Possibility of Nuclear Cogeneration Development in the Region of Paks

Endre Börcsök[1,2], **Ágnes Gerse**[2], **János Fülöp**[1,3]

[1]Óbuda University, Bécsi út 96/b, 1034 Budapest, Hungary
borcsok.endre@energia.mta.hu

[2]Centre for Energy Research, Hungarian Academy of Sciences, Konkoly-Thege Miklós út 29-33, 1121 Budapest, Hungary, gerse.agnes@energia.mta.hu

[3]Institute forComputer Science and Control, Hungarian Academy ofSciences, Kende u. 13-17, 1111 Budapest, Hungary, fulop.janos@sztaki.mta.hu

Abstract: Almost half of the greenhouse gas emission from the energy sector in the world is related to heat demand. The development of nuclear cogeneration offers a convenient option for emission reduction; however, the examination of economic constrains is essential. This study focuses on the heat demand of households in the vicinity of Paks NPP and compares the economic and environmental aspects of several domestic heating alternatives. In the first part of our work, we analyze the competitiveness of nuclear cogeneration in the district heating sector. While in the second part we consider, the optimal heaters for different building typological groups by taking into account some economic and environmental aspects, the distance from Paks NPP and the heat demand density. We have found that the development of nuclear cogeneration is economically viable for the existing district heating network,above a carbon price of 5 Euro/ton of CO_2. In a region of high heat demand density, the nuclear cogeneration-based district heating can be competitive with stand-alone heaters, in particular when the environmental external costs are considered, as well.

Keywords: heat sector; district heating; cost-benefit analysis; optimization

1 Introduction

The present paper evaluates the potential reduction of greenhouse gas (GHG) emission from the domestic heat sector by harnessing nuclear cogeneration. The EU has adopted challenging carbon emission reduction targets that will require a substantive change in the energy sector. A district heating alternative, where the heat is produced by nuclear energy and transported by hot water pipe systems to the buildings, has a high potential to contribute to the achievement of these targets. International reports demonstrate numerous excellent examples for nuclear cogeneration; and based on world energy statistics, the direct heat consumption ratio is around 1% globally [20]. In Hungary, nuclear energy-based district heating is an old-established method for low carbon residential heating. However, national statistics show that the heat consumption ratio at Paks NPP is far below the international level (Table 1). Paks NPP has four pressurized water reactors with freshwater cooling (VVER-440 Model V213) which supplyheat for 2600 households located at a distance of 4.5 km on average.

Table 1
Heat consumption ratio at Paks NPP [18]

Waste heat	Electricity	Heat consumption
65.7%	34%	0.3%

Although nuclear cogeneration has a negligible share in the Hungarian district heating sector nevertheless it is very cost effective as the heat price is extremely low in Paks (Table 2).

Table 2
District heating costs (for a 50 m^2 flat) in Hungary [8]. In Paks, the annual cost is far below the Hungarian average cost, however, the size of demand side is limited

Paks	Szarvas	Average
Nuclear	Geothermal	Natural gas
150.80 €/a	288.38 €/a	596.55 €/a

The first subject of this study was to identify the conditions where a nuclear energy-based district heating system (with transmission pipelines) could substitute a natural gas-based district heating system on a pure economic basis. In this part of the calculations, main input variables included fuel, nuclear heat and capital costs. The impact of different carbon prices was examined in a sensitivity analysis. The second part of this study was aimed at a cost comparison of nuclear-energy based district heating and conventional heating systems. This comparison was carried out using a standardized heat demand profile. The final results of the analysis enabled the assessment of the optimal heat supply portfolios in the subsequent part of this study where a general approach is presented for the selection of optimal residential heat supply portfolios, based on economic and environmental aspects. The resulting complex heat supply portfolios should be suitable to cover the seasonal heat demand profiles of different building typological groups. The guiding principle for the heat supply portfolio optimization was a distinction between the alternatives based on their fixed and variable costs. Fixed costs do not change with the energy production while variable costsare highly correlated to it. The alternatives that have moderate variable costs should cover the base load, while heaters having lower fixed costs should supply the peak demand. Although the main focus of this paper is the reduction of GHG emission, fixed and variable costs played a central role in the comparison of the heating alternatives.

