System-driven design of flexible nuclear power plant configurations with thermal energy storage

Marko Aunedi[*]
Department of Electrical and Electronic Engineering
Imperial College London, United Kingdom
e-mail: m.aunedi@imperial.ac.uk

Abdullah A. Al Kindi
Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering
Imperial College London, United Kingdom
e-mail: a.al-kindi18@imperial.ac.uk

Antonio M. Pantaleo
Department of Chemical Engineering, Imperial College London, United Kingdom
Department of Agro-Environmental Sciences, University of Bari, Italy
e-mail: a.pantaleo@imperial.ac.uk

Christos N. Markides
Clean Energy Processes (CEP) Laboratory, Department of Chemical Engineering
Imperial College London, United Kingdom
e-mail: c.markides@imperial.ac.uk

Goran Strbac
Department of Electrical and Electronic Engineering
Imperial College London, United Kingdom
e-mail: g.strbac@imperial.ac.uk

ABSTRACT

Nuclear power plants are expected to make an important contribution to the decarbonisation of electricity supply, together with variable renewable generation. Previous work by the authors identified significant potential benefits of coupling nuclear reactors with thermal energy storage (TES) and secondary power generation cycle systems to improve the plant operational flexibility. This paper presents a system modelling approach to identifying configurations of flexible nuclear plants that minimise the investment and operation cost in a decarbonised energy system, effectively proposing a system-driven design of flexible nuclear technology. Case studies presented in the paper explore the impact of system features on plant configuration choices. The results suggest that cost-efficient flexible nuclear configurations should adapt to the system they are located in. In the main low-carbon and net-zero carbon scenarios and for a standard-size nuclear unit, it was found to be cost-efficient to install around 500 MW_{el} of secondary generation capacity and 4.5 GWh_{th} of TES capacity, resulting in an equivalent TES duration of 2.2 hours. Enhancing the nuclear plant flexibility was found to be less attractive when applied to a large number of nuclear units or when exposed to high interest rates, but more attractive if battery storage cost was higher or there was no option to invest in carbon offsetting technologies. Net system benefits per unit of flexible nuclear generation for the main scenarios were quantified at £29-33m/yr for a wind-dominated system and £19-20m/yr for a solar-dominated system.

KEYWORDS

Nuclear power, power system flexibility, flexible nuclear, system-driven design, thermal energy storage.

[*] Corresponding author

INTRODUCTION

Over the past two decades, there have been significant global efforts to achieve the ambitious energy decarbonisation targets by expanding low- or zero-emission energy sources such as renewables and nuclear energy. Nuclear power plays an important role in achieving these targets, not only by reducing the emissions but also by being a reliable and non-intermittent source of power compared to renewable sources such as wind and solar [1]. However, nuclear power is still not very economically attractive due to its high capital costs compared to lower-cost renewable options, long construction times, and limited load following capabilities.

Nevertheless, nuclear power will be essential for ensuring energy security in electricity systems with high shares of variable renewable sources. Its importance has recently come into focus in light of the recent Ukraine-Russia conflict, with several European countries recognising the need to secure energy sources with reduced reliance on other countries. Security of supply represents one of the main reasons why the UK is considering future investment in nuclear power [2], in addition to the need to achieve the target of net-zero greenhouse gas emissions by 2050 under the Climate Change Act [3,4].

Nuclear power plants are commonly operated as baseload units due to their technical characteristics and economic considerations, with very high capital cost but very low operating cost. Yet, it is still essential to investigate the potential of having nuclear power plants with enhanced flexibility in order to compete with renewables in meeting the baseload demand and also in supplying peak demand. The benefits of added flexibility in energy systems with high shares of renewables have been investigated comprehensively by Strbac et al. [5], where various flexible solutions such as energy storage, demand-side response (DSR), network expansion, flexible generation technologies and sector coupling have been identified as beneficial for delivering cost-efficient integration of renewables.

Other studies have addressed the specific benefits of enhancing the flexibility of nuclear power plants in low-carbon energy systems. A study by Jenkins et al. [6] concluded that flexible nuclear operation could increase the revenues of nuclear power plants by 2-5% compared to conventional baseload units. The increase of revenues is primarily attributed to the ability of avoiding negative day-ahead electricity prices and supplying day-ahead reserves. Furthermore, Denholm et al. [7] assessed the impact of coupling thermal energy storage (TES) systems with nuclear reactors. The use of TES systems was recommended in the study to attain lower levelised cost of electricity (LCOE) and higher capacity factors, particularly in electricity systems where nuclear is competing with variable renewables such as solar and wind power.

Coupling nuclear reactors with TES systems and secondary power generation units for greater flexibility and higher revenues was also investigated in several studies. For example, Carlson et al. [8] performed a thermodynamic analysis of combining a pressurised water reactor (PWR) with a TES system and steam Rankine cycle-based power generators. In their study, four different configurations based on the location of the TES system (i.e., the charging/discharging point of TES system) were proposed. The study concluded that the configuration where the TES tanks are charged by steam extracted before the high-pressure turbines and then discharged using the optimised secondary power cycles gives the best thermodynamic performance compared to the other proposed configurations. It was also found that this option increases the capacity factor by 15% compared to operating the unit in baseload regime.

Another study by Li et al. [9] investigated the option of integrating nuclear power plant with a cryogenic-based energy storage technology and secondary power generators. The investigated configuration showed the potential of providing peak power output of 690 MW_{el}, which was 2.7 times greater than the baseload power output of 250 MW_{el}. Several other studies considered coupling nuclear reactors with different types of TES systems for enhanced flexibility. The TES systems considered include geothermal heat storage [10], molten-salt tanks [11], hot rock storage [12] and cryogenic air energy storage [13]. All of the aforementioned studies demonstrated the potential benefit of enhanced flexibility when integrating nuclear reactors with TES and secondary power cycle systems.

Duan et al. [14] performed a stylized least cost analysis of flexible nuclear power in decarbonized electricity systems while considering wind and solar resources worldwide. The study investigated the role of conventional and flexible nuclear power in 42 country-level electricity systems with carbon emission reduction constraints ranging from 50% to 100%. This study looked at different investment cost levels for nuclear plants and different wind power capacity factors. It was found that wind and solar generation provide the bulk of electricity in most of the studied regions with moderate carbon emission reduction targets (i.e., less than 80%) as this still allows some room for fossil-fuel generation sources in the electricity mix. However, the need for flexible nuclear, enabled through integration with TES, becomes critical with more stringent carbon emission constraints, as wind and solar cannot cost-effectively provide reliable power due to their intermittency and high cost of electricity storage.

Previous study conducted by the authors [15] proposed a flexible configuration of nuclear power plant consisting of: European pressurised reactors (EPR), a primary steam Rankine cycle (PSRC) system, and modular units consisting of thermal energy storage (TES) and secondary steam Rankine cycle (SSRC) systems. The modular TES-SSRC units were designed to contain four phase change material (PCM) tanks and two SSRC systems. The study included: i) optimisation of the thermodynamic parameters of the system to maximise cycle efficiency; ii) preliminary design and material selection of PCM tanks; iii) design and thermodynamic parameters optimisation of SSRC; iv) development of power system model that minimises the total investment and operation costs with and without flexible nuclear power plants; and v) quantification of system benefits (i.e., cost savings) offered by added nuclear flexibility across a range of system scenarios with decarbonised electricity supply and high shares of renewables.

The results of Ref. [15] showed that the two designed SSRC systems could operate with cycle efficiencies of 30% and 24%, depending on the temperature range of the TES systems. It was also found that replacing conventional with flexible nuclear power plants could result in whole-system cost savings between £24m/yr and £89m/yr, depending on the selected low-carbon system scenario. Furthermore, the study estimated the cost of added flexibility (i.e., the cost of SSRC and TES systems) at £42.7m/yr, which makes the proposed flexibility upgrades to the nuclear power plants economically justified in most of the plausible system decarbonisation scenarios.

The aim of this particular study it to expand the previous analysis from Ref. [15] by enhancing the high-resolution system optimisation model to be able to cost-optimise the sizes of different components of flexible nuclear plants concurrently with optimising investments in other assets in the energy system. This will allow for identifying cost-efficient system-driven configurations of nuclear plants instead of assuming fixed component sizes i.e., a pre-defined configuration as used in Ref. [15].

