30 LET NENE 2022
September 12-15
PORTOROŽ
SLOVENIA
31st International Conference Nuclear Energy for New Europe

Optimization of Sizing and Operation of a Nuclear District Heating System Using Teplator, Gas Boiler and Heat Storage

Hussein Abdulkareem Saleh Abushamah, **David Masata, Jana Jiřičková, Radek Škoda**
University of West Bohemia in Pilsen
Faculty of Electrical Engineering Univerzitní 8, 301 00, Pilsen, Czech Republic,
CIIRC, Czech Technical University in Prague, Praha 6, Czech Republic.
abushama@fel.zcu.cz, masata@fel.zcu.cz, jjiricko@kee.zcu.cz, radek.skoda@cvut.cz

ABSTRACT

Expansion of the nuclear energy-based district heating systems can effectively contribute to the elimination of CO_2 emissions, reduce the dependency on fossil fuels, supply the heating demand with higher efficiency, and are eligible to be competitive compared with the individual heating systems. Consequently, the interest in using heat-only small modular reactors for district heating applications is growing, and some concepts such as Teplator are recently proposed. A flexible operation and fast load following are required, while generally, nuclear power plants are designed to be operated at nominal capacity, and boosting flexibility at nuclear plants is technically complicated. Therefore, heat storage or auxiliary boilers could be adequate for load following and peak shaving, reducing the total costs by decreasing the required capacities of the nuclear plant and heat transmission system. In this study, the optimization of the design and operation of a nuclear district heating system using heat storage and auxiliary boilers is formulated. The capacities and hourly-based operation of the heat generation units and the charging and discharging schedule of the thermal storage are optimized. The technical constraints, such as maximum charging/discharging power rates of the heat storage, or the power ramp rate of the heat generation units, are included in the model.

1 INTRODUCTION

Space and water heating energy needs account for nearly 78% of the EU's residential energy sector, of which 40% is supplied by natural gas, while about 83% of the total EU's natural gas is imported [1, 2]. The fluctuation of the natural gas price over the last five years, in addition to its unsecured availability, reflects that this fuel could not be a long-term reliable energy source from a political ecology viewpoint. Therefore, adopting a locally available and more reliable energy mix policy is vital for enhancing long-term energy security in the EU. Various primary energy sources such as nuclear energy, fossil fuel-based like oil and natural gas, and renewable energy sources like wind, solar, geothermal, biomass and hydropower have the potential to contribute to the energy mix strategy by supplying various sectors in the form of electricity or heat. Here we focus on optimizing the hybrid energy supply system for district heating applications. District heating system mainly consists of centralized heat generation stations, heat transmission and distribution pipelines to supply the consumers' space and water heating demand. The common heat transfer medium is hot water for residential heating needs [3]. The candidate heat suppliers are a heat-only small modular reactor (Teplator), gas boilers, and heat storage. Teplator is a heavy water moderated reactor and is also designed to be operated by slightly enriched Uranium fuel (<1.2 wt% U-235) [4]. The target is to optimize the system's thermal capacity and hourly operation to meet the heat demand profile, satisfy the technical constraints, and minimise the total construction and operation costs. The system is introduced in more detail, and the problem is formulated in the following section.

2 PROBLEM STATEMENT AND FORMULATIONS

Various technologies could be utilized for district heating, such as fossil fuel-based boilers (natural gas, oil, coal, etc.), electric boilers and heat pumps, geothermal and solar energy, heat only small modular reactors (Teplator [4], DHP-400 [5]), heat recovery from excess industrial heat, and combined heat and power (CHP) generation units. Depending on several factors such as the availability and reliability of the energy sources and technologies, scale and location of the heat demand, economic and environmental factors, etc., the optimization process results in a different optimum energy-mix solution.