2 Methodology

In the economic assessment of nuclear cogeneration, the fuel costs and the operation and maintenance (O&M) costs of existing natural gas-based district heating systems were considered as "base case"; they were compared to the costs of the nuclear heat supply, including the investment costs of a transmission pipe system and its corresponding O&M costs [1]. In a simple cost-benefit analysis, we focused on the payback time of the investment costs considering the decrease in heat production costs. The technical lifetime of the existing heaters was extended to the end of the examined time interval; therefore, the costs of a retrofit were beyond the scope of this study. It should, however, be noted that the technical lifetime of heat transmission pipelines is extremely long (50-60 years) compared to natural gas boilers (25-35 years) or to the remaining lifetime of Paks NPP (20-25 years). The time horizon for this study was defined around 20-40 years to reduce the uncertainty in the calculations; at the same time, an uninterrupted availability was assumed for the nuclear energy generation (future Paks II NPP). In the net present value (NPV) calculation, the investment costs are realized in the starting year (C_n, $n=0$) and were "discounted" to the present value of costs. As an extension of the district heating system, a pair of insulated pipelines of near-surface installation in rural land, several pump stations and a heat exchanger unit at the power plant were considered when calculating the net present value of costs [5]. Sizing has a strong influence on costs. In general, the transmission pipeline should have a capacity that is equivalent to 50% of the thermal peak demand and can cover 85% of the thermal energy consumption. The annual difference between the fuel and O&M costs of the natural gas-based heat supply and the nuclear energy-based heat supply (B_n; $n=1,...,40$) was discounted and summed up to the present value of benefits. The discount rate and the examined time horizon were chosen as $r=4\%$ and 40 years, respectively (1)-(3). The specific cost of the nuclear heat was estimated from the base load electricity prices, the efficiency of the nuclear power plant and the O&M costs of the transmission pipeline. In case of the existing natural gas-based district heating, the fuel and O&M costs of a thermal power plant were considered.

The present values of the stream of benefits and costs are as follows:

$$PV(B) = \sum_{n=0}^{N} \frac{B_n}{(1+r)^n}, \qquad (1)$$

$$PV(C) = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n}. \qquad (2)$$

The assessment of the overall economic impact over the whole lifetime of the project was done by calculating the net present value:

$$NPV = PV(B) - PV(C). \qquad (3)$$

Unfortunately, the long time horizon along with the assumption of constant fuel prices and O&M costs involves a degree of uncertainty in the calculations. Since the forecasted costs (fuel and carbon price, neglected retrofit of gas boilers…) raise the revenues of the investment significantly, our calculations can be considered like a "worst-case study". A further question was whether the enlargement of the existing district heating network that is presently coupled with large-scale multi-flat buildings is appropriate. For a comparison, three building typological groups were defined: large-scale multi-flat buildings, medium-scale multi-flat buildings and single family houses with state-of-the-art heating alternatives [4]. In these three groups, the heat demand densities are different; and their influence on the capital costs of the extension of the district heating network is significant [14]. The comparison is based on a uniform assumption on the heat demand of households (a thermal peak load of 10.6 kW), disregarding the fact that the average area and the energy needs are different for the three building typological groups. The annual costs of residential heating for this standardized heat demand were compared to each other, respecting the technical lifetime of the alternatives (at a discount rate of 4%). Of course, we assumed ideal operating conditions when applying this approach; we took into account the maximum possible full load hours for the comparison of the alternatives, by calculating specific heat prices [3]. In addition to the techno-economic evaluation, also the impacts of the carbon emission prices and the external costs of the environmental impacts were taken into account as two separate assessments. The environmental impact assessment was based on the forecasted external costs of state-of-the-art technology options for year 2020 [15].

Subsequently, the optimal portfolios of heating alternatives for local communities were evaluated in the scope of this study: starting from a pure economic analysis (i.e. variable and fixed costs while neglecting carbon prices), involving the carbon costs additionally, and finally, the environmental impacts of the 25 technologies. The methodology of the transportation problem [6] was chosen to determine the optimal portfolio where the 25 alternatives ($a_1, \ldots a_{25}$) represent the supply points with set $I = \{1,\ldots,25\}$, and the three building typological groups are the demand points. The seasonality of the heat demand requires a detailed monthly data set for each building typological group ($w_1 \ldots w_{12}, w_{13} \ldots w_{24}, w_{25} \ldots w_{36}$) where $J = \{1,\ldots,36\}$. The alternatives represented by the supply points were assigned to the installed capacities ($p_1, \ldots p_{25}$). The monthly maximum (j) of heat generation e_{ij}can be calculated by using the installed capacity p_i. The value of e_{ij} is equal to the product of the installed capacity and the empirical utilization time $e_{ij} = h_{ij} \cdot p_i$ [10], [11].