Key contributions of this paper include: i) development of a novel energy system model that is able to co-optimise investment and operation in electricity and hydrogen production and storage assets as well as optimise the investment in flexible nuclear plant components, ii) development of reliable cost estimates for flexible nuclear plant components based on extensive survey of recent literature; and iii) carry out a range of case studies for two archetypal systems (North and South) and a wide range of system scenarios to investigate how system features affect cost-optimal choices for flexible nuclear plant configurations.

METHOD

This section presents the layout for upgrading a conventional nuclear power plant with a TES system and secondary power generation cycles. This is followed by the formulation of a detailed electricity system model developed in order to determine cost-efficient designs of flexible nuclear plant in order to minimise overall system cost in a low-carbon electricity system.

Power plant configuration and description

The assumed layout of a flexible nuclear power plant is shown in Figure 1, which consists of:

1) Nuclear power island with a European pressurised reactor (EPR) and a steam generator (SG);
2) Primary steam Rankine cycle (PSRC) system that is directly connected to the SG;
3) Two TES systems (TES-1 and TES-2), each consisting of two PCM tanks that are connected in series (system TES-1 includes PCM-1 and PCM-2 tanks and system TES-2 consists of PCM-3 and PCM-4 tanks); and
4) Two secondary power generation cycle systems (SSRC-1 and SSRC-2). System SSRC-1 is operated by thermal energy stored in system TES-1 while system SSRC-2 is operated by utilising the heat stored in system TES-2.

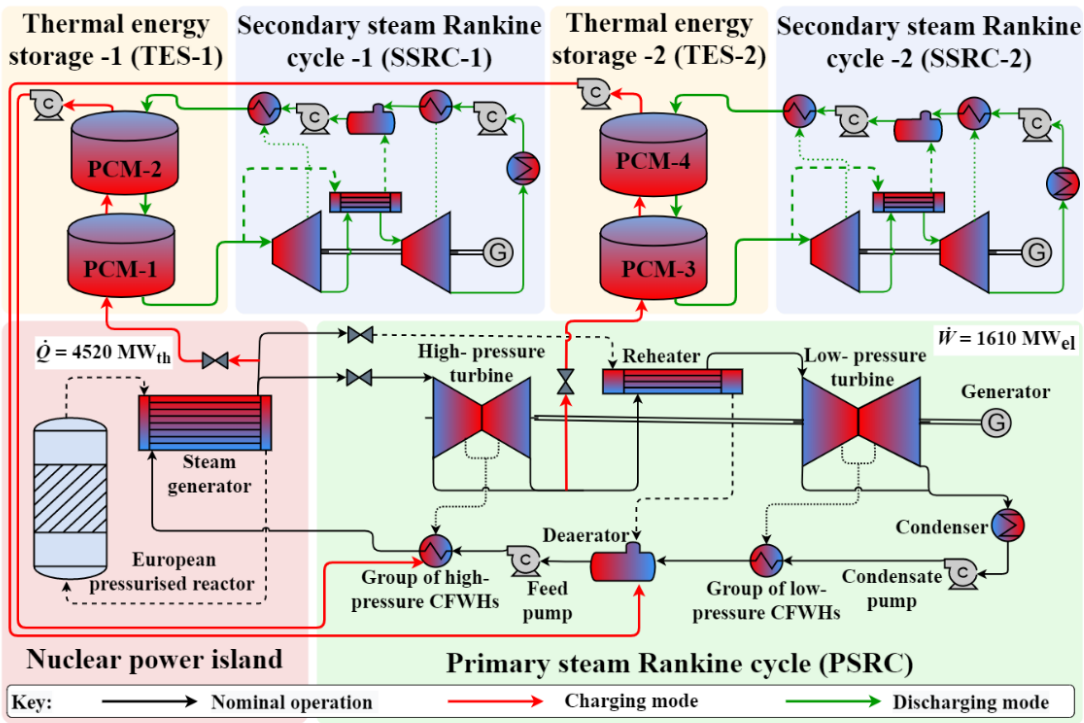


Figure 1. Simplified schematics of the proposed flexible nuclear plant layout, which consists of conventional nuclear power plant (nuclear power island and PSRC system) and modular TES-SSRC units (SSRC-1, SSRC-2, TES-1 and TES-2 systems). Detailed layout with all cycle components can be found in Ref. [15].

The main operating conditions of the EPR, SG, PSRC, SSRC, and TES systems are listed in Table 1. Other thermodynamic parameters of the PSRC and the SSRCs, the material selection for the PCM tanks and the thermodynamic model explanation and set up can be found in Ref. [15].

Table 1. Key thermodynamic parameters of the considered flexible nuclear power plant [15].

Parameter	**Value**
European pressurised reactor thermal power (MW_{th})	4520
Steam generator outlet temperature (°C)	293
Steam generator outlet pressure (kPa)	7800
PSRC maximum electrical power output (MW_{el})	1610
PSRC thermal efficiency (%)	35.7
SSRC-1 thermal efficiency (%)	29.6
SSRC-2 thermal efficiency (%)	23.7
TES-1 charging steam temperature (°C)	293
TES-1 charging steam pressure (kPa)	7800
TES-2 charging steam temperature (°C)	221
TES-2 charging steam pressure (kPa)	2390

In typical operating conditions, the EPR and the SG would aim to continuously operate at full output in order to maximise their economic returns and take advantage of low fuel cost. However, during off-peak demand periods the PSRC system could operate at less than full-rated power output of 1610 MW_{el}, and the excess heat from the reactor could be stored in the attached TES systems. The stored heat can then be discharged to operate the SSRC systems during periods of high demand.

Whole-energy system modelling with flexible nuclear investment decisions

Investment decisions for various components of flexible nuclear plants have been integrated into a whole-energy system investment model presented in [16] and further modified in [15], in order to allow for identifying cost-efficient configurations of flexible nuclear plants. This paper builds on the previously developed WeSIM modelling framework that captures the interactions across various time-scales and across various asset types at high temporal granularity, which is critical for studying low-carbon energy systems with high shares of variable renewable generation [16]. This framework allows for quantifying cost-efficient portfolios of different flexibility options, such as demand-side response (DSR), energy storage or flexible generation technologies. The system optimisation model presented here has been implemented in FICO Xpress Optimisation framework [17].

The main inputs and outputs of the system optimisation model are illustrated in Figure 2, which also includes the information received from the thermodynamic nuclear plant model described in the previous section. This information refers to the thermodynamic performance parameters of flexible nuclear plant components, including part-load and full-load efficiency of PSRC and SSRC generators, and charging and discharging efficiencies of PCM-based TES. Other inputs into the system model include the investment cost assumptions for electricity generation and storage assets and hydrogen production and storage assets, hourly profiles for electricity and hydrogen demand, fuel cost assumptions and system-level carbon constraints. Key outputs from the model include the investment decisions for production and storage assets as well as their hourly operation. These decisions also include the decisions for cost-optimal investment in flexible nuclear plant components, which also allows for quantifying their net system benefits.

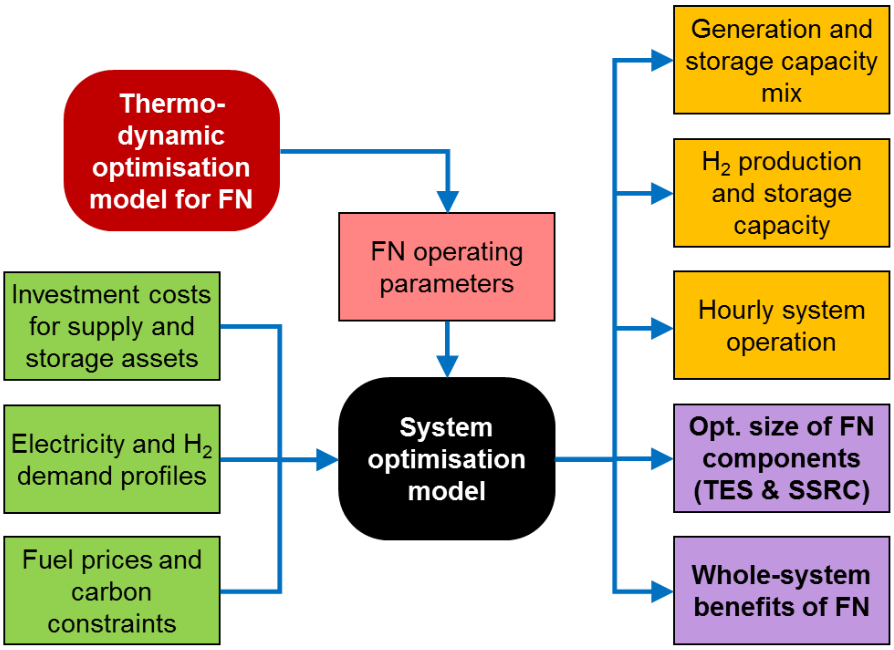


Figure 2. Flowchart of the main inputs and outputs from the thermodynamic plant model and system optimisation model (FN = Flexible Nuclear).

