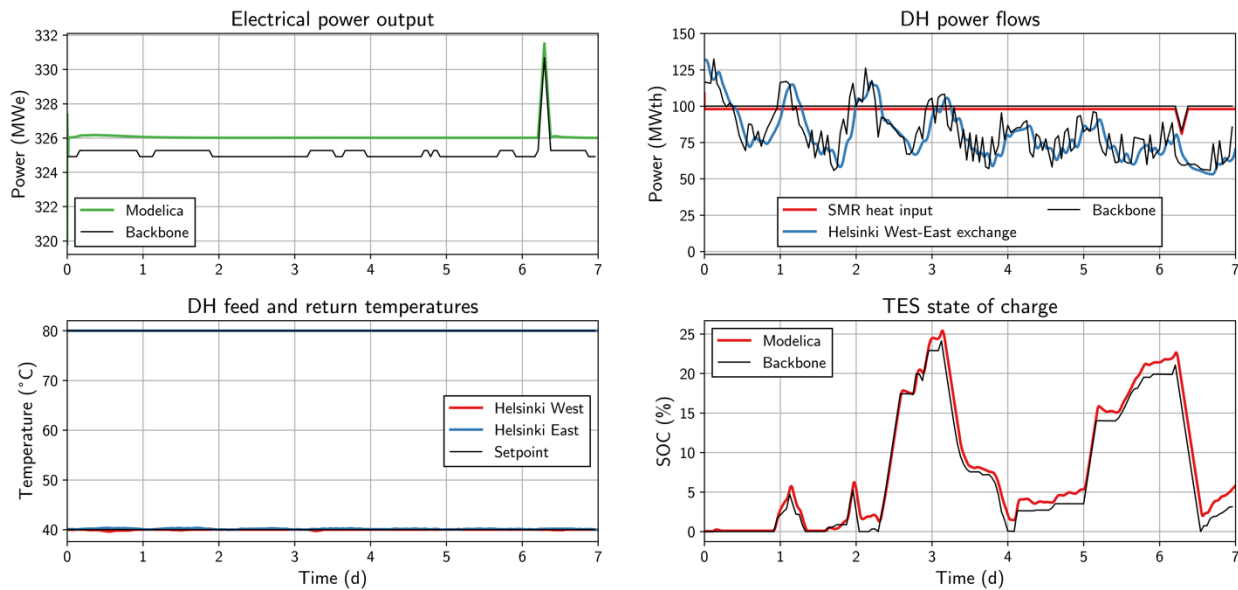
Similarly, the results for the summer case are presented below. Figure 6 displays the results obtained by testing the optimal profiles given by the original Backbone model, whereas Figure 7 shows the simulation results at the end of the iterations. The rationale behind testing the consistency between the models also in the summer scenario is to verify that the system is able to meet the requirements, also in case of different temperature levels compared to the nominal ones. As a matter of fact, the components of the district heating networks, such as the heat exchangers, were sized considering the temperature conditions of the winter season (Martos Nogales & Masotti, 2024), which are notably higher compared to those in summer.

As in the previous scenario, the electrical power output considered in the first version of the Backbone model is independent from the heat extraction, which leads to a highly variable optimised profile despite the almost constant district heat supply, as shown in the upper part of Figure 6. Correcting the operational map governing the reactor’s operation, a better consistency is achieved with the updated Backbone model. Notably, also the electrical power profile predicted by the updated Backbone model, shown in the top-left plot of Figure 7, exhibits a slightly variable trend, despite the steady thermal power extraction. This variation arises from the modelling approach adopted in Backbone, where the reactor power was defined within a narrow operational range rather than a fixed value to represent its operation at nominal conditions.



**Figure 6. Comparison between optimal profiles and dynamic simulation for the summer scenario (first iteration).**

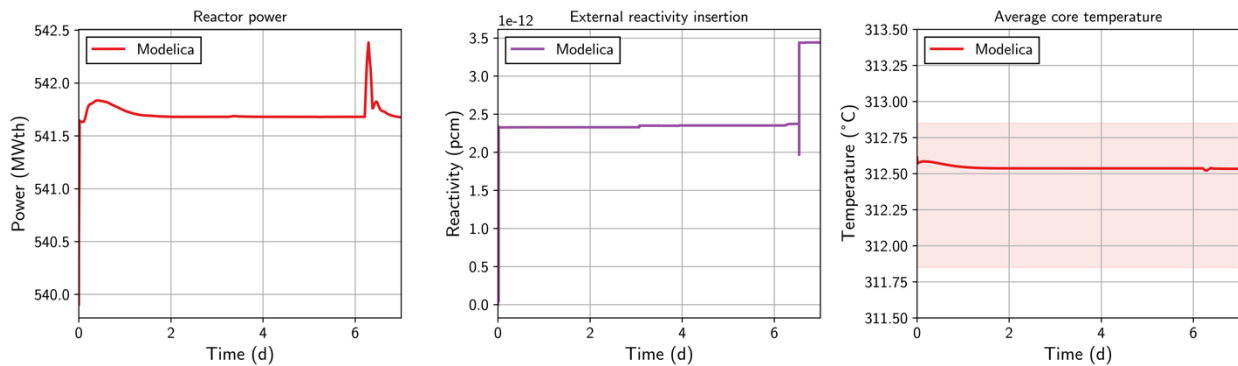
In this scenario, the power exchanges between distribution networks vary rapidly; however, the amplitude of these variations remains limited. In addition, the transferred heat remains confined between 50 and 125 MW<sub>th</sub> delivered from Helsinki West to Helsinki East, meaning that the power reversal observed in the previous scenario does not occur. As a result, the simulation outcomes are in fair agreement in both iterations, once again taking into account the transmission delay and the significantly smoother behaviour arising from dynamic and inertial effects. The improved consistency in terms of power flows translates into a close match of the feed and return temperatures with the corresponding setpoints, as demonstrated in Figure 6 and Figure 7. In addition, the results reported in the figures show that, as far as the TES dynamics is concerned, a significant improvement in terms of consistency between the codes has been achieved by updating the Backbone model.



**Figure 7. Comparison between optimal profiles and dynamic simulation for the summer scenario (final iteration).**

It is worth highlighting that there is a small reduction in thermal power extraction at the final part of the weekly transient, which is effectively met by the dedicated TES control system. A variation in extracted thermal power could have a direct impact on the NPP operation, as it could propagate from the balance of plant to the primary loop. The simulation outcomes obtained with the Modelica simulator for the nuclear steam supply system are displayed in Figure 8. The thermal power extraction at the end of the transient has a negligible impact on the core power, leading to a variation of less than 1 MW<sub>th</sub>. This perturbation has a minor impact also on the average core temperature, which, remaining within the allowed limits, does not trigger any external reactivity insertion through control rods.

Furthermore, the steam extraction leads to a stabilisation of the nuclear reactor at a slightly higher level compared to the nominal value of 540 MW<sub>th</sub>. This behaviour occurs only in the summer scenario as it is driven by the lower temperature levels on the district heating side. These lead to a lower steam return temperature, which in turn affects the primary side and the core power due to neutronic feedback mechanisms. The higher thermal power produced by the reactor causes a higher electrical power output, which is compatible with the result observed in the first plot of Figure 7, with the value predicted by Modelica consistently higher than the Backbone profile. Generally speaking, an increase of the reactor power beyond its rated value should be avoided for safety reasons. In this context, this requirement could be achieved, for instance, by reducing the thermal power demand for power conversion by acting on the turbine admission valve.

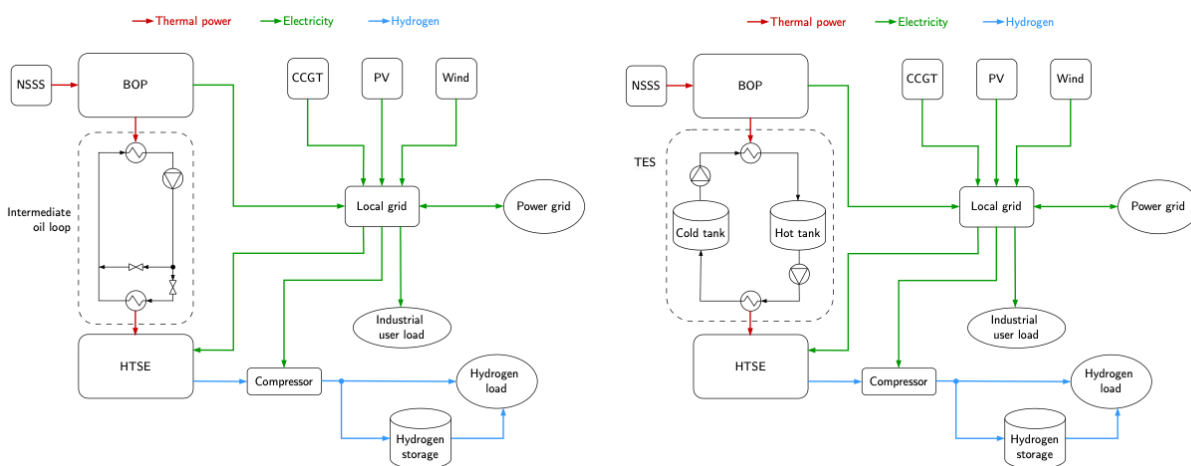


**Figure 8. Impact of heat extraction on the nuclear steam supply system.**

In conclusion, updating the Backbone model according to Modelica’s feedback enabled better consistency between the tools. The optimisation framework delivered more physically representative power flows, determined by the coordination of different heat sources and storage devices to meet a given heat demand. In the selected weeks, the thermal power extraction from the NPP remains almost steady at its maximal value, but also in the case of variable extractions, such as in the case of the summer scenario, it has been observed that the SMR could be operated at its rated conditions while meeting this variable heat demand by allocating the excess thermal power for electricity generation. However, given the minimal thermal power variation in the selected summer week, further studies conducted on weeks with higher variabilities in extracted thermal power should be performed to support this observation.

### 3 Southern European Case

The Southern European case examines the potential deployment of two E-SMR modules to decarbonise both heat and electricity supplied to an industrial district, considering the industrial harbour of Fos-sur-Mer in Southern France as the reference location. Based on the optimisation of different configurations presented in Deliverable 3.2, two reference architectures, resulting from the *run7* optimisation results (Lavialle et al., 2024), were selected and modelled for the analyses in Task 3.3. The configuration identified by *run7* was chosen as it was demonstrated to be the most cost-effective solution that met the European Taxonomy requirements for greenhouse gas emissions in hydrogen production (Lavialle et al., 2024).



**Figure 9. Coupled (left) and decoupled (right) energy hub architectures (Martos Nogales & Masotti, 2024).**

In the architectures, shown in Figure 9, the operation of several power sources – namely, the nuclear reactor, a Combined Cycle Gas Turbine (CCGT), photovoltaic (PV), and a wind farm – is coordinated to meet the industrial electricity demands and the energy needs of a High Temperature Steam Electrolysis (HTSE) hydrogen production plant. Consistently with the assumptions in Deliverable 3.2, a constant load demands for both electrical and hydrogen consumption were selected. A hydrogen storage system is included to decouple the HTSE operation from the load profile, thereby enhancing the flexibility of the integrated system. It is worth noting that the energy hub is assumed to serve exclusively the industrial district, meaning that the excess electricity delivered to the power grid is not considered to be remunerated. Moreover, the HTSE hydrogen production plant is assumed to be the only heat consumer, relying exclusively on the thermal power extracted from the NPP. As in the Northern European case, the reactor is kept at its rated conditions, while flexibility is achieved by allocating a variable fraction of thermal power either for power conversion or for non-electric applications.