Generally, the maximal value of empirical utilization time, which is approximately equivalent to a capacity factor of 50%, can be used constantly all over the year. However, in the cases of the air source heat pumps and the solar thermal alternatives [17], also a seasonal effect appears in the coefficienth_{ij}. The variable x_{ij} represents the actual amount of heat produced at supply point i in month j. For each unit of heat produced at the supply point i and shipped to the demand point j incurs a constant per unit variable cost (c_{ij}); nevertheless, instead of the general case,a more realistic constant per unit variable cost $c_i = c_{ij}$ was used in the present paper.

Although the described problem is essentially similar to the transportation problem [4], nevertheless, the facts that the p_i's are variables and they appear in the objective function with constant fixed cost coefficients (d_i), indicate that a slightly modified method is needed (Table 3).

Table 3

Variables of the transportation problem

heating alternatives	single family houses			medium-scale multi flat buildings			large-scale multi flat buildings			
Natural gas stand-alone heater	$x_{1,1}$	…	$x_{1,12}$	$x_{1,13}$	…	$x_{1,24}$	$x_{1,25}$	…	$x_{1,36}$	p_1
:	:		:	:		:	:		:	:
:	:		:	:		:	:		:	:
Solar thermal district heating	$x_{25,1}$		$x_{25,12}$	$x_{25,13}$		$x_{25,24}$	$x_{25,25}$		$x_{25,36}$	p_{25}
	w_1	…	w_{12}	w_{13}	…	w_{24}	w_{25}	…	w_{36}	

The demand constraints of the problem could be interpreted as

$$\sum_i x_{ij} = w_j \tag{4}$$

and the supply constraints in the form of $x_{ij} \le e_{ij} = h_{ij} p_i$. Based on the installed capacities p_i, as variables, the supply constraints can be converted into the form:

$$x_{ij} - h_{ij} \cdot p_i \le 0 \tag{5}$$

for each month and building typological group j. The variable x_{ij} could be interpreted as the "partialuse" of capacity p_{ij} in month j, with the formula: $x_{ij} = h_{ij} \cdot p_{ij}$, where $p_{ij} \le p_i$ for each alternative i and month j. Also, the constrains and sign restrictions $x_{ij} \ge 0$ need to be transformed:

$$p_{ij} \ge 0, \tag{6}$$

and after completing by the objective function

$$\sum_{i \in I} \left(d_i \cdot p_i + c_i \sum_{j \in J} h_{ij} \cdot p_{ij} \right) = z(\min) \tag{7}$$

the mathematical optimization results in a linear programming (LP) problem. The problem defined by (4)-(7) could be summarized in a standard form:

$$\sum_{i\in I}\sum_{j\in J} c_i \cdot h_{ij} \cdot p_{ij} + \sum_{i\in I} d_i \cdot p_i = z(\min) \tag{8}$$

$$\sum_i h_{ij} \cdot p_{ij} = w_j \tag{9}$$

$$p_i - p_{ij} \geq 0 \text{ for all } i \in I \text{ and } j \in J \tag{10}$$

$$p_{ij} \geq 0 \text{ and } p_i \geq 0 \text{ for all } i \in I \text{ and } j \in J \tag{11}$$

where the formulas (8) and (10) can be replaced by:

$$\sum_{i\in I}\sum_{j\in J} c_i \cdot h_{ij} \cdot p_{ij} + \sum_{i\in I} d_i \cdot p_i^* = z(\min)\ ;\quad p_i^* = \max_j \{p_{ij}\} \tag{12}$$

The optimal solution of this linear programming problem provides the preferential portfolio of the heating alternatives.