Mathematical formulation of the whole-system model. The formulation of the system model presented here assumes a single-node system without considering any distribution, transmission or interconnection assets. A shortened form of the objective function for the mixed-integer linear problem is given in equations (1)-(4). The model minimises the total system cost, which is the sum of annualised investment and operation cost associated with power generation and battery energy storage systems (BESS) (2), flexible nuclear plants (3) and hydrogen supply and storage (4). The annual operating cost is quantified across all 8,760 hours of a year.

The objective function consists of three main terms:

$$\min z = \varphi_{\mathrm{el}} + \varphi_{\mathrm{fn}} + \varphi_{\mathrm{H2}} \tag{1}$$

$$\varphi_{\mathrm{el}} = \sum_{g=1}^{G} \pi_g^{\mathrm{gen}} \mu_g^{\mathrm{gen}} + \sum_{s=1}^{S} \pi_s^{\mathrm{bs}} \mu_s^{\mathrm{bs}} + \sum_{t=1}^{T} \sum_{g=1}^{G} c_{g,t}^{\mathrm{gen}} \tag{2}$$

$$\begin{aligned}\varphi_{\mathrm{fn}} = {} & \sum_{f=1}^{F} \left(\pi_{\mathrm{PSRC},f}^{\mathrm{fn}} \mu_{\mathrm{PSRC},f}^{\mathrm{fn}} + \pi_{\mathrm{SSRC},f}^{\mathrm{fn}} \mu_{\mathrm{SSRC},f}^{\mathrm{fn}} + \pi_{\mathrm{TES},f}^{\mathrm{fn}} \mu_{\mathrm{TES},f}^{\mathrm{fn}} + \pi_{\mathrm{SG},f}^{\mathrm{fn}} \mu_{\mathrm{SG},f}^{\mathrm{fn}} \right) \\ & + \sum_{t=1}^{T} \sum_{f=1}^{F} F_f^{\mathrm{fn}} h_{\mathrm{SG},f,t}^{\mathrm{fn}}\end{aligned} \tag{3}$$

$$\begin{aligned}\varphi_{\mathrm{H2}} = {} & \sum_{e=1}^{E} \pi_e^{\mathrm{elH2}} \mu_e^{\mathrm{elH2}} + \sum_{r=1}^{R} \pi_r^{\mathrm{ref}} \mu_r^{\mathrm{ref}} + \sum_{u=1}^{U} \pi_u^{\mathrm{hs}} \mu_u^{\mathrm{hs}} \\ & + \sum_{t=1}^{T} \left[\sum_{i=1}^{I} F_i^{\mathrm{imp}} \xi_{i,t}^{\mathrm{imp}} + \sum_{e=1}^{E} A_e^{\mathrm{elH2}} \xi_{e,t}^{\mathrm{elH2}} + \sum_{r=1}^{R} \left(A_r^{\mathrm{ref}} + Y_{\mathrm{gas}} L_r^{\mathrm{gas}} \right) \xi_{r,t}^{\mathrm{ref}} \right]\end{aligned} \tag{4}$$

Component investment costs are expressed as products of per-unit cost parameters (π) and decision variables for total capacity (μ). The generation operating cost term (c^{gen}) is the function of generation output decision variables (p) and reflects the variable operating costs, no-load costs and start-up costs of thermal generators. Hydrogen system cost include the investment cost of electrolysers, reformers and hydrogen storage as well as their operating costs, which also include the cost of gas for methane reformer operation.

Energy balance constraints. Power balance constraint ensures that the net output of generation and BESS meets the electricity demand for each time interval, t, across all demand segments and to supply power to methane reformers and electrolysers:

$$\sum_{g=1}^{G} p_{g,t}^{\text{gen}} + \sum_{f=1}^{F} p_{f,t}^{\text{fn}} + \sum_{s=1}^{S} \left(p_{\text{dch},s,t}^{\text{bs}} - p_{\text{ch},s,t}^{\text{bs}}\right) = \sum_{k=1}^{K} d_{k,t}^{\text{el}} + \sum_{r=1}^{R} L_r^{\text{el}} \xi_{r,t}^{\text{ref}} + \sum_{e=1}^{E} L_e^{\text{el}} \xi_{e,t}^{\text{elH2}} \tag{5}$$

Hydrogen balance equation ensures that total output of hydrogen from production technologies meets the total hydrogen demand (which also includes the use of hydrogen for power generation):

$$\sum_{r=1}^{R} \xi_{r,t}^{\text{ref}} + \sum_{e=1}^{E} \xi_{e,t}^{\text{elH2}} + \sum_{i=1}^{I} \xi_{i,t}^{\text{imp}} = \sum_{u=1}^{U} \left(\xi_{\text{ch},u,t}^{\text{hs}} - \xi_{\text{dch},u,t}^{\text{hs}}\right) + \xi_t^{\text{gen}} + \Xi_t^{\text{ext}} \tag{6}$$

Generator-level constraints for thermal generators. Detailed constraints for thermal and variable renewable generators are omitted here for brevity. They include limits on generation output, unit commitment variables, number of allowed new units and generator dynamic constraints (ramping, start-up, reserve, response, inertia, minimum up/down times). Their detailed treatment can be found in [16].

Generator-level constraints for flexible nuclear generators. Investments in flexible nuclear components are subject to pre-specified limits:

$$\mu_{\text{PSRC},f}^{\text{fn}} \le M_{\text{PSRC},f}^{\text{new}}, \mu_{\text{SSRC},f}^{\text{fn}} \le M_{\text{SSRC},f}^{\text{new}}, \mu_{\text{SG},f}^{\text{fn}} \le M_{\text{SG},f}^{\text{new}}, \mu_{\text{TES},f}^{\text{fn}} \le M_{\text{TES},f}^{\text{new}} \tag{7}$$

Number of units in synchronised operation is bound by the total capacity added by the system:

$$n_{\text{PSRC},f,t}^{\text{fn}} P_{\text{PSRC},f}^{\text{fn,max}} \le \mu_{\text{PSRC},f}^{\text{fn}}, n_{\text{SSRC},f,t}^{\text{fn}} P_{\text{SSRC},f}^{\text{fn,max}} \le \mu_{\text{SSRC},f}^{\text{fn}} \tag{8}$$

Electricity output limits for PSRC and SSRC components are formulated as follows:

$$n_{\text{PSRC},f,t}^{\text{fn}} P_{\text{PSRC},f}^{\text{fn,min}} \le p_{\text{PSRC},f,t}^{\text{fn}} \le n_{\text{PSRC},f,t}^{\text{fn}} P_{\text{PSRC},f}^{\text{fn,max}} \tag{9}$$

$$n_{\text{SSRC},f,t}^{\text{fn}} P_{\text{SSRC},f}^{\text{fn,min}} \le p_{\text{SSRC},f,t}^{\text{fn}} \le n_{\text{SSRC},f,t}^{\text{fn}} P_{\text{SSRC},f}^{\text{fn,max}} \tag{10}$$

TES charging and discharging is limited by the installed TES capacity:

$$h_{f,t}^{\text{TES,ch}}, h_{f,t}^{\text{TES,dch}} \le \mu_{\text{TES},f}^{\text{fn}} \tag{11}$$

TES energy balance equation at time t considers its state-of-charge (SOC) at the previous interval plus any charging or discharging activity adjusted for efficiency losses:

$$q_{\text{TES},f,t}^{\text{fn}} = q_{\text{TES},f,t-1}^{\text{fn}} + \Delta \left(\eta_{\text{TES,Ch}}^{\text{fn}} \, h_{f,t}^{\text{TES,ch}} - \frac{1}{\eta_{\text{TES,Dch}}^{\text{fn}}} h_{f,t}^{\text{TES,dch}} \right) \tag{12}$$

The limit on maximum energy stored in TES expressed via the product of its heat power and duration:

$$q_{\text{TES},f,t}^{\text{fn}} \le \mu_{\text{TES},f}^{\text{fn}} \tau_{\text{TES},f}^{\text{fn}} \tag{13}$$