In this study, the candidate heat sources are a nuclear heat-only reactor, namely Teplator, gas boilers, and heat storage. The reason for choosing Teplator is its unique feature of reusing spent nuclear fuel with almost zero cost, where a significant amount of the already irradiated fuel from nuclear power plants is available in several EU countries [3]. The gas boiler is the auxiliary candidate heat source which may be required during the maintenance periods of the Teplator and for peak shaving and fast load following. Heat storage can enhance the system's operation flexibility and may lead to a lower total cost, increasing the nuclear unit's capacity factor. The demand is an annual hourly-based profile, which needs to be supplied by optimum operation scheduling of the heat sources and heat storage. The proposed system is illustrated in Fig. 1.

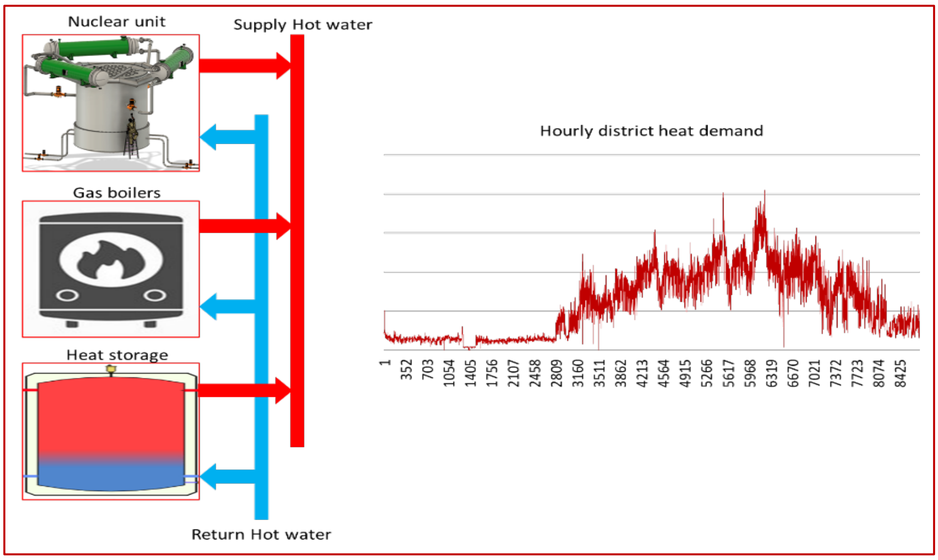

Figure 1: Schematic drawing of the proposed heat supply system.

2.1 Formulation of the objective function

The target is to find the optimum thermal capacities and technologies of the heat generation and storage units, as well as their optimum hourly operation scheduling, in order to meet the heating demand, satisfy the technical constraints, and minimise the total construction and operation costs over the decision-making period (DMP). The Present Value (PV) of the costs (represents today's value of the future cash flows considering the annual interest rate), which is one of the critical terms in comparing different investments alternatives and selecting the most profitable ones, is the objective function determined to be minimized.

The overnight investment cost is equivalent to the PV of the construction cost. Therefore the construction costs associated with the nuclear plant (Teplator), gas boiler plant, and heat storage plant are expressed in (1, 2, 3), respectively. Concerning the nuclear heat plant, since Teplator is a small modular reactor and its thermal power capacity is linked to its design, therefore the number of Teplator units (N^{Tep}) is the integer decision-making variable, and the construction cost (CC_{PV}^{Tep}) is derived from multiplying the number of Teplator units by the one unit's investment cost (IC^{Tep}). The capacity of the gas boiler or heat storage plants on a scale of MW could be chosen within a broad continuous range. Consequently, their construction cost is formulated based on the specific per power unit investment cost. In Eqs. (2, 3) the terms (Cap^{GB}, Cap^{HS}) are the capacities as decision-making variables, and (SIC^{GB}, SIC^{HS}) are the per MW and MWh investment costs of gas boiler and heat storage plants, respectively. The total construction cost of the heat supply station is given in (4).