However, an alternative interpretation of the problem described above could be a continuous relaxation of the simple facility location problem [7]. The basic idea of this alternative interpretation is the new expression of *z* objective function with discrete Δp_{is} values, where $\sum_s \Delta p_{is} = p_i$. The solution of the simple facility location problem can be realized by a dynamic algorithm based on the knapsack problem. This approach, with a simple algorithm, is commonly used in the different fields of energy [9], [16]; however, this interpretation emphasizes the special characteristics of the results. The very first step of the algorithm is the definition of the knapsacks by increasing series of the constants of the demand constraints $w_j = \sum_i x_{ij}$ for all building typological groups $j=g(s)$, $s=1,...,12$. The knapsacks are defined by 12 demand increments $\Delta w_s = w_{g(s)} - w_{g(s-1)}$, $w_{g(0)} = 0$. Each knapsack *s* is represented by the increasing installed capacity of *i* alternatives $\sum_i h_{ig(s)} \cdot \Delta p_{is} = \Delta w_s$ to supply the Δw_s demand increments. Likewise, any *s* knapsacks and each alternative *i* are interlinked with $\left(d_i + c_i \sum_{k=s}^{12} h_{ig(k)}\right) \cdot \Delta p_{is}$ costs.

The most favourable $m(s)$ alternative supplies the Δw_s demand increments of the knapsacks *s*. At the same time, the dynamic algorithm of the knapsack problem generates the special structure of the monthly heat supply and the installed capacity in the most beneficial way,

$$\sum_{s=1}^{12}\left(d_{m(s)} + c_{m(s)} \sum_{k=s}^{12} h_{m(s)g(k)}\right) \cdot \Delta p_{m(s)s} = z'(\min) \tag{13}$$

that can be considered as an optimal solution to the simple facility location problem.

Proposition 1. The substitution of the monthly heat supply $h_{ij} \cdot p_i = w_{ij}$ from a given alternative *i* of installed capacity p_i in a mixed heat supply of $\sum_{l=1}^{n} h_{lj} \cdot p_{lj} = w_{ij}$ by newly installed capacities of p_l^*, $l \in \{1,\ldots,n\}$ is disadvantageous in the optimization process, if p_i satisfies the following inequalities:

$$d_i \cdot p_i + c_i \sum_{j=1}^{12} h_{ij} \cdot p_i \le d_l \cdot p_l^* + c_l \sum_{j=1}^{12} h_{lj} \cdot p_l^* \quad \text{for each } l \in \{1,\ldots,n\}. \tag{14}$$

*Proof.*Let Q be a selection of heating alternatives in an optimal solution. Then $\sum_{l \in Q} h_{lj} \cdot \overline{p}_{lj} = w_{ij}$ for all $j \in \{1,\ldots,12\}$ where $\overline{p}_{lj} \le p_{lj}$. Consequently, the monthly heat supply w_{ij} for the whole year can be guaranteed by installed capacity $\overline{p}_l^*$. If we transform the arrangement of the monthly heat supply

$$\sum_{l \in Q} \left(d_l \cdot p_l^{**} + c_l \sum_{j=1}^{12} h_{lj} \cdot p_l^{**} \right) \le \sum_{l \in Q} \left(d_l \cdot \overline{p}_l^* + c_l \sum_{j=1}^{12} h_{lj} \cdot \overline{p}_{lj} \right) \text{ where } \quad p_l^{**} = \frac{\sum_{j=1}^{12} h_{lj} \cdot \overline{p}_{lj}}{\sum_{j=1}^{12} h_{lj}},$$

furthermore, for all p_l^{**} there exists a p_{il} where

$d_i \cdot p_{il} + c_i \sum_{j=1}^{12} h_{ij} \cdot p_{il} \le d_l \cdot p_l^{**} + c_l \sum_{j=1}^{12} h_{lj} \cdot p_l^{**}$, then along with the constrains (14) and $p_i = \sum_{l \in Q} p_{il}$, these together result in

$$d_i \cdot p_i + c_i \sum_{j=1}^{12} h_{ij} \cdot p_i \le \sum_{l \in Q} \left(d_l \cdot \overline{p}_l^* + c_l \sum_{j=1}^{12} h_{lj} \cdot \overline{p}_{lj} \right) \qquad \blacksquare$$

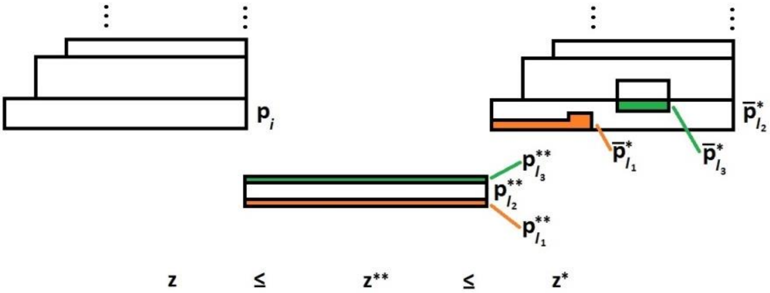

Figure 1
Knapsack replenishment with newly installed capacities

Based on these results, we conclude that a homogeneous supply of the monthly heat demand increments is more advantageous than the intermittent heat supply from newly installed capacity (Fig. 1).