The SG heat output bounds are implemented as follows:

$$\omega_{\mathrm{SG},f}^{\mathrm{fn,min}}\mu_{\mathrm{SG},f}^{\mathrm{fn}} \leq h_{\mathrm{SG},f,t}^{\mathrm{fn}} \leq \mu_{\mathrm{SG},f}^{\mathrm{fn}} \tag{14}$$

Heat balance equations for the whole flexible nuclear plant take into account the output of SG, heat consumption of PSRC and SSRC generators and the charging and discharging decisions for TES:

$$h_{\mathrm{SG},f,t}^{\mathrm{fn}} - h_{f,t}^{\mathrm{TES,ch}} = h_{\mathrm{PSRC},f,t}^{\mathrm{fn}} = \alpha_{\mathrm{PSRC},f}^{\mathrm{fn}} n_{\mathrm{PSRC},f,t}^{\mathrm{fn}} + \beta_{\mathrm{PSRC},f}^{\mathrm{fn}} p_{\mathrm{PSRC},f,t}^{\mathrm{fn}} \tag{15}$$

$$h_{f,t}^{\mathrm{TES,dch}} = h_{\mathrm{SSRC},f,t}^{\mathrm{fn}} = \alpha_{\mathrm{SSRC},f}^{\mathrm{fn}} n_{\mathrm{SSRC},f,t}^{\mathrm{fn}} + \beta_{\mathrm{SSRC},f}^{\mathrm{fn}} p_{\mathrm{SSRC},f,t}^{\mathrm{fn}} \tag{16}$$

To reflect limited annual availability due to e.g., maintenance, a limit is imposed on total annual SG output:

$$\sum_{t=1}^{\tau} h_{\mathrm{SG},f,t}^{\mathrm{fn}} \leq \mu_{\mathrm{SG},f}^{\mathrm{fn}} \Omega_{\mathrm{SG},f}^{\mathrm{fn}} T \tag{17}$$

System-wide carbon constraint. Total carbon emissions in the system result from the operation of thermal generators and methane reformers, and are subject to a user-specified annual target value:

$$\Delta \sum_{t=1}^{T} \left(\sum_{\substack{g=1 \\ g \in TG}}^{G} \left(\alpha_g^{\mathrm{gen}} n_{g,t}^{\mathrm{gen}} + \beta_g^{\mathrm{gen}} p_{g,t}^{\mathrm{gen}} \right) \epsilon_g^{\mathrm{gen}} + \sum_{r=1}^{R} L_r^{\mathrm{gas}} \xi_{r,t}^{\mathrm{ref}} \epsilon_r^{\mathrm{ref}} \right) \leq \Phi_{\mathrm{CO_2}} \tag{18}$$

Calculating system benefits of flexible nuclear units. System value of flexible nuclear generation in this paper has been quantified as a *net system benefit* of replacing a standard nuclear unit with a flexible alternative that also includes TES and SSRC generation, while taking into account the investment cost required for installing the TES and SSRC components. To quantify these benefits, the whole-system model is run not just for scenarios that optimise flexible nuclear configurations, but also for cases where flexible nuclear components were not available for investment, which allowed to construct a series of *counterfactual* scenarios. Any reduction in total system cost between counterfactual and flexible nuclear runs is quantified as net system benefit of flexible nuclear, which also includes the installation cost of flexible nuclear components.

Scenarios used for quantifying cost-efficient configurations of flexible nuclear plants

Given that the primary purpose of the analysis presented in this paper is to determine system-driven cost-efficient configurations of flexible nuclear plants, a number of various system scenarios have been used in the analysis to study the key drivers for the system-driven design of flexible nuclear plants. Two generic geographic systems have been assumed, North and South, both sized to broadly match the size of the UK electricity system with an annual demand of 400 $\mathrm{TWh_{el}}$. Key differences between the two systems are detailed in Table 2.

Table 2. Key features of North and South electricity systems.

Parameter	North	South
Electrified heating demand	High	Low
Cooling demand	Low	High
Onshore wind capacity factor	36%	35%
Offshore wind capacity factor	58%	49%
Solar PV capacity factor	14%	24%

In all scenarios it was assumed that there is one nuclear unit on the system, with the PSRC rating of 1610 MW_{el}. (The exception to this was the scenario that assumed 5 such units were present in the system.) In counterfactual scenarios this unit was assumed to have a conventional configuration with just the SG and PSRC. In flexible nuclear scenarios the model was allowed to add SSRC and TES capacity to the nuclear unit (or units) at a given cost, if this is cost-efficient, i.e., if it leads to lower total system cost.

A range of scenarios was investigated for each of the two systems (North and South), as specified in Table 3. The aim of defining these scenarios was to investigate the impact of various system features and assumptions on cost-efficient system-driven design of flexible nuclear plants. System features included in the scope of the analysis include the system carbon emission target, number of nuclear units in the system, higher interest rate, cost of battery storage, and the availability of investment into carbon offsets through Bioenergy with Carbon Capture and Storage (BECCS).

Table 3. List of system scenarios used for studying cost-efficient configurations of flexible nuclear plants.

No.	Scenario description
1	Net zero carbon system
2	Carbon intensity target of 25 gCO_2/kWh
3	Carbon intensity target of 50 gCO_2/kWh
4	5 nuclear units instead of one
5	High interest rate (IR) of 8.9% instead of 5%
6	Higher cost of battery storage (50% higher than baseline)
7	No investment in carbon offsets (BECCS)

Cost assumptions for flexible nuclear plant components

The specific investment costs of the SSRC and TES systems (PCM tanks) are estimated based on the information available in the relevant literature, as listed in Table 4. The SSRC system costs are obtained from steam Rankine cycle-based power generation blocks with similar sizes and similar technical properties. The reported costs of PCM tanks refer to similar PCM tank designs (i.e., with a shell and tubes) and with similar temperature limits.

The average of the specific investment cost of SSRC systems is £702/kW_{el} and the maximum relative difference between the reported costs is 17%. This suggests that using the average specific investment cost is an acceptable assumption. Furthermore, the average specific investment cost of the PCM tanks is £15.9/kWh_{th} with a standard deviation of £1.6/kWh_{th}, which also suggests the average value is a reasonable estimate. Note that the assumed GBP/USD and GBP/EUR exchange rates were 0.80 and 0.85, respectively, based on Ref. [18].

Table 4. Specific investment costs of SSRC systems and PCM tanks.

Component	Cost 1	Cost 2	Cost 3	Average	Standard deviation
SSRC systems (£/kW_{el})	643 [19]	748 [20]	715 [21]	702	43.9
PCM tanks (£/kWh_{th})	14.6 [22]	15.4 [23]	17.7 [24]	15.9	1.6

RESULTS AND DISCUSSION

This section presents the results of the modelling runs when optimising the configuration of flexible nuclear plant across a wide range of system scenarios. Key results include the configuration of the flexible nuclear plant i.e. the sizing of SSRC and TES components for a given size of SG and PSRC components; system cost savings resulting from cost-optimal flexible nuclear configurations; and illustrative hourly operation of the components of flexible nuclear plant.

Counterfactual system scenarios

In counterfactual scenarios for the North and South systems the generation and storage portfolios have been cost-optimised without the presence of flexible nuclear plants. The composition of these counterfactual portfolios is shown in Figure 3.

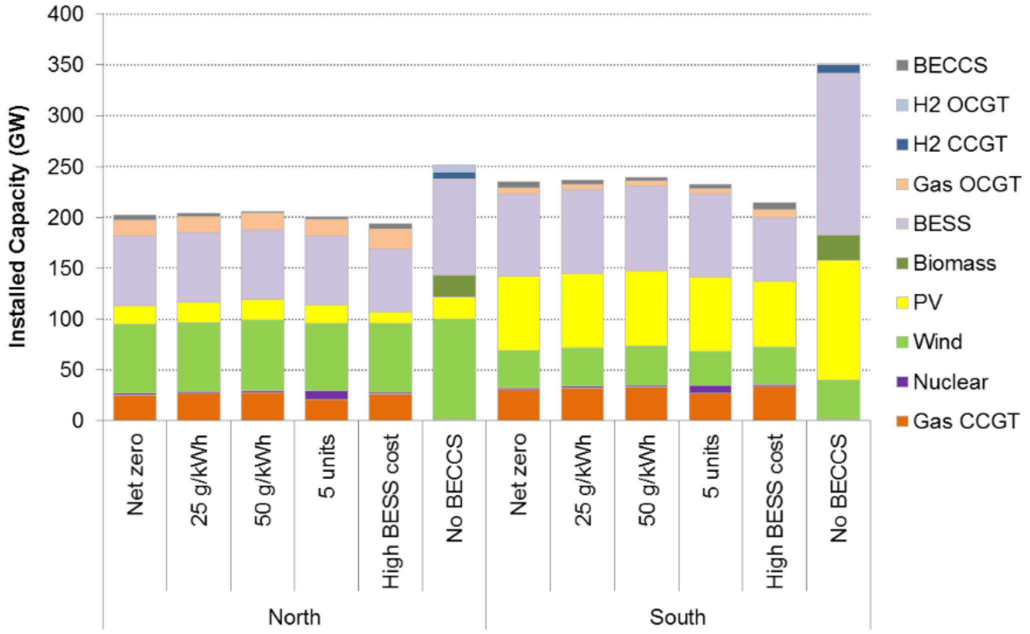


Figure 3. Installed electricity generation and battery storage (BESS) capacity across various scenarios for North and South systems.