$$CC_{PV}^{Tep} = N^{Tep} \cdot IC^{Tep} \tag{1}$$

$$CC_{PV}^{GB} = Cap^{GB} \cdot SIC^{GB} \tag{2}$$

$$CC_{PV}^{GB} = Cap^{HS} \cdot SIC^{HS} \tag{3}$$

$$CC = CC_{PV}^{Tep} + CC_{PV}^{GB} + CC_{PV}^{HS} \tag{4}$$

The recurring annual operation and maintenance cost (OMC) of the system expressed in (9) consists of two main terms, fixed and variable yearly operation costs are formulated in (6, 7), respectively. The fixed OMC represents the costs that do not change over time, are independent of the production level and associated with expenditures on staffing, repairs, insurance, etc. This term is given per capacity unit of gas boiler and heat storage and per number of Teplator modules. The annual variable OMC expressed in (7) represents the heat generation (*H*) dependent costs, where (SFC, $SCEC$, $SVOC$) are the specific (per MWh) fuel, carbon emission and variable operation and maintenance costs. The hourly heat generation by each unit is a decision-making variable indexed by a subscript (i). Regarding heat storage, the heat generation is negative during the charging period and positive during the discharging time. The charging/discharging cost is included in the formulations; however, it could be neglected, as its specific cost ($SHCDC$) is mainly related to the pumping electricity consumption, which is only about 1% of the thermal charged/discharged heat.

$$FOMC_a\ (€) = (N^{Tep} \cdot FOMC_a^{Tep} + Cap^{GB} \cdot FOMC_a^{GB} + Cap^{HS} \cdot FOMC_a^{HS}) \tag{6}$$

$$VOMC_a\ (€) = \sum_{i=1}^{8760} (H_i^{Tep} \cdot SHGC^{Tep} + H_i^{GB} \cdot SHGC^{GB} + |H_i^{HS}| \cdot SHCDC^{HS}) \tag{7}$$

$$SHGC^S = SFC^S + SCEC^S + SVOC^S \qquad S\text{: } Tep,\ GB \tag{8}$$

$$OC_a = FOMC_a + VOMC_a \tag{9}$$

Finally, the objective function (OF), i.e. the present value of the total construction and operation cost of the entire system over the decision making period (DMC), is expressed in (10), where (r) is the annual interest rate.

$$OF = CC + OC_a \sum_{n=1}^{DMP} \frac{1}{(1+r)^n} \tag{10}$$

2.2 Formulation of the technical constraints

The optimum solution is feasible when the technical constraints of the system are satisfied. The total hourly heat supplied by the nuclear plant, gas boiler and heat storage must comply with the hourly demand (HD^i) as expressed in (11). Obviously, each plant's hourly generated heat must not exceed the nominal thermal capacity as given in (12). Moreover, the hourly changing of the heat generation must be within the practical range as given in (13), where (R_S) is the nominal ramp rate of the heat source introduced as a percentage of the nominal capacity. Here a one-month forced shutdown is considered for the maintenance and refuelling of Teplator, assumed to be during the summer, as expressed in (14).

$$HD^i = H^i_{Tep} + H^i_{Gb} + H^i_{Hs}, \quad i=1,2,\dots,8640 \tag{11}$$

$$H^i_S \leq Cap_S, \quad S\text{: Tep, GB}, \quad i=1,2,\dots,8640 \tag{12}$$

$$H^{i-1}_S - Cap_S.R_S \leq H^i_S \leq H^{i-1}_S + Cap_S.R_S, \quad S\text{: Tep, GB}, \quad i=2,3,\dots,8640 \tag{13}$$

$$H^i_{Tep}=0, \qquad i=1294-2019 \text{ (one month in summer)} \tag{14}$$

The technical constraints concerning the heat storage operation must be met. The stored heat at each hour (i) is determined in (15), which must not be exceeded during each discharging period (16), and the charged heat must not be larger than the free capacity of the heat storage at each hour (17). The hourly storage's input/output heat is limited to the nominal charging/discharging rates of the heat storage ($R^{ch}_{Hs}, R^{dch}_{Hs}$) as expressed in (18).

$$SE^i_{Hs} = SE^{i-1}_{Hs} - H^{i-1}_{HS}, \qquad i=2,3,4,\dots\dots,8640 \tag{15}$$

$$H^i_{Hs} \leq SE^i_{Hs}, \quad Discharging, \ H^i_{Hs} > 0, \quad i=1,2,3,4,\dots\dots,8640 \tag{16}$$

$$-H^i_{Hs} \leq Cap_{Hs} - SE^i_{Hs}, \ Charging, \qquad H^i_{Hs} < 0 \tag{17}$$

$$-R^{ch}_{Hs} \leq H^i_{Hs} \leq R^{dch}_{Hs} \tag{18}$$

The optimization here is a large mixed-integer linear problem, coded using Matlab software, simulated for the typical case study addressed in Section 3, and the achieved results are reported in Section 4.