Proposition 2. The substitution of the monthly heat supply from a given alternative i of an existing p_i installed capacity by the heat supply from an existing p_l installed capacity is disadvantageous if

$$d_i \cdot p_i^* + c_i \sum_{j=1}^{12} h_{ij} \cdot p_i^* \le d_l \cdot p_l^* + c_l \sum_{j=1}^{12} h_{lj} \cdot p_l^* \tag{15}$$

for all installed capacities $l \in \{1,\ldots,n\}$ where $\sum_{j=1}^{12} h_{ij} \cdot p_i^* = \sum_{j=1}^{12} h_{lj} \cdot p_l^* = w_i$ (Fig. 2).

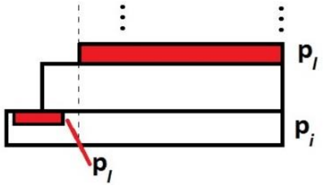

Figure 2

Knapsack replenishment with existing capacities

Proof. For each installed capacity $l \in H$ there exists an annual amount of heat supply $w_l = \sum_{j=1}^{12} h_{lj} \cdot p_{lj}$, $w_l < w_i$ such that

$$d_l \cdot p_l^* + c_l w_l \le d_i \cdot p_i^{**} + c_l w_l \quad \text{and} \quad p_i^{**} \le p_i^* \tag{16}$$

By the reason of constrains (15)-(16), we can identify the inequality $c_i < d_i \cdot \frac{p_i^{**} - p_i^*}{w_i - w_l} + c_l$ where the quotient $\frac{p_i^{**} - p_i^*}{w_i - w_l}$ cannot be positive, therefore $c_i < c_l$. Accordingly, the substitution of the heat supply from a given alternative i of an existing p_i^* installed capacity by another, existing alternative of heat supply, results in a higher objective function value. ■

The conclusion of the two propositions is that the supply of heat demand increments Δw_r should be provided in a homogeneous way for an optimal solution.

In the present study, the proposed problem was solved in the same way as a LP problem in GAMS environment [19], furthermore, by the dynamic algorithm of the knapsack problem. The negligible differences in the final results of the objective function values were related to round-off errors.

3 Results

The detailed analysis suggests that the substitution of the natural gas-based district heating by nuclear cogeneration can be beneficial, considering the lower fuel costs, O&M costs and carbon costs. The effects of two variables (heat demand *e* and distance of transport *t*) are crucial to the cost-benefit analysis. Analogously, the NPV of the optional extension of the nuclear cogeneration depends on variables*e* and *t*, therefore a multivariable NPV(*e*,*t*) function can be defined. The NPV(*e*,*t*) decreases as a function of the distance and increases as a function of the heat demand volume, i.e. $NPV_t'(e,t) < 0$ and $NPV_e'(e,t) > 0$. The limitcurve defined by NPV(*e*,*t*)=0 determines the minimal heat demand values where the investment can be economically viable. Based on the analysis, it is worth to compare the annual heat demand of some existing district heating networks in the region of Paks with the position of the limit curve.

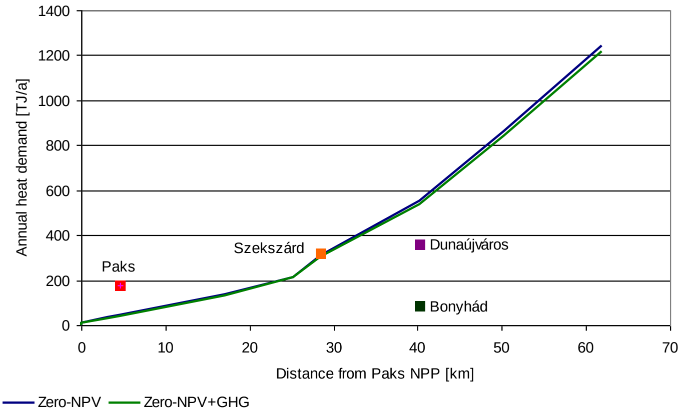

Figure 3

Towns in the region of Paks where the nuclear energy-based district heating can be competitive (40 years long payback period; 4% discount rate; carbon price of 5 Euro/ton of CO_2)