In the North system wind represents the dominant generation technology, as the achievable annual utilisation factors are much higher than in the South, resulting in a low LCOE. Generation portfolio in the South, on the other hand, is dominated by solar PV generation, driven by its higher capacity factor compared to the North system. In order to mitigate the variability in wind and PV output, in all scenarios there is a significant volume of battery storage (BESS), in the range of 62-95 GW in the North and 63-159 GW in the South. In addition to RES generation, all scenarios except “No BECCS” feature a considerable amount of unabated gas generation (CCGT and OCGT); its carbon footprint is mitigated by a relatively small amount of BECCS generation that plays the role of carbon offset in order to deliver a given emission target. In the Net zero scenario the required BECCS capacity is 4.6-5.9 GW, which reduces in less stringent emission scenarios (25 and 50 g/kWh).

In the No BECCS scenario the model was not allowed to invest in carbon offsetting BECCS technology, which effectively also prevented any unabated gas generation as part of the generation mix. As a result, the electricity demand is met by an increased amount of RES generation, supplemented by 21-25 GW of biomass generation and 9-14 GW of hydrogen generation (note that the volume of nuclear generation was fixed so the model could not add any further nuclear capacity). Although not depicted in Figure 3, it is worth noting that in addition to investing in hydrogen generation capacity in the “No BECCS” scenarios, the model also invested in about 730 GWh of hydrogen storage and 14-15 GW_{el} of electrolyser capacity.

Figure 4 shows the breakdown of annual electricity supply across technologies for all counterfactual scenarios used in the study. Given that baseload low-carbon generation such as nuclear and BECCS operate at relatively high annual capacity factors close to 90% (unlike RES generators), their contribution in annual electricity supply is more pronounced than their contribution to the capacity portfolio in Figure 3. The contribution of battery storage in annual electricity supply is shown as negative quantity that represents the difference between total annual discharging and total annual charging (where the latter is greater due to roundtrip efficiency losses). Note that because the use of hydrogen generation in the "No BECCS" scenarios also required the production of hydrogen from electrolysis, this resulted in increased demand for electricity compared to other scenarios, in order to supply the additional electrolyser demand.

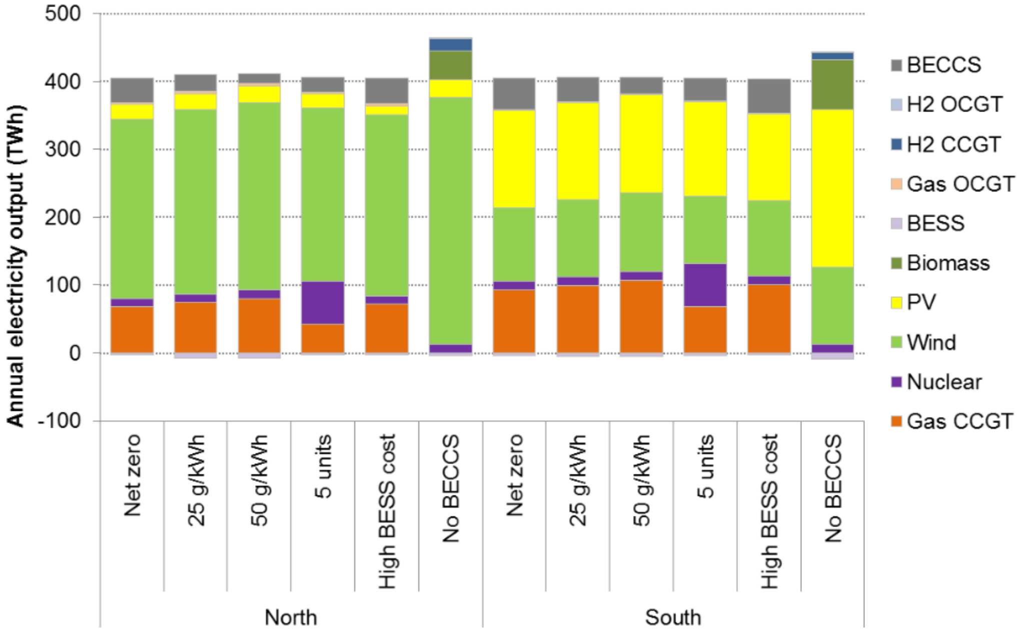
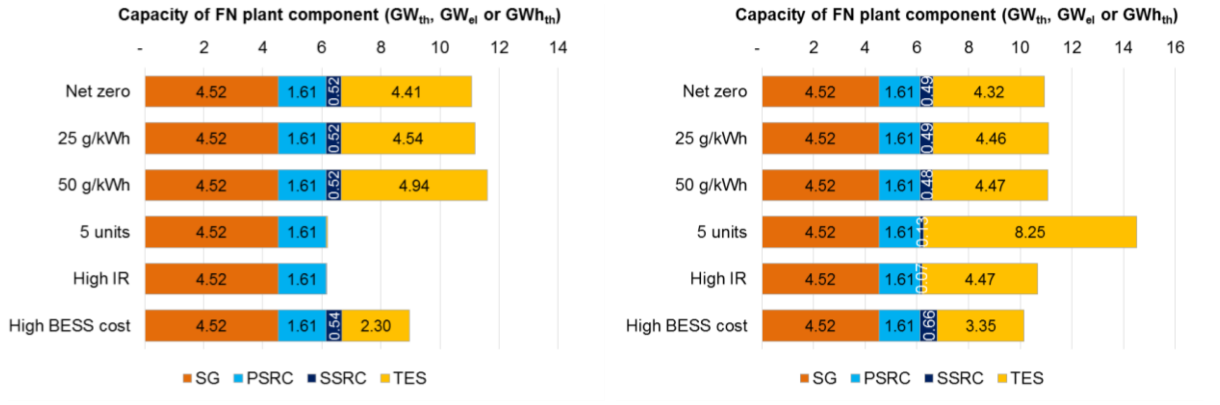


Figure 4. Annual electricity output across various scenarios for North and South systems.

Cost-efficient configurations of flexible nuclear plants

In each of the counterfactual scenarios the model was then allowed to add cost-optimal volumes of flexible components of nuclear plants, i.e., SSRC and TES capacity. All studies assumed a constant capacity of SG and PSRC components. The least-cost configurations of nuclear plants for various scenarios for the North and South systems are presented in Figure 5, with the exception of the "No BECCS" scenario, which is presented separately due to large differences in scale. Note that the sizes of different components in Figure 5 are presented using different units: GW_{th} for SG, GW_{el} for PSRC and SSRC, and GWh_{th} for TES. Also note that the capacities have been expressed per one nuclear unit, so that in cases with 5 units any added SSRC and TES capacity has been divided by 5.



a) North b) South

Figure 5. Cost-optimal configurations of flexible nuclear plants across various scenarios for North and South systems. SG and PSRC sizes are kept constant for all scenarios and SSRC and TES sizes are optimised.

In the first three scenarios (Net Zero, 25 g/kWh and 50 g/kWh) the model adds very similar amounts of SSRC capacity: 520 MW_{el} in the North system and 480-490 MW_{el} in the South system. These values are very close to the SSRC capacity of the pre-configured flexible nuclear plant assumed in Ref. [15]. The size of TES added by the model in these scenarios is 4.4-4.9 GWh_{th} in the North and 4.3-4.5 GWh_{th} in the South system, with slightly higher values observed in scenarios with less strict emission targets. When these values are divided by the SSRC size and adjusted for SSRC electric conversion efficiency (26.3%), the duration of TES in terms of hours of SSRC operation is found to be broadly between 2.2 and 2.5 hours. This is significantly more than the 1-hour duration previously assumed in Ref. [15].