3 CASE STUDY

The problem of optimizing the proposed system's design capacities and hourly operation is solved for a typical heat demand profile, considering the techno-economic parameters addressed in Table 1. The large-scale heat demand model here has a peak of 205 MW, produced from enlarging a small city's accurate district heating profile.To ensure that the nuclear unit will be operated within the feasible range of load following, a low hourly ramp rate of only 1% of its nominal capacity is considered in the optimization. No limit for thermal energy storage is specified, but a maximum of 40 MW of thermal power is considered for heat storage. The capacity of gas boilers could be up to the demand peak, with a fast ramp rate required for load following. Some of these data are reported by [4, 6]. The maintenance shutdowns of gas boiler and heat storage are short enough to be neglected. Teplator uses spent nuclear fuel, i.e. with no cost, but the refuelling process is included in its annual operation and maintenance (O&M) cost.

Table 1: Techno-economic parameters.

Parameter	Teplator – 150 MW	Gas boiler	Heat storage
DMP (year)	50		
Maximum thermal power	N^{Tep}×150 MW N^{Tep}=0, 1, 2, …	Demand peak	40 MW
Lifetime (year)	50 [4]	25	50
Maintenance shutdown (days/yr)	30	0	0
Power ramp rate	± 0.5 MW/hr	± Nominal capacity/hr	± 0 – 40 MW/hr
Investment cost	30 M€ [4]	60 000 €/MW [6]	3 000 €/MWh [6]
Fixed O&M (per year)	12 M€	2 k€/MW [6]	8.6 €/MWh [6]
Variable O&M cost	1.1 €/MWh	1.1 €/MWh [6]	0
Fuel cost €/MWh	Spent fuel: 0 [4] Fresh fuel: 6	40	0

4 RESULTS

Table 2 addresses the optimized design capacities of the heating units (based on the techno-economic parameters given in Table 1), and Fig. 2 illustrates the optimized hourly operation of the system, supplying the hourly-based heat demand profile. The results show that the nuclear unit, Teplator, is the economic and technically feasible main heat source. In contrast, gas boiler and heat storage are required for peak shaving, load following, and during the maintenance period of the nuclear heat source.

Table 2: The optimized design capacities of the heating units.

Heating source	Teplator	Gas boiler	Heat storage
Capacity	150 MW	52 MW	800 MWh
Present value of the total cost	69.64 M€		