In the framework of Task 3.3, two different energy hub architectures are considered, both previously described in Deliverable 2.5 (Martos Nogales & Masotti, 2024). As displayed in Figure 9, the two layouts differ in terms of thermal interconnection between the NPP and the HTSE. In the first configuration, shown on the left-hand side of Figure 9, the heat extracted from the NPP is delivered to the hydrogen production plant via an intermediate oil loop. In this arrangement, the HTSE operation is tightly coupled to the one of the power conversion system, as variations in hydrogen production directly affect the heat requirements, and, consequently, electricity generation, as observed in the previous case study. On the other hand, in the second configuration, the NPP's Balance Of Plant (BOP) and HTSE operations are decoupled by a TES based on the two-tank sensible heat storage technology (Martos Nogales & Masotti, 2024). This allows the NPP to produce variable electrical output by allocating excess thermal energy for TES charging, while the HTSE heat demand is met independently through discharging the heat accumulated in the TES.

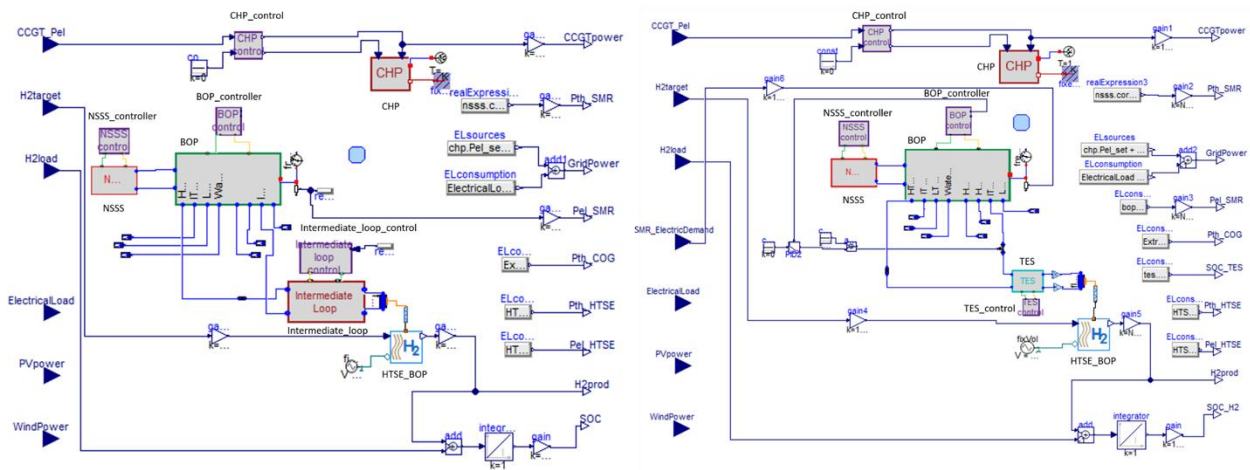
### 3.1 Overview of the tools

Similarly to the case study described in Section 2, the two hybrid system architectures were modelled both in the Modelica language to investigate their dynamic behaviour and in the techno-economic optimisation tool PERSEE to define the optimal architecture and operational strategy. The following sections provide a brief overview of these models, along with the PEGASE co-simulation platform, employed to facilitate the coupling between the tools.

#### 3.1.1 Dynamic simulator

Deliverable 2.5 provided a detailed description of the two dynamic simulators, illustrated in Figure 10. The modelling activities focused on the thermally interconnected components of the energy hub, i.e., the NPP, the HTSE, and, in the decoupled configuration, the TES. On the other hand, the dynamics of the electrically coupled components and the hydrogen storage system were represented using simplified models. As mentioned in Deliverable 2.5, the simulators were assembled using components of the TANDEM Modelica library (Simonini et al., 2024b), specifically including the HTSE model based on the ThermoSysPro library (El Hefni & Bouskela, 2019), while other components rely on the aforementioned ThermoPower library.

Due to the simplified modelling approach for the non-nuclear power sources, only a few of the simulators' inputs are actively influencing the dynamic simulation, whereas the others are used to provide the time profiles for the simplified components (e.g., renewable power production). Notably, the decoupled architecture features an additional input with respect to the coupled case, namely the SMR's electrical power demand. This is related to the aforementioned operational mode for this layout, in which electricity generation can be adjusted independently from the hydrogen production target of the electrolyser.



**Figure 10. Dynamic simulators for the coupled (left) and decoupled (right) energy hubs (Martos Nogales & Masotti, 2024).**

As in the previous case study, the inputs and outputs characterising the dynamic simulation play an instrumental role in the integration with the techno-economic optimisation tools, both for applying the optimal setpoints to be tested with the simulator and for comparing the model’s response with the time profiles considered in the linear optimisation.

### 3.1.2 PERSEE

PERSEE<sup>2</sup> is an optimisation software developed by CEA since 2018 to support decision-making for optimal energy mixes at various scales—from industrial sites to entire countries. It uses a modular C++ MILP core to model multi-energy systems, integrating techno-economic and environmental factors (Ruby et al., 2024). The PERSEE model described in Deliverable 3.2 was adapted to be consistent with the operational strategy and performance profiles implemented and obtained from the dynamic simulators. In particular, the main scenarios relied on the assumption that the heat extraction from the NPP was constant, discharging the excess thermal power that was not absorbed by the HTSE in an ideal sink. Moreover, the additional analysis about the E-SMR flexibility (Lavialle et al., 2024), the thermal power produced by the reactor was not constrained to the rated conditions, optimising also the core power over time. In the frame of Task 3.3, the model has been adapted by fixing the SMR core power to the rated value, while maintaining PERSEE’s cogeneration type 3 mode (Lavialle et al., 2024) to enable a variable distribution of this thermal power for power conversion or other purposes. As a result of this significant modification in the operational philosophy, which in turn leads to considerable differences in the optimal dispatch strategy, the results in terms of economic performance

<sup>2</sup>As part of an open source release, PERSEE that stood for “oPtimizER for System Energy management” was renamed to Cairn.

between this work and those presented in Deliverable 3.2 are not directly comparable, despite the same techno-economic parameters being used in the updated PERSEE models. The two optimisation models used in this study are shown in Figure 11 and Figure 12. Notably, the technologies that were discarded in the *run7* scenario, such as hydrogen production via steam methane reforming, were removed from the model.

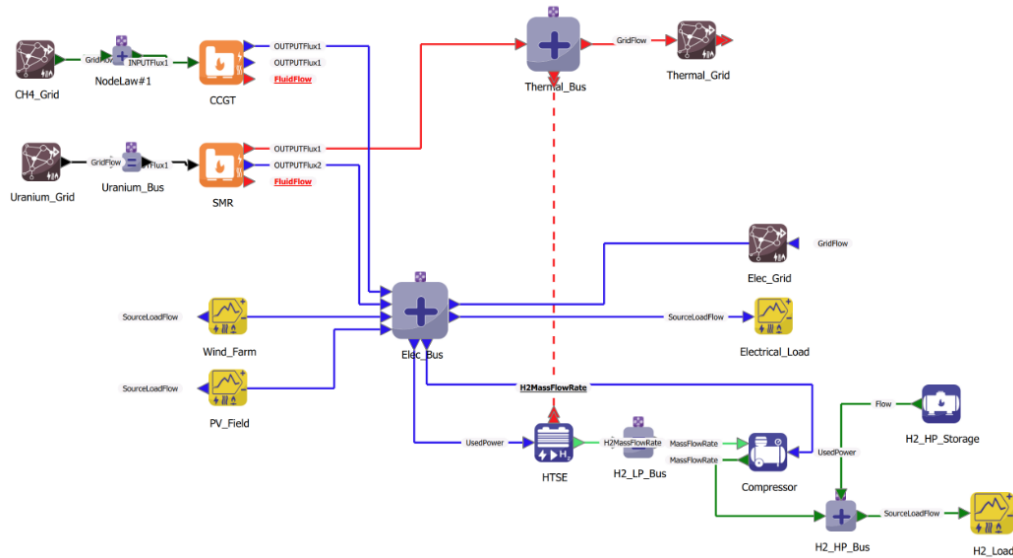


Figure 11. PERSEE model for the coupled energy hub architecture.

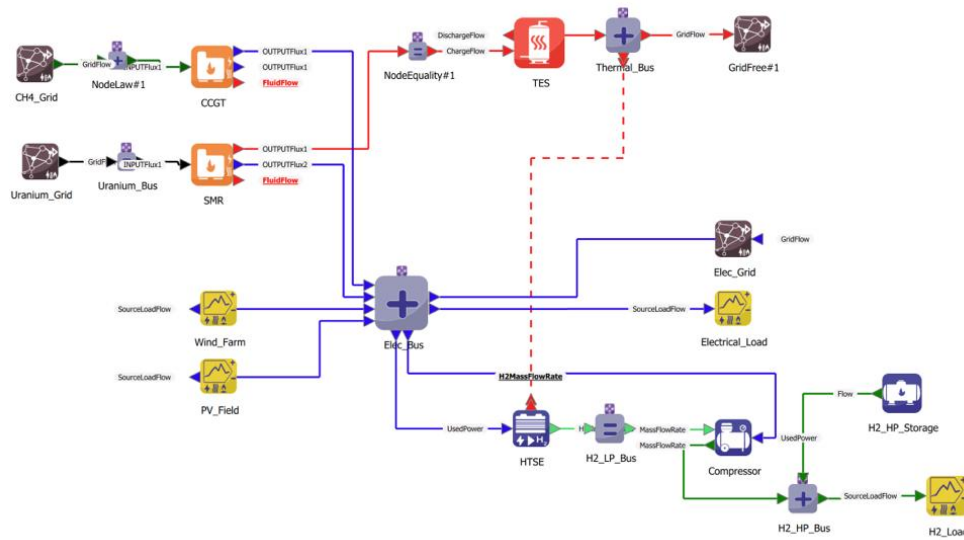


Figure 12. PERSEE model for the decoupled energy hub architecture.

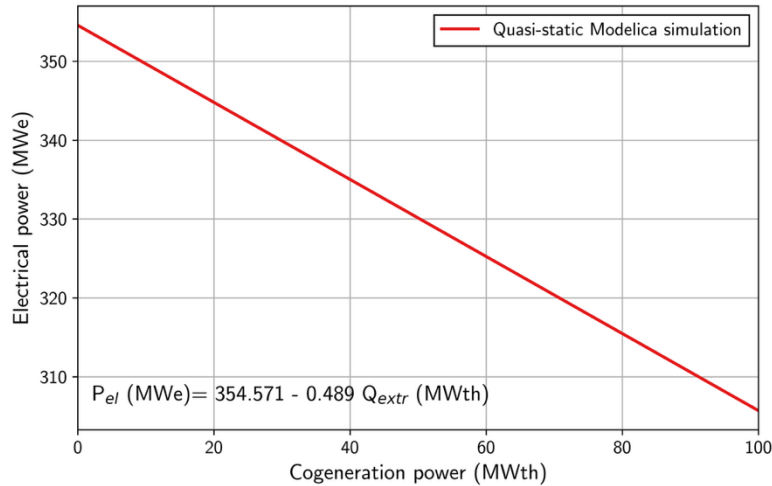
### 3.1.3 PEGASE

The co-simulation platform PEGASE has been developed by CEA since 2016 to analyse and optimise complex energy systems. It relies on co-simulation via the Functional Mockup Interface (FMI) standard and time sequencing, running FMI-compliant modules in a defined order. PERSEE, with its FMI wrapper, can be integrated into PEGASE to work alongside more detailed models, such as the dynamic simulators. In this work, the platform applies Model Predictive Control (MPC), using PERSEE's MILP optimiser to determine optimal setpoints for controlling the non-linear, dynamic system simulators. This setup enables the hard-coupling between the Modelica simulators and the PERSEE models, allowing dynamic aspects to be integrated in the optimisation phase.