In the North system scenarios with 5 units and High IR the model does not choose to add any flexibility to nuclear units as part of the cost-optimal solution. The benefits of flexibility offered by battery storage are higher in those scenarios then the benefits of enhancing the flexibility of nuclear plants. In the High IR scenario this occurs because of higher cost of enabling nuclear flexibility due to a higher interest rate, while in the scenario with 5 units higher nuclear capacity reduces the output of unabated gas plants and therefore releases some of their capacity to provide flexibility cost-effectively.

In contrast, the flexibility requirements in the South system are higher due to greater fluctuations in PV output, so in the South the model adds some SSRC and TES capacity even when 5 nuclear units are present on the system or with high interest rates. In these cases the model adds less SSRC capacity per unit then in the first three scenarios (although note that in the 5 units scenario the 130 MW_{el} of additional SSRC capacity per unit means 650 MW_{el} of SSRC capacity added in total). At the same time the volume of TES added is still significant at 8.2 GWh_{th} in the “5 units” scenario and 4.5 GWh_{th} in the “High IR” scenario, resulting in both cases in a similar TES duration of around 17 hours.

Finally, the high BESS cost slightly increases the SSRC capacity added by the model, to 540 MW_{el} in the North and 660 MW_{el} in the South, but on the other hand the added TES capacity reduces to 2.3 GWh_{th} (North) and 3.3 GWh_{th} (South). This can be explained by the counterfactual scenario with high BESS cost having less battery storage, less PV generation and more gas generation, all of which result in lower requirements for flexibility. The resulting TES durations in these two scenarios are 1.1 h in the North and 1.3 h in the South.

The results for cost-optimal configurations of flexible nuclear plants for the two "No BECCS" scenarios are presented in a separate chart in Figure 6 alongside the main Net Zero scenarios.

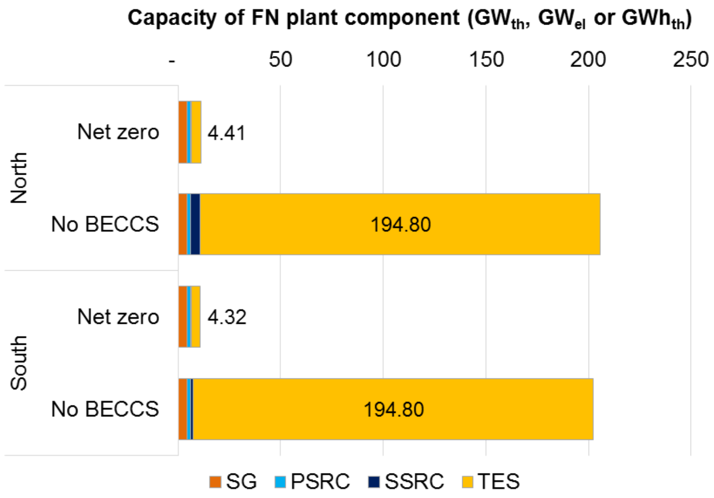


Figure 6. Cost-optimal configurations of flexible nuclear plants for baseline net zero and No BECCS scenarios for North and South systems.

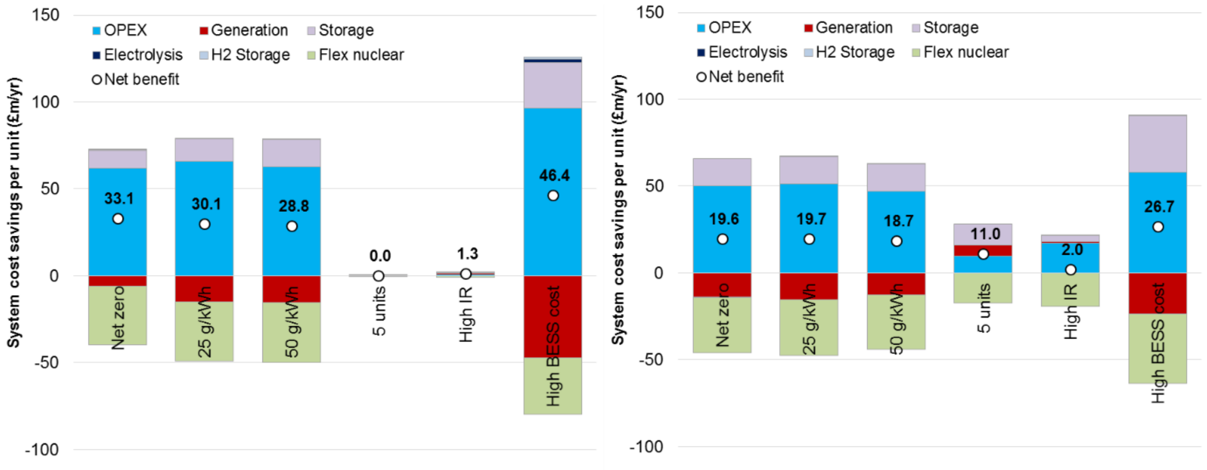
As noted before, the "No BECCS" scenario features a significant volume of hydrogen production (electrolysis), storage and H_2-fuelled electricity generation, as well as substantially higher volumes of BESS compared to other scenarios. Therefore, when flexible nuclear components are offered as investment options to the cost minimisation model, the cost-optimal solution maximises the TES volume by reaching the highest allowed volume specified in the model (100 units of 1,948 MWh_{th} each). This is because in this scenario the system cannot rely on relatively cheap controllable gas generation (as its carbon emissions cannot be offset through BECCS), but rather has to invest in longer-term energy storage in the form of hydrogen, while also significantly increasing BESS capacity.

Although dwarfed by the increase in TES capacity in Figure 6, the sizes of SSRC also increase in the "No BECCS" scenarios, to 4.7 GW_{el} in the North system and 1.4 GW_{el} in the South system.

The option to build relatively low-cost energy storage in the form of TES as part of flexible nuclear plants, therefore represents a highly attractive proposition, so that TES displaces some of the long-term hydrogen storage. Additional modelling experiments without the limit on new TES units revealed that the unconstrained cost-optimal volume of TES would be 370 GWh_{th} (North) and 495 GWh_{th} (South), also accompanied by significantly higher SSRC capacities. However, such high TES capacities acting as large-scale energy reservoirs are likely to exceed the space constraints of nuclear power plants in reality. Hence, these results could be interpreted to mean that realistic nuclear plants in these scenarios should maximise the amount of TES they install as part of delivering a more flexible plant configuration.

System benefits of flexible nuclear configurations

Flexible nuclear components get chosen as investment options by the cost-optimising model because they can reduce the overall system cost. It is therefore of interest to quantify the magnitude of system cost reduction delivered through more flexible nuclear plant configurations. To that end, Figure 7 quantifies changes in total system cost between relevant counterfactual scenarios and scenarios with the option to invest in flexible nuclear plants. System cost savings are broken down into key cost components (generation, operation, storage, electrolysis and H_2 storage) and contrasted against the cost of investing into flexible nuclear components in order to quantify net changes in total system cost. The "No BECCS" scenarios are again not shown due to differences in scale, and are therefore discussed separately.



a) North b) South

Figure 7. System cost savings from flexible nuclear plants across various scenarios for North and South systems.

In the first three North system scenarios the net system benefits are in the range of £29-33m/yr, which represents the difference between gross system benefits of £63-67m/yr and the annualised investment cost into flexible nuclear components of around £34m/yr. System cost savings are achieved predominantly by reducing the operating cost (OPEX) of BECCS and gas CCGT generators, reducing the investment cost of battery storage, while on the other hand investing slightly more in wind generation as the system with flexible nuclear is more capable of mitigating wind output fluctuations. Similar savings structure is observed in the South system for the first three scenarios, although the magnitude of total net savings is lower at around £19-20m/yr.

In scenarios with 5 units and High IR the observed net system benefits are negligible in the North system, while in the South the respective benefits are £11m/yr and £2m/yr. Net system benefits in the "High BESS cost" scenarios are expectedly higher than the baseline Net zero scenarios, amounting to £46m/yr in the North system and £27m/yr in the South system.

Finally, in the "No BECCS" scenarios, which are not presented in Figure 7, the maximisation of TES capacity results in even higher net system benefits: £266m/yr in the North system and £94/yr in the South system. In these scenarios a significant proportion of system cost savings comes from TES displacing hydrogen storage and electrolyser investment.