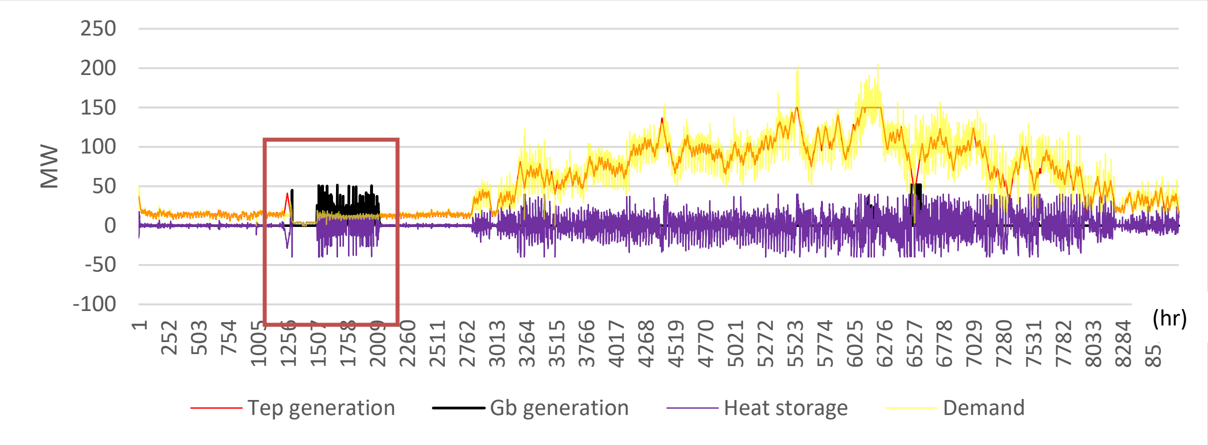

Figure 2: The hourly optimized heat supply by Teplator, gas boiler, and heat storage.

To clarify the cooperation of these three units in supplying the demand, let us focus on a smaller duration, illustrated in Fig. 2, where the Teplator shuts down for one month of annual maintenance. The operation optimization shows that the Teplator power increases to charge the heat storage before the smooth forced shutdown. Then as Teplator is out of generation, the gas boiler also is operated at the required times to recharge the heat storage, and both contribute to the load following.