## 3.2 Methodology

The first step performed for enabling the coupling between the optimisation tool and the dynamic simulator is to ensure that the operational parameters characterising the performances of the single components are consistent. In this regard, the performance map for the high-temperature steam extraction simulated in Modelica, shown in Figure 13, was used to calculate the parameters required to describe the type 3 cogeneration mode in PERSEE. It should be noted that there is a significantly higher degradation in power conversion efficiency in the case of steam extraction at the high-pressure turbine inlet rather than at its outlet, as it can be observed by comparing this performance map and the power loss factor with the one shown in Figure 3. Despite this drawback, the high temperature steam extraction point was selected due to the higher temperature requirements of the TES and the HTSE, which are higher than the district heating needs and can hardly be met via low temperature steam extraction. Notably, the parameters and variables exchanged between the codes (both in the soft-linked and hard-linked approach) are strongly dependent on the considered NHES architecture, both in terms of technologies integrated in the energy systems and their operational points, as illustrated by the different operational maps for the same reactor design in the Northern and Southern European cases.

In addition, the parameters characterising the HTSE performance, namely the electric efficiency and the specific thermal power consumption, were updated according to the feedback of the Modelica model.



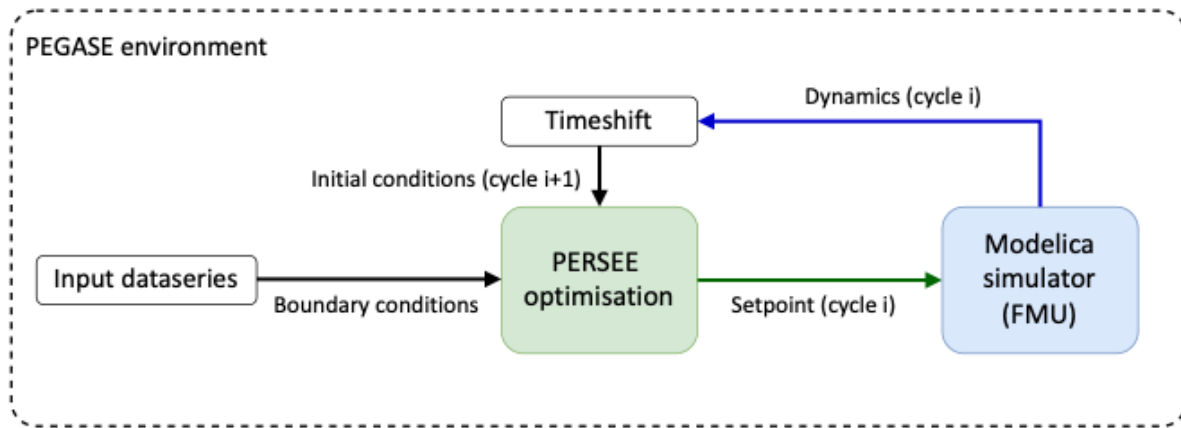
**Figure 13. Operational map showing the impact of high temperature steam extraction on the E-SMR electrical power output.**

After updating the parameters and the SMR component settings to enable a flexible heat extraction while maintaining a constant core power, the optimal capacities of the single components were determined through dedicated PERSEE optimisations. The resulting capacities were then included in the dynamic simulator, for instance by adjusting the number of HTSE modules to match the nominal capacity provided by PERSEE (Martos Nogales & Masotti, 2024).

As far as the dispatch optimisation of the power flows within the hybrid system is concerned, both soft-linked and hard-linked coupling approaches were considered for comparison. In the soft-linked approach, the setpoints derived from the stand-alone PERSEE optimisation are provided to the Modelica models through the dedicated inputs, checking that the proposed operational strategy can be met while maintaining the process variables within the allowed limits and, in general, verifying that the behaviour of the system is consistent with the one considered in the techno-economic optimisation. An equivalent analysis is presented in Deliverable 3.5 (Martos Nogales et al., 2025), where the profiles obtained from the PERSEE optimisation are compared with the dynamic responses of the system simulated in both Modelica and in ECOSIMPRO.

The optimisation of the energy hub case is also performed by adopting a hard-linking between the optimisation code and the dynamic model, leveraging the PEGASE co-simulation platform to optimise the dispatch strategy by relying on both tools. In this setup, an explicit coupling between the tools is adopted since the relatively long simulation horizon, in the order of days and weeks, and, consequently, the required time resolution, does not justify the need to increase the complexity of an implicit coupling with the tighter, iterative exchanges of variables between the tools. Figure 14 summarises how the integration between the tools is performed in the hard-

linked approach. The PERSEE optimisation, similarly to the stand-alone case, relies on external timeseries to define the boundary conditions of the system, such as renewable power availability, load demands, etc. (Laviolle et al., 2024). In the first step, the optimisation is performed and the setpoints required for the Modelica model are delivered to the dynamic simulator, encapsulated in a Functional Mock-up Unit (FMU). The dynamic simulation is then executed using these setpoints, and its output is explicitly used in the next optimisation cycle. As a matter of fact, each new optimisation cycle starts from the state of the system determined by the latest dynamic simulation rather than from the state predicted by the PERSEE simulation at the end of the former cycle.



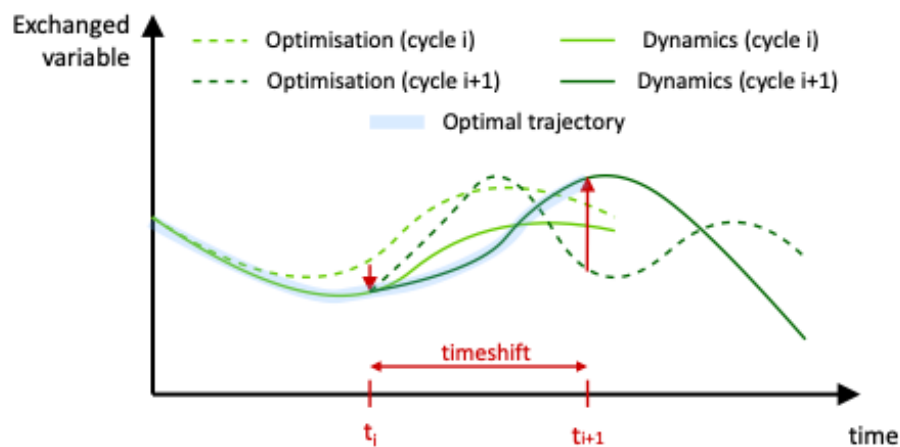
**Figure 14. Schematic summarising the hard-linked optimisation process.**

The variables exchanged between the two codes, i.e., the PERSEE setpoints required to drive the dynamic simulation and the variables describing the system’s state after the dynamic simulation, are listed in Table 1. The Modelica models require the hydrogen production target for the control of the HTSE unit (Simonini et al., 2024a), whereas the hydrogen load is used to estimate the SOC of the hydrogen storage system by integrating the difference between demand and production. In the decoupled configuration, where the TES separates the BOP and HTSE operation, the target electricity generation of the NPP also needs to be specified.

Layout	PERSEE setpoints	Dynamic feedback variables
Coupled architecture	H <sub>2</sub> production target H <sub>2</sub> load	H <sub>2</sub> storage SOC
Decoupled architecture	H <sub>2</sub> production target H <sub>2</sub> load NPP electricity production target	H <sub>2</sub> storage SOC TES SOC

**Table 1. Variables exchanged between PERSEE and Modelica in the hard-linked approach.**

A key element in this coupling approach is the timeshift parameter. As described in Figure 14, the Modelica output variables are processed by the PEGASE *Timeshift* module, which enables the repetition of the optimisation from a previous timestep, starting a new cycle given the system's state predicted by Modelica. Figure 15 depicts a schematic of how different cycles are interacting with each other and how the timeshift parameter influences the difference between the behaviour over time of the two tools. The schematic refers to the state variables delivered from Modelica to PERSEE (in this study, the SOCs). Generally speaking, the difference between the value considered in the PERSEE optimisations and that computed by Modelica tends to increase over time, due to the discrepancies resulting from the non-linearities captured in the latter tool. After a certain time, specified by the timeshift parameter, the PERSEE simulation provides a new set of optimal profiles for the follow-up cycle, restarting from the state predicted by Modelica rather than its estimate. This process is highlighted in red in Figure 15, where the arrows indicate that after an interval defined by the timeshift, the PERSEE initial conditions for the next optimisation cycle are imposed to coincide with the state given by Modelica. Finally, the trajectory determined by the Modelica simulations with the updated setpoints, highlighted in blue in Figure 15, represents the optimal operational strategy achieved with a more physically representative model of the NHES.



**Figure 15. Role of the timeshift parameter in the hard-linked approach.**

It is important to emphasise that, as will be demonstrated in the following sections, the consistency between the dynamic simulation and the MILP optimisation is strongly dependent on the timeshift parameter. As a matter of fact, this parameter is related to the frequency at which the variables between the two tools are exchanged: for lower timeshifts, the PERSEE optimisation is updated according to Modelica's feedback on the system's state more often, resulting in a closer alignment between the profile used in the PERSEE optimisation and the one

simulated in Modelica. These reduced discrepancies over time, thereby improving the physical representativeness of the resulting optimal dispatch strategy.

### 3.3 Results

Before delving into the dispatch optimisation results, the outcomes of the layout optimisation for the updated PERSEE models are reported in Table 2. As aforementioned, these results are not directly comparable to the *run7* case presented in Deliverable 3.2, since, as it can be observed in the SMR’s electrical and thermal power limits, a different operational strategy has been considered for this component. The optimised architectures for the coupled and decoupled energy hub configuration are largely similar, except for the components related to the hydrogen production plant (i.e., HTSE, compressor, and hydrogen storage system). In the decoupled case, the capacities of these components are reduced, thanks to the improved operational flexibility enabled by the decoupling function of the TES.

In the following sections, the dispatch optimisations in the soft-linked and hard-linked approaches are presented, adopting models with the component characteristics described in the table below.