Hourly operation of flexible nuclear components

Finally, in order to illustrate short-term operation of flexible nuclear components, two illustrative hourly operation diagrams are provided for selected weeks for North and South systems.

Figure 8 represents a winter week in the North system for the Net zero scenario. The chart shows hourly variations in SG heat output, power output of PSRC and SSRC, thermal input into and output from TES and the TES state-of-charge (SOC). To illustrate system drivers for the utilisation of flexible nuclear components, the chart also shows the net system demand profile, which is obtained by deducting wind and PV generation from system electricity demand.

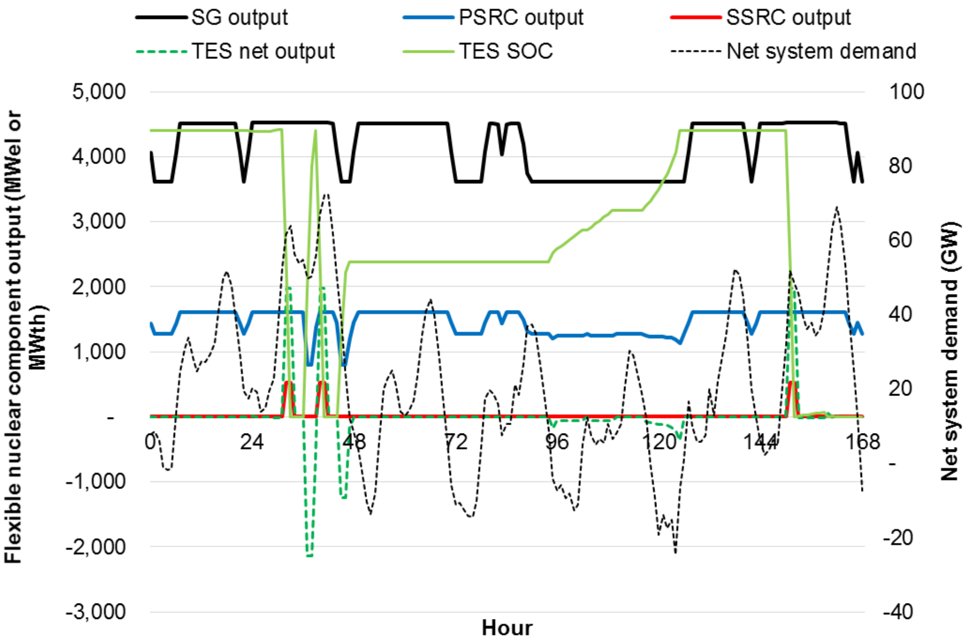


Figure 8. Hourly operation of flexible nuclear generation during a winter week in the North system for the Net zero scenario. Net system demand represents the difference between system demand and total wind and PV output, and is plotted against the right-hand axis.

The results suggest that TES and SSRC are utilised to generate electricity during periods of high net demand on days 2 and 7 of the week shown in Figure 8. On some occasions the TES is charged immediately after being discharged in order to be ready for the next peak (day 2), while on others it charges gradually during periods of relatively lower net demand driven by higher wind output (days 3-5) in order to be ready to discharge again when net demand increases. In general, there is no regular daily pattern of TES and SSRC utilisation, but rather a correlation with high and low wind output periods (resulting in low and high net system demand).

In the South system, on the other hand, as shown in Figure 9, the operation of flexible nuclear components follows a fairly regular daily cycle. The week depicted in Figure 9 is a summer week with significant contribution from solar PV generation, reflected in sharp dips in net system demand around the middle of each day. The optimal operating strategy for flexible nuclear plant in this case is to minimise its PSRC output around midday, and use excess heat from SG to charge TES. As net demand increases sharply in early evening hours, the PSRC output returns to is maximum level, supplemented by additional generation from SSRC in order to utilise energy stored in TES during periods of high PV output. One can also observe that, unlike in the North system, TES gets fully charged and discharged every day.

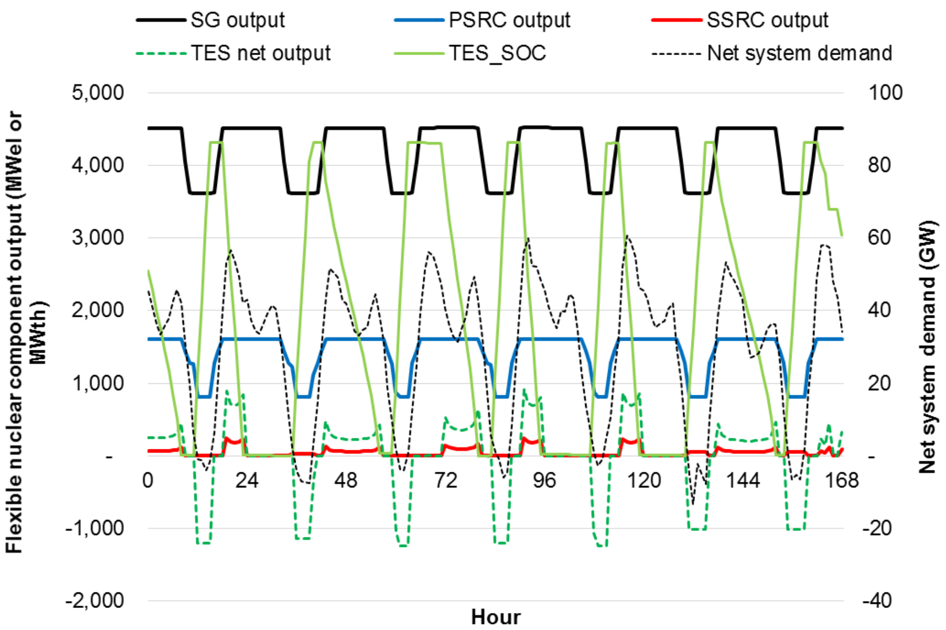


Figure 9. Hourly operation of flexible nuclear generation during a summer week in the South system for the Net zero scenario. Net system demand represents the difference between system demand and total wind and PV output, and is plotted against the right-hand axis.

CONCLUSIONS

This paper proposed a novel high-resolution system optimisation model that determines cost-optimal sizes of different components of flexible nuclear plants as part of cost optimisation of the wider energy system. This approach identifies cost-efficient system-driven configurations of nuclear plants as function of system characteristics. Based on plausible cost estimates for flexible nuclear plant components based on extensive literature survey, a range of system scenarios have been analysed to study the impact of system features on cost-optimal choices for flexible nuclear plant configuration.

The results suggest that for a standard-size nuclear unit assumed in the paper, with the PSRC capacity of 1610 MW_{el}, it would be cost-efficient to install around 500 MW_{el} of SSRC capacity as well as around 4.5 GWh_{th} of TES capacity in most low-carbon and net-zero carbon systems considered in the study. This would result in an equivalent TES duration of 2.2 hours, which is substantially higher than the 1-hour duration assumed in previous work [15]. Enhancing the nuclear plant flexibility was found to be less attractive when applied to a large number of nuclear units or when exposed to high interest rates in the North system, which was characterised by high heating demand and wind as the dominant renewable resource. On the other hand, in the South system dominated by PV generation and characterised by milder weather, flexible nuclear investment was attractive even in those scenarios.

High BESS cost was found to slightly increase the cost-optimal SSRC capacity, but on the other hand reduce the added TES capacity. Finally, in net-zero carbon scenarios without available carbon offsets (BECCS) the model maximised the TES volume in flexible nuclear suggesting its high value for the net-zero systems. Nevertheless, such high TES capacities may not be feasible in reality due to space constraints.

Net system benefits per unit of flexible nuclear generation for the main net-zero and low-carbon scenarios were found to be in the range of £29-33m/yr in the North and £19-20m/yr in the

South, suggesting a positive economic effect of investing in flexible nuclear plant components. Net benefits reduce in scenarios with 5 units and high interest rates, but increase slightly with higher BESS cost. In scenarios without available BECCS carbon offsets the net benefits of flexible nuclear increase substantially, although this increase would be subject to constraints on the volume of TES that can be realistically added to a nuclear plant.

Future work in this area will continue to study the thermodynamic properties of various flexible nuclear plant configurations in order to validate the feasibility of various system-driven configurations and refine the solution, while also establishing a feedback loop into the detailed thermodynamic design of plant components.