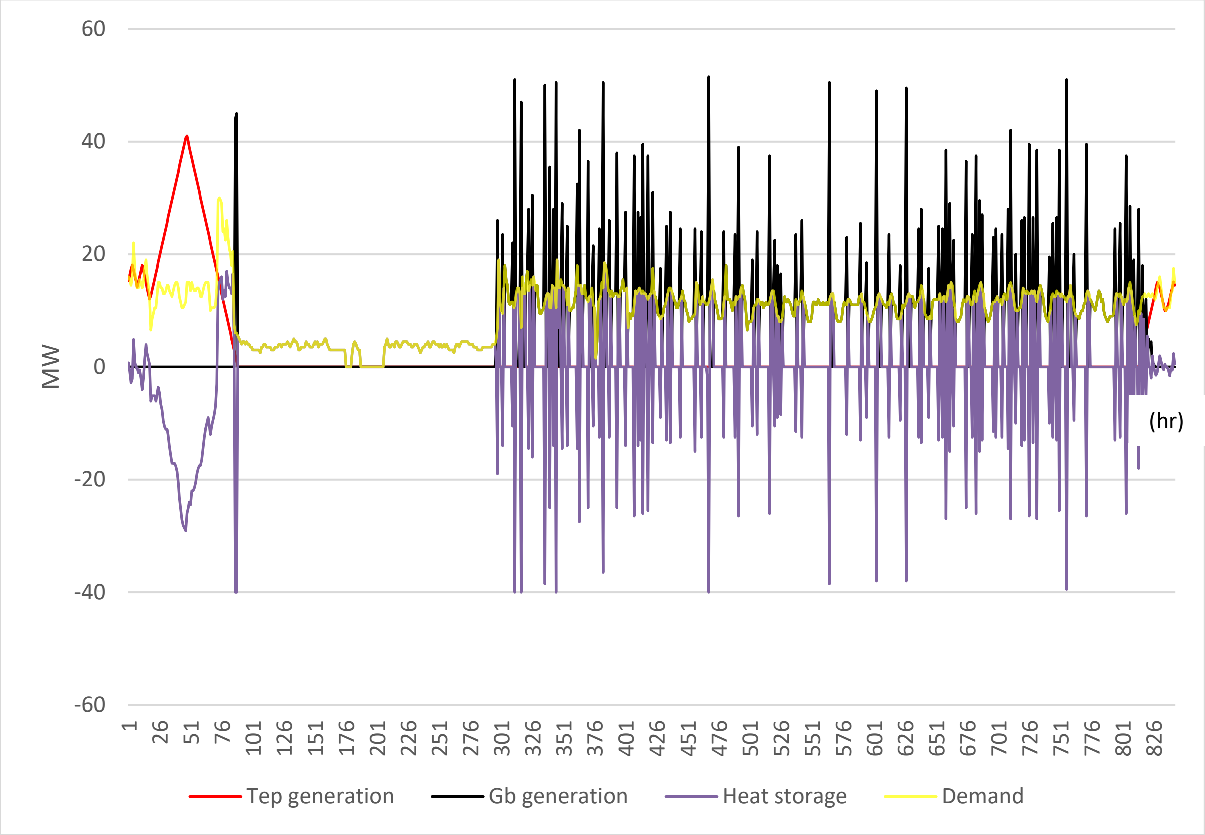

Figure 3: Cooperation of the heat units during Teplator’s shutdown

Fig. 4 illustrates a close look at the hourly operation of the system for a typical small duration. When there is a soaring demand, the gas boiler is operated since the smooth power change of the Teplator and the nominal thermal power of heat storage is insufficient for the load following.

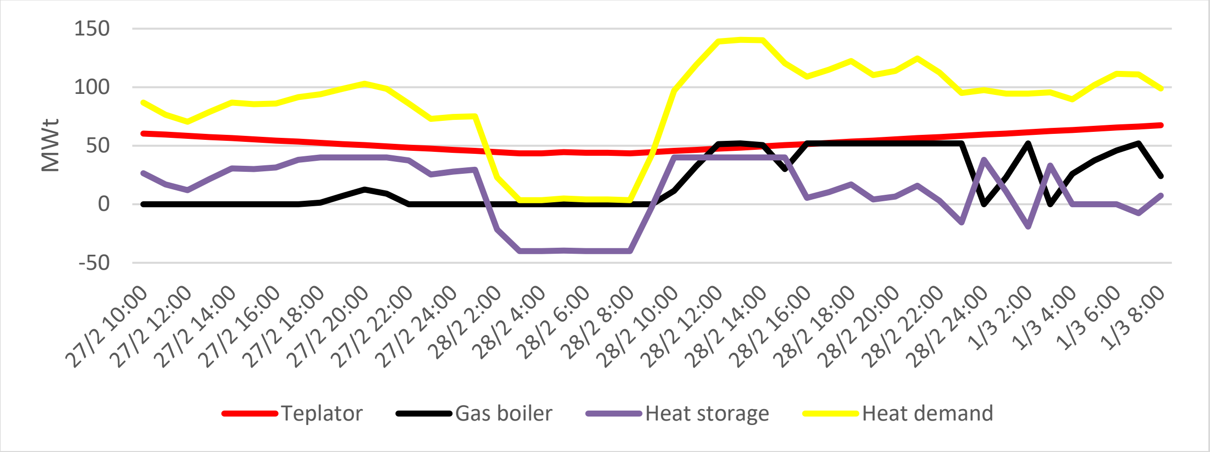

Figure 4: Hourly operation of the system for a typical duration.

From the economic point of view, using Teplator as the main heat source supported by peak shaving and load following units is an economical solution for large-scale district heating applications. Thanks to the unique feature of reusing spent nuclear fuel, the critical cost factor, i.e. the fuel cost, is eliminated. Consequently, according to the sensitivity analysis illustrated in Fig. 5, Teplator is the main heat source, even though the gas price falls to 4 €/MWh, which seems unlikely to happen. Furthermore, in case of the unavailability of spent nuclear fuel (SNF) reserves and using fresh nuclear fuel instead, the system's total cost is nearly doubled compared with the usage of spent fuel. Even though the gas price dropped to 10 €/MWh, the nuclear unit remained the competitive main heat source.