Component	Variable	Coupled architecture	Decoupled architecture	<i>run7</i> setup
SMR	Number of units (-)	2	2	2
	Min-Max electrical power (MW <sub>e</sub> )	305-355	305-355	310-310
	Min-Max thermal power (MW <sub>th</sub> )	0-100	0-100	100-100
PV Field	Peak power (MW <sub>e</sub> )	200	200	196
Wind Farm	Number of units (9.5 MW <sub>e</sub> )	3	3	0
CCGT	Min-Max electrical power (MW <sub>e</sub> )	0-89	0-89	0-87
HTSE	Max electrical power (MW <sub>e</sub> )	372	368	350
H <sub>2</sub> Storage	Storage capacity (kg)	15187	15088	13840
TES	Storage capacity (MWh <sub>th</sub> )	NA	264	NA

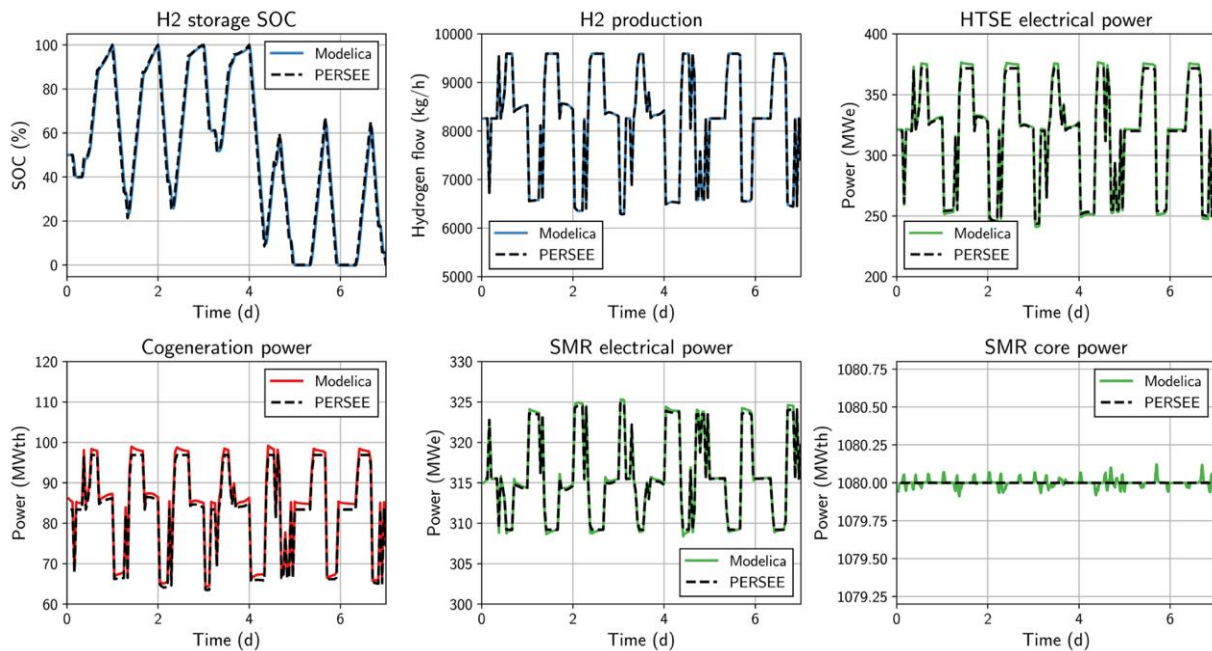
**Table 2. Layout optimisation results.**

### 3.3.1 Soft-linked optimisation

In the soft-linked approach, the optimal setpoints derived from a stand-alone PERSEE optimisation were fed into the dynamic simulator to verify the system’s behaviour in the proposed dispatch strategy. For illustrative purposes, the weekly simulation presented in Deliverable 3.5 (Martos Nogales et al., 2025) is proposed.

#### 3.3.1.1 Coupled hydrogen production

The simulation outcomes for the coupled energy hub architecture employing the soft-linked approach are presented in Figure 16. The Modelica simulation is consistent with the optimal profiles derived from the PERSEE optimisation, with only minimal discrepancies between the two tools. The power flows within the system are also in good agreement, although some deviations, especially for the thermal power flows, can be observed due to the non-linearities of the heat transfer processes. Moreover, as shown in the bottom right plot of Figure 16, the highly variable hydrogen production, and associated electricity production, are met causing minimal perturbations on the SMR primary loop.



**Figure 16. Soft-linked optimisation results for the coupled energy hub layout.**

### 3.3.1.2 Decoupled hydrogen production

The outcome is considerably different in the decoupled energy hub architecture. In this case, the NHES operation is driven not only by the hydrogen production target but also by electricity generation demand from the SMR. These setpoints have a direct impact on the TES operation, in particular on its SOC, as they are strongly related to the thermal power exchanged with the storage device during the charging and discharging phases. However, the exchanged thermal power is affected by the non-linearities, delays, and other dynamic effects of the BOP, TES, and HTSE models. These factors lead to a discrepancy between the power flows computed by Modelica and those assumed by PERSEE. Moreover, controlling directly the thermal power flows leads to a better agreement in terms of TES behaviour (and, consequently, to a different system's state and optimal trajectory), albeit with more remarkable differences in the electrical power generations, as demonstrated in Deliverable 3.5 (Martos Nogales et al., 2025). Figure 17 displays the results obtained with the soft-linked optimisation, and, despite the differences in terms of power flows appear to be minimal, the mismatch between the profiles leads to an increase in the TES SOC error over time, as it reflects the accumulation of errors throughout the simulation. The divergence between the PERSEE profile and the Modelica outcome ultimately results in a simulation failure before the end of the weekly transient, due to the complete draining of the hot tank, leading a non-physical conditions which the simulator is unable to process. This failure could be avoided by refining the TES controller to prevent discharging at low SOC levels, or, conversely, charging when the storage level exceeds a defined threshold. However, such an improvement to the dynamic model would not improve the consistency between the two codes.

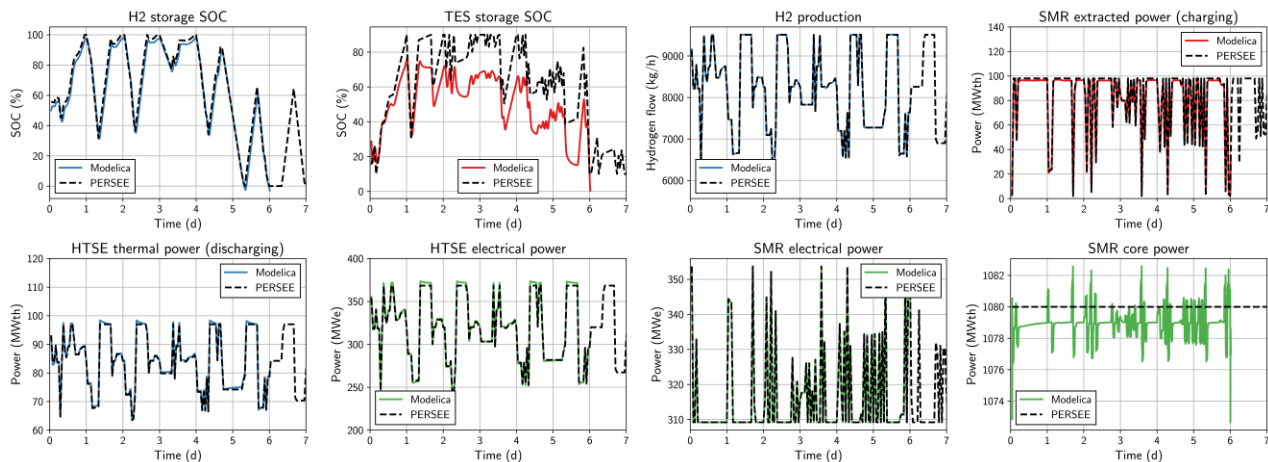


Figure 17. Soft-linked optimisation results for the decoupled energy hub layout.

This result highlights the need for a tighter interaction between the optimisation tool and the dynamic simulator in order to capture the strong interaction between thermally connected components, as well as the significant inertial effects associated with the TES decoupling function. In this regard, adopting a hard-linked optimisation approach could contribute to mitigating this issue, ensuring a better alignment between the two tools.

### 3.3.2 Hard-linked optimisation

The results obtained in the hard-linked optimisation approach are presented in this section. Both energy hub architectures were optimised with different simulation configurations, summarised in Table 3. The aim is to compare different tools-coupling strategies on different timescales, ranging from daily to yearly simulation horizons, as well as various levels of interaction, in order to assess their impact on the optimal operational strategy and the overall system performance.

Parameter	Daily	Weekly		Yearly
Length	3 days	1 week		1 year
Timestep	15 minutes	15 minutes		1 hour
Futuresize	24 hours	24 hours		24 hours
Timeshift	1 hour	12 hours	3 hours	6 hours

**Table 3. Simulation setups for the hard-linked optimisations.**

In addition to the previously described timeshift parameter, the *futuresize* also plays a fundamental role in the definition of the optimal dispatch strategy. Specifically, it determines the future time horizon which is assumed to be known to the optimiser. The variables assumed to be known in this horizon are those provided by the system’s boundary conditions, such as renewable energy potential and gas price evolution. In these cases, it is assumed to have a 24-hour future foresight. Although common optimisation setups assume to have perfect knowledge of the entire optimisation horizon, using larger futuresizes would be increasingly unrealistic since environmental and market conditions can only be forecasted with limited confidence over longer periods. For the yearly simulation, the optimisation timestep is increased from 15 minutes to 1 hour, allowing for a coarser time resolution compared to the other short-scale simulations.

#### 3.3.2.1 Coupled hydrogen production

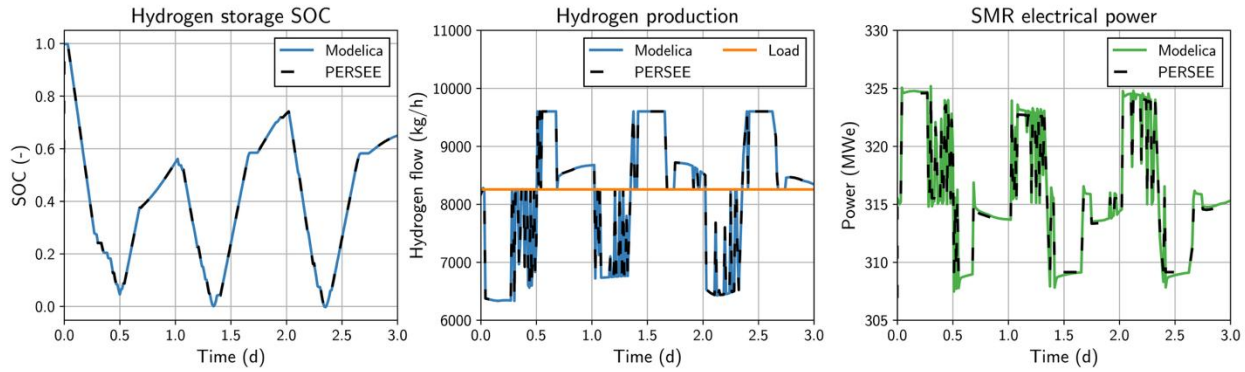
According to the outcomes of the soft-linked approach, it is reasonable to expect that also in the hard-linked case, the error between Modelica and PERSEE will be minimal in the coupled energy hub architecture. However, the simulation outcomes are included for the sake of completeness,

and with the goal of comparing the result with the stand-alone PERSEE optimisation given the different simulation setups (e.g., in terms of known future forecast).