ACKNOWLEDGMENT

The research presented in this paper has been supported by the UK Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/R045518/1] (IDLES Programme). For the purpose of Open Access, the authors have applied a CC BY public copyright licence to any Author Accepted Manuscript version arising from this submission.

NOMENCLATURE

Subscripts/superscripts and acronyms

BECCS	bioenergy with carbon capture and storage	IR	interest rate
BESS	battery energy storage system	LCOE	levelised cost of electricity
bs	battery storage	max	maximum
CAPEX	capital (investment) cost	min	minimum
CCGT	combined cycle gas turbine	new	new capacity
ch	charging	OCGT	open cycle gas turbine
dch	discharging	OPEX	operating cost
DHN	district heat network	PCM	phase change material
DSR	demand-side response	PSRC	primary steam Rankine cycle
el	electricity supply system	PV	photovoltaics
elH2	electrolysis	ref	methane reforming
EV	electric vehicle	RES	renewable energy sources
ext	external (demand)	SG	steam generator
fn, FN	flexible nuclear	SOC	state of charge
gen	generation	SSRC	secondary steam Rankine cycle
HP	heat pump	TES	thermal energy storage
hs	hydrogen storage	WeSIM	whole-electricity system investment model
imp	hydrogen imports		

Greek symbols

Δ	duration of unit interval (hours)	μ	total capacity (MW)
Φ	annual emission limit (tCO_2/yr)	ξ	hydrogen production or consumption (MW_{H2})
Ω	maximum annual utilisation factor	π	per-unit cost (£/MW/yr)
α	no-load heat rate (MWh_{th}/hr)	τ	storage duration (hours)
β	incremental heat rate (MW_{th}/MW_{el})	φ	system cost component (£)
δ	duration of unit time interval (hours)	ω	relative minimum output level
η	efficiency (%)	ϵ	carbon emissions per unit of fuel (tCO_2/MWh)

Symbols

A	variable operation cost coefficient (non-fuel) (£/MWh)	d	electricity demand (MW_{el})
E	number of electrolyser assets	e	electrolyser asset index
F	number of flexible nuclear assets	f	flexible nuclear asset index
G	number of power generation assets	g	generation asset index
H	number of hydrogen storage assets	h	heat output/input (MW_{th})
I	number of hydrogen import sources	i	hydrogen import source index
K	number of demand segments	k	demand segment index
L	specific consumption per unit of H_2 output (MW/MW_{H2})	n	number of units in operation
M	maximum capacity (MW)	p	power output (MW_{el})
R	number of methane reformer assets	q	state of charge of TES (MWh_{th})
S	number of battery storage assets	r	methane reformer asset index
T	number of unit time intervals	s	battery storage asset index
U	number of hydrogen storage assets	t	time interval (hours)
Y	cost of fuel (£/MWh)	u	hydrogen storage asset index
c	operating cost function (£)	z	total system cost (£)

REFERENCES

1. International Atomic Energy Agency (IAEA), Climate Change and Nuclear Power 2020, https://www.iaea.org/publications/14725/climate-change-and-nuclear-power-2020. [Accessed: 13-Jun-2022]
2. Campbell, C., As Putin threatens nuclear disaster, Europe learns to embrace nuclear energy again, Time, 2022. https://time.com/6169164/ukraine-nuclear-energy-europe/ [Accessed: 13-May-2022]
3. Department of Business, Energy & Industrial Strategy, Nuclear Industrial Strategy – The UK's Nuclear Future, 2013, https://www.gov.uk/government/publications/nuclear-industrial-strategy-the-uks-nuclear-future. [Accessed: 13-Jun-2022]
4. Department of Business, Energy & Industrial Strategy, Climate Change Act 2008 (2050 Target Amendment) Order 2019, https://www.legislation.gov.uk/uksi/2019/1056. [Accessed: 13-Apr-2021]
5. Strbac, G., Pudjianto, D., Aunedi, M., Djapic, P., et al., Role and value of flexibility in facilitating cost-effective energy system decarbonisation, *Progress in Energy*, 2, 2020.
6. Jenkins, J.D., Zhou, Z., Ponciroli, R., Vilim, R.B., Ganda, F., de Sisternes, F., Botterud, A., The benefits of nuclear flexibility in power system operations with renewable energy, *Applied Energy*, vol. 222, pp. 872-884, 2018.
7. Denholm, P., King, J.C., Kutcher, C.F. and Wilson, P.P.H., Decarbonizing the electric sector: Combining renewable and nuclear energy using thermal storage, *Energy Policy*, vol. 44, pp. 301-311, 2012.
8. Carlson, F. and Davidson, J.H., On the use of thermal energy storage for flexible baseload power plants: Thermodynamic analysis of options for a nuclear Rankin cycle, *Journal of Heat Transfer*, vol. 142, 052904, 2020.
9. Li, Y., Cao, H., Wang, S., Jin, Y., et al., Load shifting of nuclear power plants using cryogenic energy storage technology, *Applied Energy*, vol. 113, pp. 1710-1716, 2014.
10. Forsberg, C., Hybrid systems to address seasonal mismatches between electricity production and demand in nuclear renewable electrical grids, *Energy Policy*, vol. 62, pp. 333-341, 2013.
11. Alameri S.A., A coupled nuclear reactor thermal energy storage system for enhanced load following operation, Ph.D. Dissertation, Colorado School of Mines, Colorado, USA, 2015.
12. Forsberg, C., Brick, S. and Haratyk, G., Coupling heat storage to nuclear reactors for variable

electricity output with baseload reactor operation, *Electricity Journal*, vol. 31, pp. 23-31, 2018.
13. Forsberg C.W., Heat in a bottle, *ASME Mechanical Engineering*, vol. 141, pp. 36-41, 2019.
14. Duan, L., Petroski, R., Wood, L. and Caldeira, K., Stylized least-cost analysis of flexible nuclear power in deeply decarbonized electricity systems considering wind and solar resources worldwide, *Nature Energy*, vol. 7, pp. 260-269, 2022.
15. Al Kindi A.A., Aunedi M., Pantaleo, A.M., Strbac, G. and Markides, C.N., Thermo-economic assessment of flexible nuclear power plants in future low-carbon electricity systems: Role of thermal energy storage, *Energy Conversion and Management*, vol. 258, 115484, 2022.
16. Pudjianto, D., Aunedi, M., Djapic, P. and Strbac, G., Whole-system assessment of value of energy storage in low-carbon electricity systems, *IEEE Transactions on Smart Grid*, vol. 5, no. 2, pp. 1098-1109, 2014.
17. FICO Xpress Optimization, https://www.fico.com/en/products/fico-xpress-optimization [Accessed: 13-Jun-2022]
18. Bank of England Database, Daily spot exchange rates against Sterling, https://www.bankofengland.co.uk/boeapps/database/Rates.asp?Travel=NIxAZx&into=GBP [Accessed: 21-May-2022]
19. International Renewable Energy Agency (IRENA), Renewable power generation costs in 2020, 2021, Abu Dhabi, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf [Accessed: 27-Apr-2022]
20. Black, G.A., Aydogan, F. and Koerner C.L., Economic viability of light water small modular nuclear reactors: General methodology and vendor data, *Renewable and Sustainable Energy Reviews*, vol. 103, pp. 248-258, 2019.
21. Dersch, J., Paucar, J., Schuhbauer, C., Schweitzer, A. and Stryk, A., Blueprint for Molten Salt CSP Power Plant, Final report of the research project "CSP-Reference Power Plant" No. 0324253, 2021, Cologne, Germany. https://elib.dlr.de/141315/1/Blueprint%20for%20Molten%20Salt%20CSP%20Power%20Plant.pdf [Accessed: 27-Apr-2022]
22. Bai, F., Wang, Y., Wang, Z., Sun, Y. and Beath, A., Economic evaluation of shell-and-tube latent heat thermal energy storage for concentrating solar power applications, *International Conference on Concentrating Solar Power and Chemical Energy Systems (SolarPACES) 2014*, *Energy Procedia*, vol. 69, pp. 737-747, 2015.
23. Jacob, R., Saman, W., Belusko, M. and Bruno, F., Techno-economic analysis of phase change material thermal energy storage systems in high temperature concentrated solar power plants, *Asia-Pacific Solar Research Conference*, 2014.
24. Jacob, R., Belusko, M., Fernandez, A.I., Cabeza, L.F., Saman, W. and Bruno, F., Embodied energy and cost of high temperature thermal energy storage systems for use with concentrated solar power plants, *Applied Energy*, vol. 180, pp. 586-597, 2016.