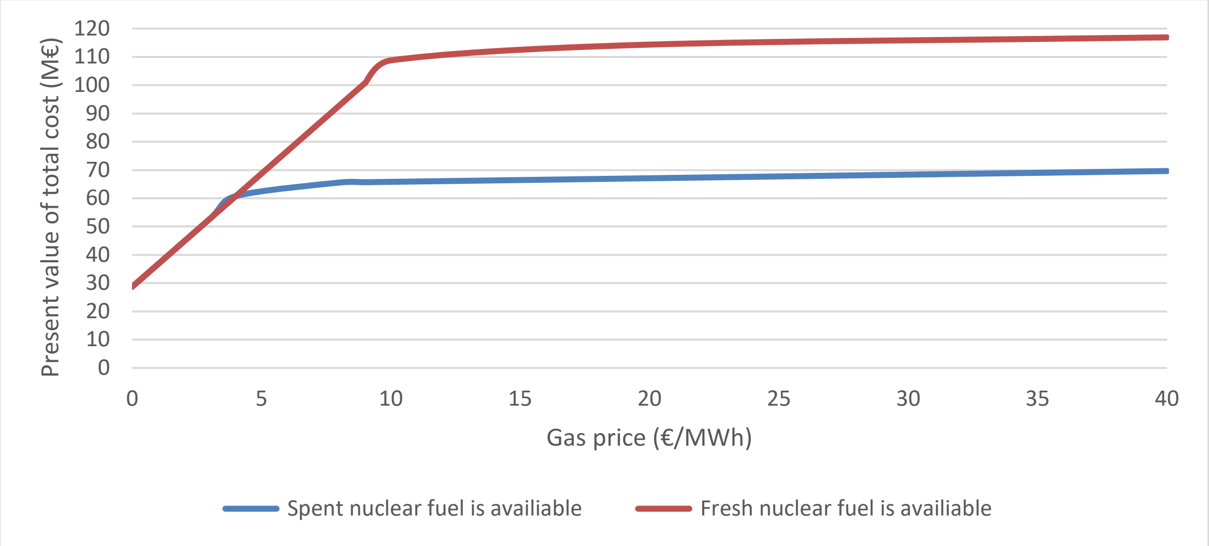

Figure 5: Sensitivity of the system to gas price.

Table 3: Optimum thermal capacities of the heating units.

Fuel		Optimum thermal capacities		
Nuclear fuel price (€/MWh)	Gas price (€/MWh)	Teplator	Gas Boiler (MW)	Heat Storage
0 (spent fuel)	0 - 4	0	165	800 MWh, 40 MW
	>4	150	52	800 MWh, 40 MW
6 (fresh fuel)	0 - 10	0	165	800 MWh, 40 MW
	>10	150	52	800 MWh, 40 MW

5 CONCLUSIONS

This study confirms the high potential of heat-only reactors such as Teplator for being a reliable, economical, and carbon-free solution for district heating applications. The probable low flexibility of the nuclear units is compensated, the load following is enhanced, and the total heat generation capacity is reduced when the heat storage and auxiliary boilers are employed for peak shaving and load following. The auxiliary gas boiler and heat storage units are also required to cover the demand during the maintenance period of the Teplator's annual maintenance and refuelling process in summer. The opportunity of reusing spent nuclear fuel offered by Teplator technology highly reduces the total costs thanks to eliminating the fuel expenses. The energy supply security could be improved where other fuel alternatives like natural gas are unavailable locally.

ACKNOWLEDGMENTS

This work was supported by the UWB university grant [SGS- 2021-018], and by the Czech technological agency grants [TK 03030109] (Development of technological unit for innovative energy storage using phase change of material), and [TK 02030069] (Energy storage for electricity generation).

REFERENCES

[1] Energy consumption in households - European Commission.

[2] Werner, Sven. “International review of district heating and cooling.” Energy 137 (2017): 617-631.

[3] Abushamah, Hussein Abdulkareem Saleh, et al. “Economics of reusing spent nuclear fuel by Teplator for district heating applications.” International Journal of Energy Research 46.5 (2022): 5771-5788.

[4] Skoda, Radek, et al. “TEPLATOR: nuclear district heating solution.” Proceedings of International Conference Nuclear Energy for New Europe. 2020.

[5] Lindroos, Tomi J., et al. “A techno-economic assessment of NuScale and DHR-400 reactors in a district heating and cooling grid.” Energy Sources, Part B: Economics, Planning, and Policy 14.1 (2019): 13-24.

[6] Danish Energy Agency, Technology data, “https://ens.dk/en/our-services/projections-and-models/technology-data”