#### Daily scale

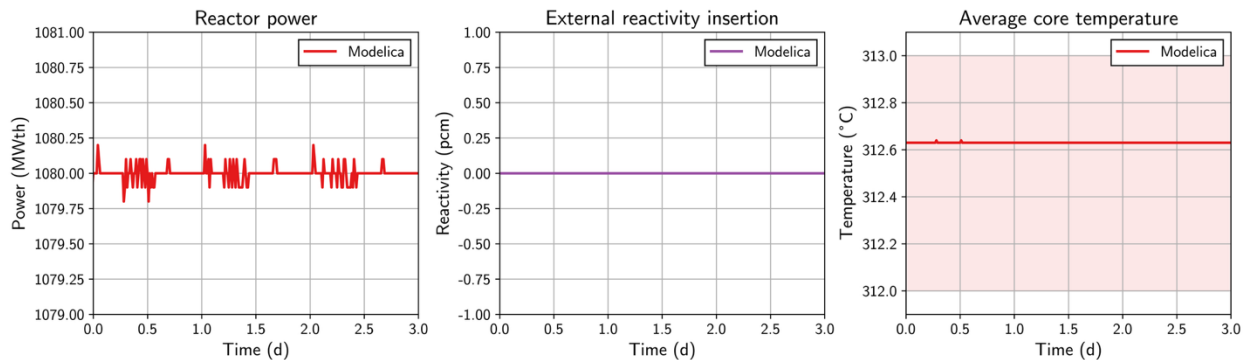
As anticipated in Table 3, the daily scale simulation setup spans over three days in length, with a number of optimisation cycles determined by the 1-hour timeshift. Figure 18 shows the optimal dispatch strategy estimated by the hard-linked optimisation, with the state variable exchanged between Modelica and PERSEE, i.e., the hydrogen storage SOC, remaining consistent throughout the whole simulation, as also observed in the soft-linked approach. The highly variable hydrogen production setpoint delivered from PERSEE to Modelica in each optimisation cycle is effectively met by the control system included in the dynamic simulator. As described in Section 3.3.1, the high variability in terms of hydrogen production translates into a fluctuating electricity generation due to the direct coupling between the steam cycle and the hydrogen production plant.

These oscillations are driven by the short timestep of the PERSEE optimisation, which leads to the computation of a new optimal hydrogen production target every 15 minutes, but also to the relatively short timeshift parameter, as it causes the start of a new optimisation cycle, which updates the setpoint delivered to the Modelica FMU, every hour. Given that similar oscillations were observed in the soft-linked simulation with a timestep of 1-hour, it can be concluded that the latter parameter is the dominant factor for the observed oscillations. In practical cases, such rapid and frequent variations on both the HTSE and the steam cycle can hardly be met due to technical constraints, e.g., thermo-mechanical stresses, that are not captured by the Modelica simulator. To address this limitation, the PERSEE model could be further refined by including additional constraints on ramping rate limits and the number of allowed ramps in a given interval, for instance. Moreover, such a short timestep would be representative of scenarios requiring rapid power adjustments; for instance, when exploring the use of the HTSE to support short-term load following. In an energy hub configuration, where industrial processes are the primary energy consumer, such rapid power variations may be less relevant. Generally speaking, the optimisation setup is strongly dependent on the type of application the user intends to study with the tools, which can range from short-term controllability analyses to long-term energy planning. As a result, both the timestep and the timeshift parameter should be adapted to reflect the temporal dynamics and resolution appropriate for the specific case. However, the goal of this report is to showcase the methodological strategy for performing a hard-linked optimisation by relying on multiple tools, and to compare the results obtained with different simulation parameters, rather than providing a realistic operational strategy applicable in real-world scenarios.



**Figure 18. Exchanged variables in the hard-linked daily optimisation of the coupled energy hub.**

One of the advantages of performing a hard-linked optimisation is the ability to simulate the behaviour of the most critical NHES components, such as the reactor’s primary loop, during the optimisation phase itself. For example, Figure 19 displays the response of several key variables of the SMR operation obtained in the hard-linked, daily-scale optimisation. It can be observed that the reactor power remains nearly constant at its rated value throughout the whole transient, despite the significant variability characterising the secondary side operation. The stable working conditions are further evidenced by the constant core average temperature, which remains always within the allowed limits and, as a result, does not trigger any external reactivity insertion.

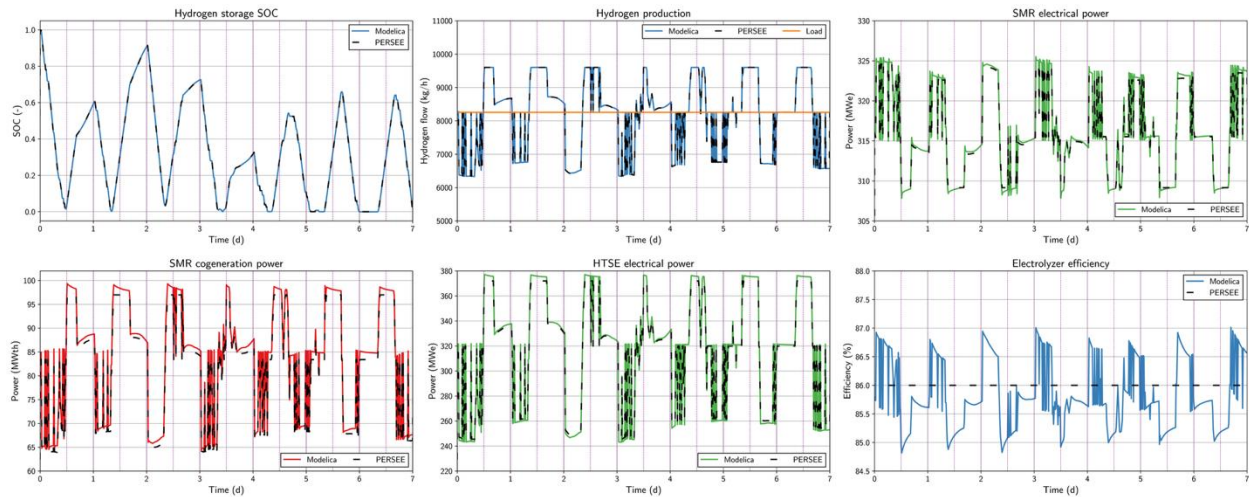


**Figure 19. Nuclear Steam Supply System (NSSS) variables in the hard-linked daily optimisation of the coupled energy hub.**

Weekly scale

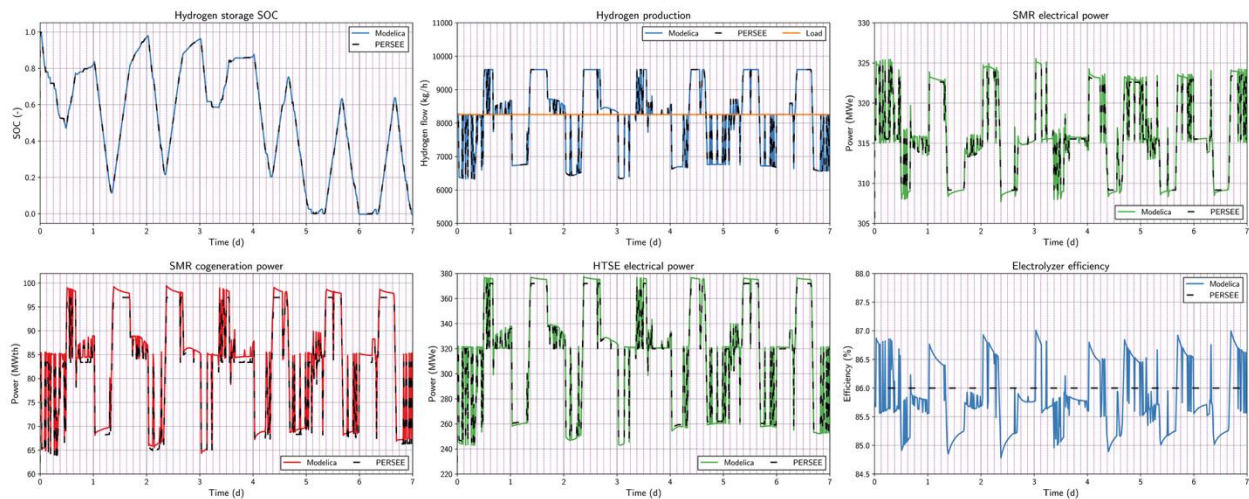
As far as the weekly simulation is concerned, the goal is to focus on the impact of the timesteps parameter in the simulation. Figure 20 and Figure 21 show to outcomes adopting a 12-hour timestep and a 3-hour timestep, respectively. This parameter determines the number of optimisation cycles that are performed within the same simulation horizon, whose starting point is identified by the vertical, purple lines in the plots. In correspondence of this time instance, a

new optimisation cycle in PERSEE is initiated using the feedback from the dynamic model for the starting conditions. Similarly to the daily simulation, also the weekly horizon is characterised by pronounced fluctuations in terms of power flows, especially in the 3-hour timeshift case where the optimisation is updated more frequently.



**Figure 20. Hard-linked optimisation of the coupled energy hub on a weekly scale with a 12-hour timeshift.**

For this energy hub architecture, differences in the operational strategy are not dictated by a modification of the cycle initialisation point following Modelica’s feedback, but rather by a different foresight of the future horizon, which is displaced according to the timeshift parameter. As a matter of fact, with the beginning of a new optimisation cycle, the same future horizon length is considered, but shifted forward considering the new cycle’s starting time. However, the overall dispatch strategy in the two hard-linked simulations and the PERSEE stand-alone optimisation are comparable, with an increase in hydrogen production when renewables production is high (which leads to an increase of hydrogen storage state) and a reduction during nights.

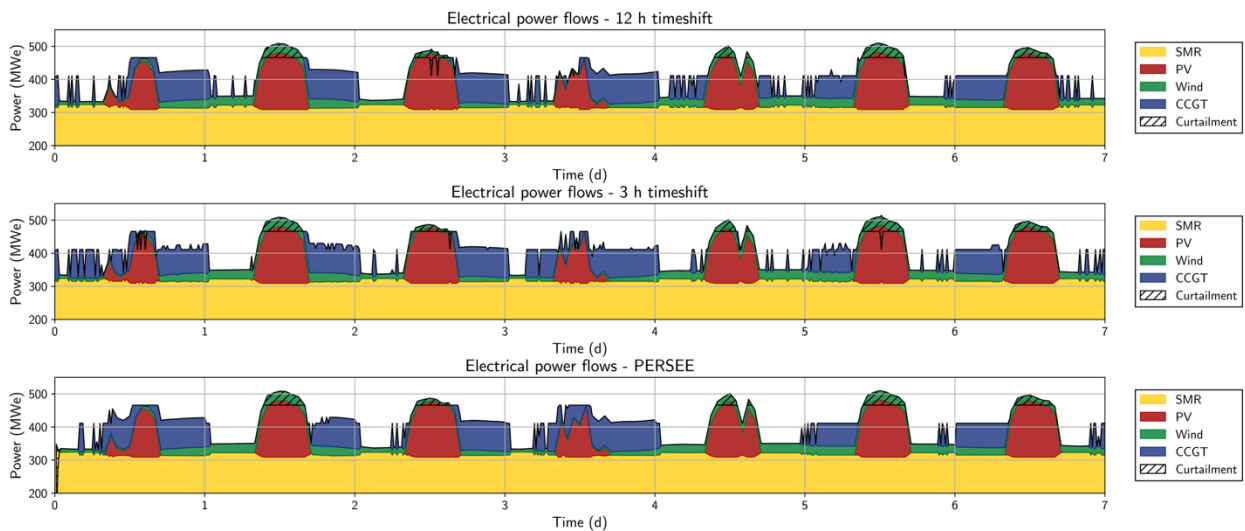


**Figure 21. Hard-linked optimisation of the coupled energy hub on a weekly scale with a 3-hour timeshift.**

A comparison between the techno-economic parameters, including the energy allocation within the NHES over the weekly simulation, is presented in Table 4. Overall, due to the good agreement between the PERSEE setpoints and the Modelica responses, the selected performance indicators differ only slightly. This statement is further supported by the similar operational strategies in the three cases, as shown in the previous figures and Figure 22. It is worth noting that Table 4 includes two additional indicators for the hard-linked setup, namely the H<sub>2</sub> injection and the net H<sub>2</sub>-SOC correction. The former represents the amount of hydrogen that is imported into the NHES to meet the demand in case the PERSEE optimisation fails to find a feasible solution in an optimisation cycle, whereas the net hydrogen storage SOC correction quantifies the variation in terms of hydrogen accumulated in the storage system. This variation is given by the discrepancies between the hydrogen storage SOC estimated by PERSEE at the end of each optimisation cycle and the SOC computed by the dynamic model, which is used as the starting point for the subsequent cycle. If this parameter is positive, it indicates that the PERSEE module tends to underestimate the charging of the storage device, resulting in the need to add the required amount of hydrogen to the storage system according to Modelica’s feedback. In the proposed weekly simulation, the PERSEE optimisation is able to find a solution in every optimisation cycle, without the need for external hydrogen imports. Moreover, given the nearly identical profiles for the variables computed in PERSEE and Modelica, the SOC correction remains of negligible magnitude, as indicated by the relative H<sub>2</sub>-SOC correction computed as the ratio between the net H<sub>2</sub>-SOC correction and the total storage capacity.

Variable	Unit	12 h timeshift	3 h timeshift	Soft-linked
HTSE electrical energy	GWh <sub>el</sub>	53.18	53.15	53.04
CCGT electrical energy	GWh <sub>el</sub>	5.79	5.8	5.66
SMR electrical energy	GWh <sub>el</sub>	53.08	53.08	53.09
Curtailed electrical energy	GWh <sub>el</sub>	0.74	0.76	0.79
H <sub>2</sub> injection	tons	0	0	0
Net H <sub>2</sub> -SOC correction	tons	-0.04	-0.04	NA
Relative H <sub>2</sub> -SOC correction	-	-0.003	-0.003	NA
Total emissions	ktons	2.93	2.93	2.86
Undiscounted Net OPEX	m€	1.36	1.35	1.34

**Table 4. Comparison of techno-economic variables in the weekly optimisation of the coupled energy hub.**



**Figure 22. Comparison of the optimal dispatch strategy between hard-linked optimisations and stand-alone PERSEE simulation for the coupled energy hub.**

Yearly scale

The techno-economic parameters exhibit some differences in the yearly optimisation of the coupled architectures, as illustrated in Table 5. In particular, the PERSEE optimisation finds a feasible solution only by importing approximately 22 tons of hydrogen. However, this contribution is not accounted for in the computation of the SOC in the dynamic simulation of the NHES, meaning that the hydrogen injection is compensated in the subsequent optimisation cycle by removing the corresponding amount of hydrogen from the storage system. As a result, the SOC correction tends to offset the hydrogen imports. Nonetheless, this mismatch in terms of produced and accumulated hydrogen has a minor impact on the overall results, representing only 0.03% of the total hydrogen supply over the yearly simulation.

Comparing the operational costs – and, consequently, the total costs as the capital expenditures are identical in hard-linked and stand-alone simulations – it is observed that the costs are slightly higher in the hard-linked optimisation. This difference is driven both by variations in system state at the beginning of each optimisation cycle due to Modelica’s feedback, which can result in a sub-optimal trajectory compared to the previous cycle, as well as by the different forecast capability. Specifically, the perfect knowledge of the optimisation horizon that is assumed in the stand-alone PERSEE optimisation leads to a more efficient utilisation of the resources, reducing the reliance on the CCGT unit and the curtailed energy compared to the hard-linked optimisation.

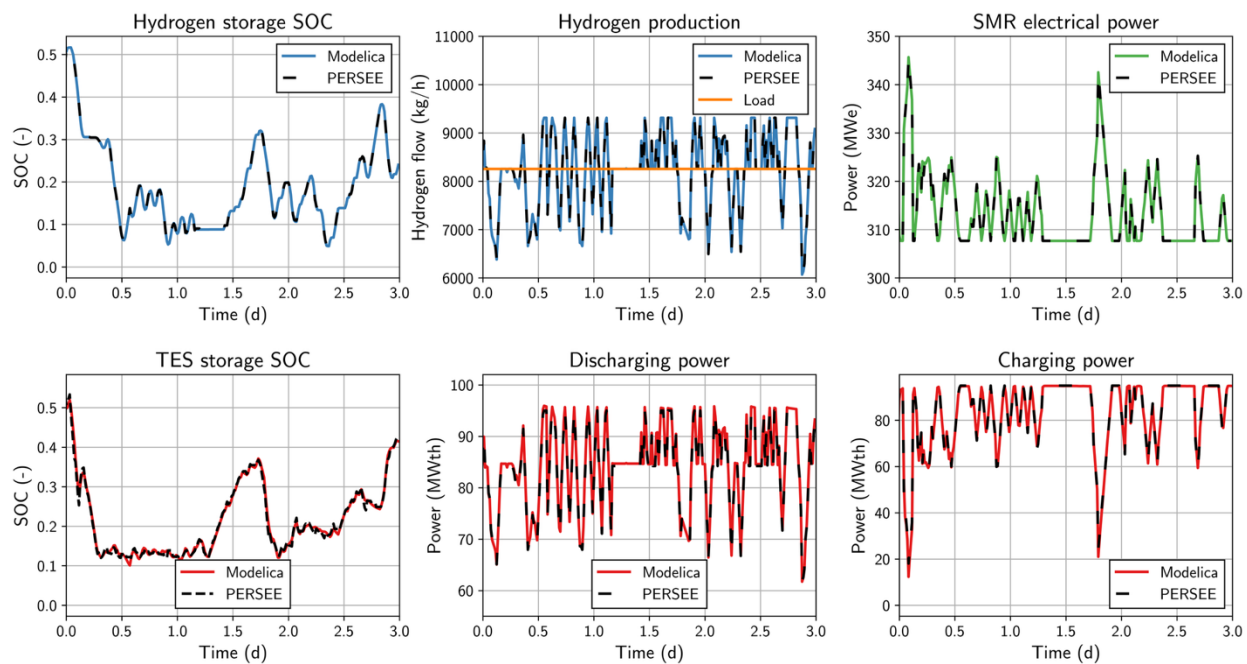
Variable	Unit	Hard-linked	Soft-linked
HTSE electrical energy	GWh <sub>el</sub>	2802	2802
CCGT electrical energy	GWh <sub>el</sub>	385	339
SMR electrical energy	GWh <sub>el</sub>	2764	2764
Curtailed electrical energy	GWh <sub>el</sub>	65	18
H <sub>2</sub> injection	tons	21.89	0
Net H <sub>2</sub> -SOC correction	tons	-22.65	NA
Relative H <sub>2</sub> -SOC correction	-	-1.49	NA
Discounted emissions	ktons	3765	3343
Discounted Net OPEX	bm€	1.06	1.04
Total costs	bm€	3.69	3.67

**Table 5. Comparison of techno-economic variables in the yearly optimisation of the coupled energy hub.**

### 3.3.2.2 Decoupled hydrogen production

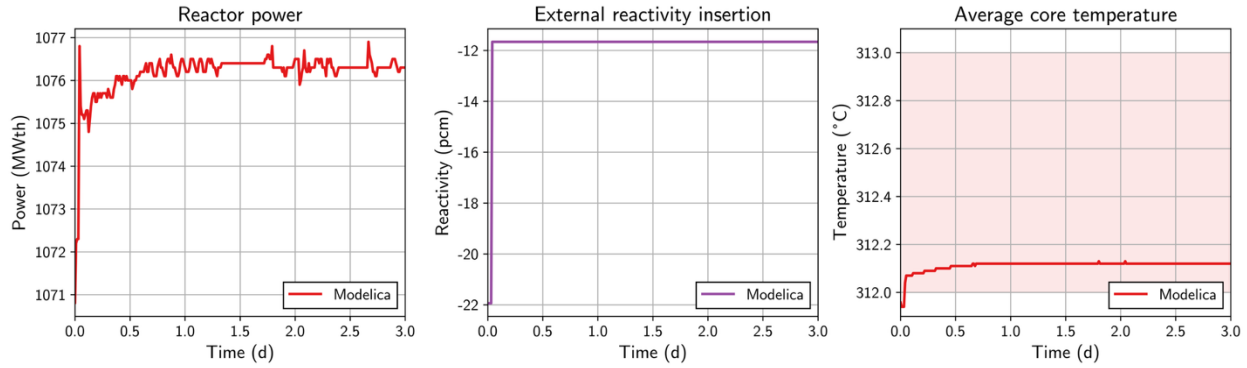
#### Daily scale

The same simulation setups were adopted to perform the hard-linked optimisations for the decoupled energy hub architecture. Figure 23 shows the results for the daily-scale simulation. In this case, it can be seen that the hydrogen production is independent of the SMR electricity generation, which is controlled to meet the PERSEE setpoint by adjusting the TES charging power. Notably, it can be observed how the hydrogen production profile is proportional to the TES discharging power, whereas the SMR electrical power is inversely correlated to the TES charging power. In contrast to the results obtained with the soft-linked optimisation, the TES SOC resulting from the two codes shows a fair agreement. This consistency can be attributed to the 1-hour timeshift parameter, which leads to a high number of optimisation cycles starting from the SOC values provided by Modelica.



**Figure 23. Exchanged variables in the hard-linked daily optimisation of the decoupled energy hub.**

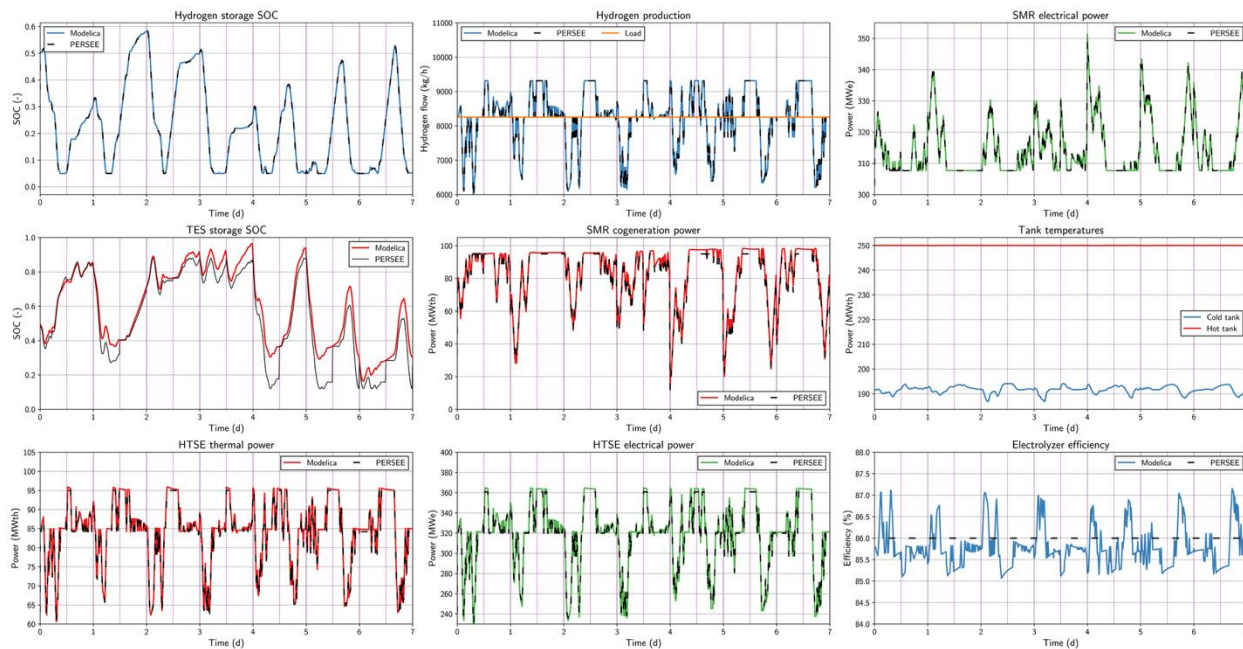
The impact of the proposed optimal dispatch strategy on the SMR operation is displayed in Figure 24. At the beginning of the simulation, a power transient triggered by external reactivity insertion at the beginning of the simulation occurs, arising from the stabilisation of the dynamic model at the SMR electricity generation setpoint provided by PERSEE. This behaviour stems primarily from the different initial states assumed the two tools. Following this initial power excursion, the core power remains stable at approximately its nominal value throughout the remainder of the transient simulation.



**Figure 24. NSS variables in the hard-linked daily optimisation of the decoupled energy hub.**

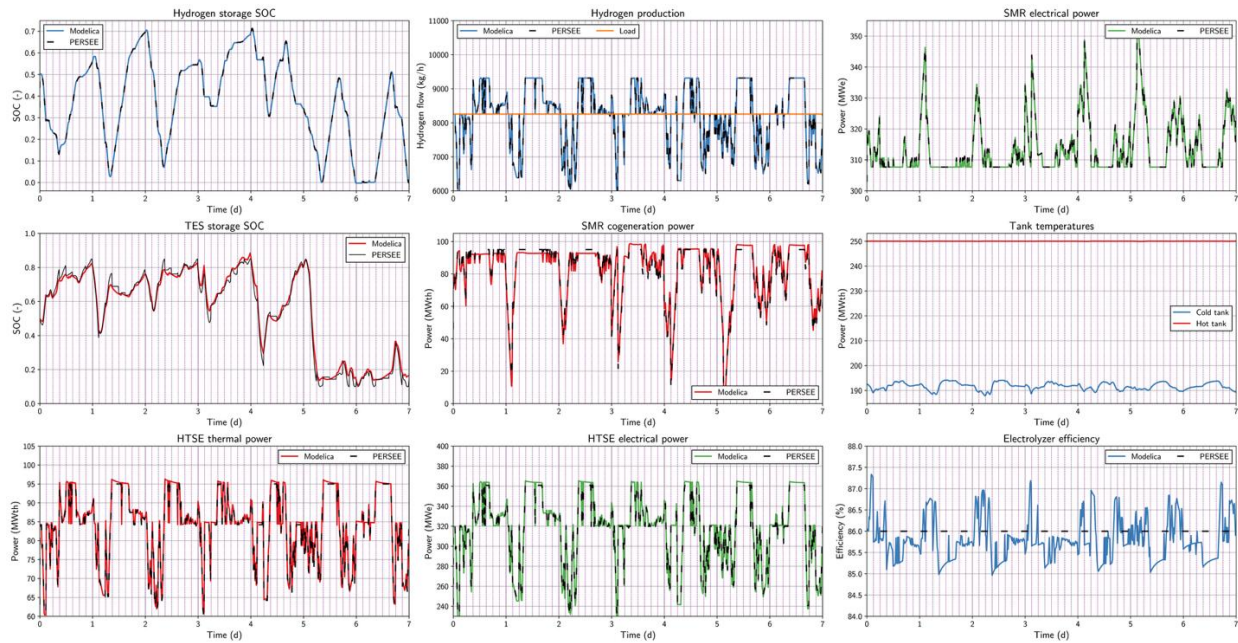
Weekly scale

As in the case of the coupled architecture, also in this configuration, two different setups for the weekly simulation are compared, adopting 12-hour and 3-hour timeshifts to assess the impact of this parameter on the optimal profiles. In the simulation outcomes for the 12-hour timeshift case, shown in Figure 25, it is evident how the initial state of each optimisation cycle is updated according to the feedback of the dynamic simulator: referring to the TES SOC trajectories, the PERSEE optimisation, represented by the black line, tends to underestimate the SOC. As a result, every 12 hours, due to the selected timeshift parameter, the SOC in the PERSEE case is forced to coincide with the Modelica output, starting the next optimisation cycle with a higher amount of thermal energy accumulated in the TES compared to the end of the previous cycle. An estimation of the amount of heat added to the system in this process is available in Table 6, with about 290 MWh<sub>th</sub> (equivalent to more than a full charging cycle, as evidenced in the relative TES SOC correction) introduced in the PERSEE optimisation. As discussed further in the next section, this additional thermal energy, which does not entail any associated costs, leads to a reduction in the operational costs of the overall system.



**Figure 25. Hard-linked optimisation of the decoupled energy hub on a weekly scale with a 12-hour timeshift.**

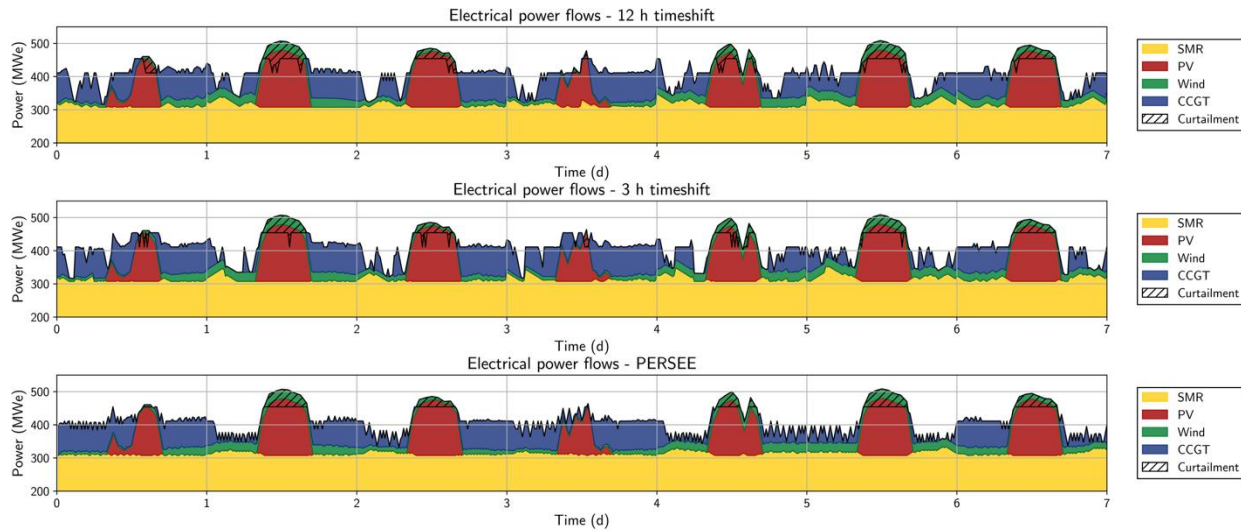
Comparing the 12-hour timeshift weekly simulation with the 3-hour timeshift case, shown in Figure 26 and Figure 27, the consistency between the Modelica outcomes and the optimal profiles used in the PERSEE optimisation is considerably improved. This aspect is particularly well visible when comparing the TES SOC profiles, with the trajectories in the 3 hours almost overlapping. The fair agreement is primarily driven by the shorter timeshift parameter, which increases the number of cycles within the same simulation horizon, thereby increasing the frequency at which the system’s state within the PERSEE optimisation is updated according to Modelica’s feedback. Another factor confirming the improved consistency is the net TES SOC correction needed in the 3-hour timeshift case, which is less than half of the one estimated in the 12-hour case. However, it should be highlighted that the better physical representativeness of the 3-hour timeshift hard-linked optimisation comes at a higher computational burden, as it required 2.4 hours CPU-time versus the 1.6 hours for the 12-hour timeshift simulation and the 2.89 seconds required for the PERSEE stand-alone optimisation. It should be noted that, in both cases, each optimisation cycle exhibits a considerable variability in simulation time, depending on the setpoints provided to the dynamic model. As a result, the increase in computational time could be related to the differences in optimal dispatch strategy rather than the simulation setups.



**Figure 26. Hard-linked optimisation of the decoupled energy hub on a weekly scale with a 3-hour timeshift.**

Variable	Unit	12 h timeshift	3 h timeshift	Soft-linked
HTSE electrical energy	GWh <sub>el</sub>	53.48	53.45	53.36
CCGT electrical energy	GWh <sub>el</sub>	6.99	6.87	6.63
SMR electrical energy	GWh <sub>el</sub>	52.81	52.74	52.68
Curtailed electrical energy	GWh <sub>el</sub>	1.34	1.19	1.02
TES charging energy	GWh <sub>th</sub>	13.69	13.83	13.95
TES discharging energy	GWh <sub>th</sub>	14.08	14.09	14.05
H <sub>2</sub> injection	tons	0	0	0
Net TES-SOC correction	GWh <sub>th</sub>	0.29	0.14	NA
Relative TES-SOC correction	-	1.09	0.53	NA
Net H <sub>2</sub> -SOC correction	tons	-0.03	-0.01	NA
Relative H <sub>2</sub> -SOC correction	-	-0.002	-0.0007	NA
Undiscounted emissions	ktons	3.5	3.4	3.3
Undiscounted Net OPEX	m€	1.39	1.4	1.4

**Table 6. Comparison of techno-economic variables in the weekly optimisation of the decoupled energy hub.**



**Figure 27. Comparison of the optimal dispatch strategy between hard-linked optimisations and stand-alone PERSEE simulation for the decoupled energy hub.**

Yearly scale

As far as the yearly simulation is concerned, a similar behaviour is observed, with the total costs in the hard-linked case being lower compared to the PERSEE stand-alone optimisation. This difference is mainly driven by how the operational costs for the SMR are calculated: in PERSEE’s cogeneration unit model, variable costs refer to the extracted thermal power rather than the total reactor power or the electrical power output. In the hard-linking approach, the PERSEE simulation tends to underestimate the TES SOC and thermal energy is added to the system “for free” to re-establish the coincidence with the Modelica model. Consequently, the thermal power delivered from the SMR to the TES is significantly lower compared to the stand-alone PERSEE optimisation, with the difference inserted into the system when starting a new optimisation cycle. Due to this underestimation of the cogeneration power, a corresponding underestimation of the SMR operational costs occurs, explaining the operational costs difference presented in Table 7. As a result, it should be noted that these optimisation results do not reflect the actual economic performance of the proposed dispatch strategy, since the optimal profiles describing the system’s operation are those defined by the dynamic simulator rather than those adopted in PERSEE to maximise the techno-economic competitiveness. Therefore, it would be more realistic to compute the operational costs and revenues according to the profiles obtained from the simulator. However, this economic assessment, which could be integrated into the co-simulation environment or performed a posteriori in future studies, would not be accounted for in the objective function (i.e., the NPV) optimised by PERSEE, which will rely exclusively on the optimal profiles generated by the MILP tool. Table 5

Variable	Unit	Hard-linked	Soft-linked
HTSE electrical energy	GWh <sub>el</sub>	2802	2802
CCGT electrical energy	GWh <sub>el</sub>	398	371
SMR electrical energy	GWh <sub>el</sub>	2754	2742
Curtailed electrical energy	GWh <sub>el</sub>	68	28
TES charging energy	GWh <sub>th</sub>	713	738
TES discharging energy	GWh <sub>th</sub>	738	738
H <sub>2</sub> injection	tons	18.4	0
Net TES-SOC correction	GWh <sub>th</sub>	25	NA
Relative TES-SOC correction	-	95	NA
Net H <sub>2</sub> -SOC correction	tons	-20	NA
Relative H <sub>2</sub> -SOC correction	-	-1.3	NA
Discounted emissions	ktons	4064	3820
Discounted Net OPEX	bm€	1.05	1.07
Total costs	bm€	3.668	3.689

**Table 7. Comparison of techno-economic variables in the yearly optimisation of the decoupled energy hub.**

As also observed in the yearly optimisation of the coupled architecture, the hard-linked simulation finds a less efficient solution in terms of resource utilisation, as evidenced by the significantly higher CCGT reliance, leading to higher greenhouse gas emissions over the optimisation horizon, as well as greater electric power curtailment. Moreover, as reported in the simulation results in Table 7, a relatively negligible amount of hydrogen is imported to ensure the optimiser finds a feasible solution, and a comparable quantity is removed at the beginning of new optimisation cycles to be consistent with the hydrogen storage SOC predicted by Modelica. As far as the required computational resources are concerned, the length of the simulation horizon, together with the relatively small timeshift needed to ensure a fair agreement between the PERSEE and Modelica profiles, leads to a substantially longer computational time, namely 2.4 days of CPU time compared to the 103 seconds required by PERSEE.

## 4 Conclusions

The present deliverable summarises the activities performed in Task 3.3 of the TANDEM project, which aims at verifying that the results from techno-economic studies are applicable over short time scales. Specifically, this work investigates the methodological framework for coupling optimisation tools with a more physically representative model of hybrid energy system architectures, developed in the object-oriented modelling language Modelica. The goal is to assess the impact of different coupling strategies on the optimal dispatch strategy of the integrated system, rather than to provide accurate estimates on the economic performance, which will be strongly dependent on the underlying techno-economic assumptions. Two coupling strategies between the tools were investigated, namely the soft-linking and the hard-linking approaches. In the soft-linking approach, the parameter in the optimisation tool were updated to be consistent with the dynamic simulator and the feasibility of the optimal dispatch strategy is verified a posteriori by running the resulting optimal setpoints in the dynamic model, with the aim of checking whether the proposed operational strategy can be met without violating the operational constraints of any NHES component. In contrast, in the hard-linking approach, the dynamics of the system are incorporated directly in the optimisation process, updating the optimal dispatch strategy according to the dynamic model's feedback at a user-defined recurrence.

The two approaches were tested on two case studies of illustrative NHES architectures defined within the framework of the TANDEM project: the Northern European Case and the Southern European Case. For the latter, two energy hub configurations with different operational characteristics were considered. In general, the results highlighted that the dynamics of thermal power flows within the system can play a crucial role in the definition of its operation. Comparing the soft-linking approach in the two case studies, a good agreement between the optimisation tool Backbone and the dynamic simulator was achieved in the district heating case, whereas significant inconsistencies emerged in the energy hub case. These discrepancies primarily stem from the selected control logic: in the district heating case, the thermal power flows are directly governed by the setpoints derived from the optimiser, ensuring a good agreement between the profiles of the two tools. In contrast, the energy hub operation is driven by the hydrogen production setpoint and, in the decoupled energy hub configuration, also by the electrical power setpoint. As a result, the thermal power flows will be indirectly determined from these variables, incorporating also the dynamic aspects of the system that are generally not accounted for in a MILP optimisation model. In particular, in the decoupled energy hub configuration, the thermal energy storage operation features strong non-linearities (e.g., due to the high thermal inertia of the tanks, delays in the transmission lines separating the TES from the steam cycle and the hydrogen production plant, heat transfer phenomena etc.) during both charging and discharging

phases. A notable improvement in terms of consistency between the optimiser and the dynamic model was achieved by hard-linking the two tools in the co-simulation platform PEGASE. In particular, through the soft-linking approach, the proposed optimal dispatch strategy proved to be infeasible a few simulation days, due to violations of operational constraints observed in the dynamic simulation. Conversely, using the hard-linked approach, it was possible to perform a yearly optimisation successfully, with the dynamic feedback refining the dispatch strategy. In the latter approach, a key factor to reduce the discrepancies between the optimised profiles and the dynamic simulator output proved to be the timeshift parameter, as it allowed to increase the frequency at which the optimised setpoints are updated according for the more physically representative system state provided by Modelica, albeit at a higher computational cost. As a matter of fact, the computational burden proved to be the main limitation of the hard-linked approach, as the simulation of the dynamic model in each optimisation cycle significantly increased the total runtime. As a result, the hard-linking approach proved to be a valuable technique for the definition of the optimal dispatch strategy on a rather short scale, i.e., daily or weekly horizons, rather than for the estimation of the global techno-economic performance of the NHES on a yearly basis, where stand-alone optimisation could offer a coherent assessment at substantially lower computational cost.

The activities carried out in Task 3.3 highlighted several limitations of the hard-linked approach that should be addressed in future work. In particular, the oscillations observed in the optimal profiles for the energy hub case are unlikely to be feasible in real-world applications due to technical constraints, such as thermo-mechanical stresses, which are not captured by the dynamic simulator. To address this, it might be worth including them through additional constraints to the MILP optimiser. These oscillations, arising also in stand-alone PERSEE optimisations, are only partially attributable to the coupling itself, which may introduce discontinuities at the beginning of each iteration with Modelica. In future work, the coupling scheme could be improved to avoid such discontinuities, for example by imposing ramping constraints not only within each optimisation horizon, but also when transitioning from one optimisation cycle to the next. In addition, the optimiser could be further refined to account for phenomena that can be represented by the linear modelling domain, such as transmission delays, to improve the consistency with the dynamic model, even in the soft-linked approach. Moreover, the techno-economic performances of the system are currently evaluated by means of the profiles derived from the optimisation rather than the actual trajectories given by the dynamic simulator. The former profiles are less physically representative, as energy products (e.g., thermal energy and hydrogen) are artificially inserted or extracted from the system “cost-free” to force the optimiser state to coincide with the one provided by Modelica. Therefore, using the trajectories of the dynamic model for the assessment of techno-economic indicators would provide more realistic and reliable results. However, this estimation remains a posteriori, as the

optimisation process itself is still based on the linear modelling domain. The analysis could be extended to other hybrid system architectures and to more detailed dynamic simulators in order to improve the applicability of the results. It may be worthwhile exploring also alternative operational strategies for the architectures considered in this work, e.g., allowing the flexible operation of the reactor, to assess their impact on both the technical and economic performance of the system. Moreover, the Northern European case study analysis should be improved and extended in future research activities, improving the representativeness of the dynamic simulator, assessing the impact of the additional constraints on the techno-economic optimisation results, and increasing the degree of interaction between the two tools.

Overall, the hard-linking approach proved to be a valuable technique to incorporate the dynamics of the system directly within the optimisation phase, enhancing the physical representativeness of the resulting dispatch strategy and contributing to the definition of the potential role of nuclear hybrid energy systems in different scenarios.

## Bibliography

- Casella, F., & Leva, A. (2006). Modelling of thermo-hydraulic power generation processes using Modelica. *Mathematical and Computer Modelling of Dynamical Systems*, 12(1), 19–33. <https://doi.org/10.1080/13873950500071082>
- El Hefni, B., & Bouskela, D. (2019). *Modeling and Simulation of Thermal Power Plants with ThermoSysPro: A Theoretical Introduction and a Practical Guide*. Springer International Publishing. <https://doi.org/10.1007/978-3-030-05105-1>
- Helistö, N., Kiviluoma, J., Ikäheimo, J., Rasku, T., Rinne, E., O'Dwyer, C., Li, R., & Flynn, D. (2019). Backbone—An Adaptable Energy Systems Modelling Framework. *Energies*, 12(17), 3388. <https://doi.org/10.3390/en12173388>
- Ikonen, J.-P., Lindroos, T. J., Crevon, S., & Lavalie, G. (2024). *D3.3 – Sensitivity of the hybrid system techno-economic analysis to uncertain key parameters*. TANDEM Project.
- Jenkins, J. D., Zhou, Z., Ponciroli, R., Vilim, R. B., Ganda, F., de Sisternes, F., & Botterud, A. (2018). The benefits of nuclear flexibility in power system operations with renewable energy. *Applied Energy*, 222, 872–884. <https://doi.org/10.1016/j.apenergy.2018.03.002>
- Kiviluoma, J., Rinne, E., Rasku, T., & Helistö, N. (2018). *Backbone—An Adaptable Energy System Model—GitLab Repository*. 2018. <https://gitlab.vtt.fi/backbone/backbone>
- Lavalie, G., Crevon, S., Ikonen, J.-P., Lindroos, T., Zezula, L., & Vobr, F. (2024). *D3.2—Presentation of dynamic techno-economic analysis for each case study*. TANDEM Project.
- Lindroos, T. J., & Pursiheimo, E. (2022). *Helsinki DHC model – GitLab repository*. <https://gitlab.vtt.fi/backbone/models/helsinki-dhc-model>

- Martos Nogales, C., Crevon, S., & Masotti, G. C. (2025). *D3.5—Cross-comparison of simulation results between PERSEE, the Modelica simulator and ECOSIMPRO for the energy hub configuration*. TANDEM Project.
- Martos Nogales, C., & Masotti, G. C. (2024). *D2.5 – Hybrid System Simulator Description*. TANDEM Project.
- Pursiheimo, E., Lindroos, T. J., Sundell, D., Rämä, M., & Tulkki, V. (2022). Optimal investment analysis for heat pumps and nuclear heat in decarbonised Helsinki metropolitan district heating system. *Energy Storage and Saving*, 1(2), 80–92. <https://doi.org/10.1016/j.enss.2022.03.001>
- Ruby, A., Parmentier, P., Crevon, S., Gaoua, Y., Piguet, A., Wissocq, T., Leoncini, G., & Laviolle, G. (2024). *PERSEE, a single tool for various optimizations of multi-carrier energy system sizing and operation*. ECOS 2024 - 37th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Rhodes, Greece.
- Simonini, G., Ferrara, V., Hammadi, Y., Hocine-Rastic, S., Lorenzi, S., Masotti, G. C., Alpy, N., Haubensack, D., Mathonniere, S., Talpin, R., Baudoux, A., Jouret, D., Pappalardo, F., & Tourneur, B. (2024a). *D2.3—Modelica models description for the ‘TANDEM’ library*. TANDEM Project.
- Simonini, G., Ferrara, V., Hammadi, Y., Hocine-Rastic, S., Lorenzi, S., Masotti, G. C., Alpy, N., Haubensack, D., Mathonniere, S., Talpin, R., Baudoux, A., Jouret, D., Pappalardo, F., & Tourneur, B. (2024b). *TANDEM Modelica library—GitLab Repository*. <https://gitlab.pam-retd.fr/tandem/tandem>
- Värri, K., Kovalainen, J., Rantakaulio, A., & Schneidesch, C. (2023). *D1.4—Description of selected study cases for safety, techno-economic analysis and optimisation*. TANDEM Project.