As it can be seen (Fig. 3), there are two towns, Paks (having an existing system) and Szekszárd that have sufficient heat demand to be supplied by nuclear heat in an economically viable way; both of them are above the limit-curve. On the basis of a partial sensitivity analysis, a supply to Dunaújváros would require a carbon price of at least 25 Euro/ton of CO_2,being considerably higher than the actual price (carbon emission price in 2015: 4.5-4.9 Euro/ton of CO_2). At present conditions, a nuclear-based heat supply is only feasible to Szekszárd where the payback period was evaluated at different carbon prices (Fig. 4).

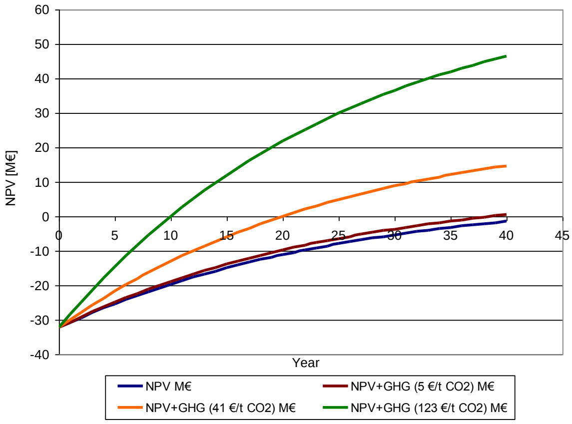

Figure 4
Time evolution of NPV for nuclear energy-based district heating at Szekszárd with different carbon prices

An increase in the carbon prices impacts the basic level of revenue and shortens the payback period of the project. In case of Szekszárd, the NPV of the investment reaches zero in 38 years when considering the present carbon price. In order to shorten the payback period to 20 years, a carbon price of 41 Euro/ton of CO_2 would be necessary; however, it should be noted that some low carbon scenarios predict even higher values than that in the energy sector. Shorter payback time seems to be not realistic as a payback time of 10 years would require a carbon price of 123 Euro/ton of CO_2.

As mentioned above, it was an important additional point of our study if the extension of the district heating network could be an economically viable solution to cover the expected increase in the heat demand [13]. This question was addressed from the point of view of the residential sector. The comparison of the heating alternatives was done by using a standardized heat demand profile for the three building typological groups and, additionally, the carbon price (17 Euro/ton of CO_2) and the external costs of environmental impacts were taken into account as two separate assessments. In comparison, the nuclear heat was the most favorable alternative for the large-scale multi flat buildings (LMB), by supposing a high penetration of the district heating network (Fig. 5). In case of the group consisting of medium-scale multi flat buildings (MMB), the nuclear district heating is competitive only when also the environmental external costs are considered in the assessment. Finally, the stand-alone heating could be the favorable option in cases of single family houses (SFH) as a result of the higher capital cost of the district heating installation.

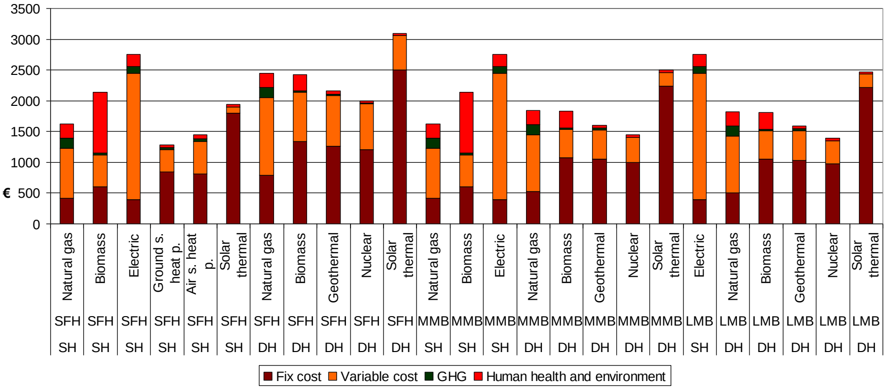

Figure 5

Annual cost of residential heating for a standardized case (140 m^2 ; 10.6 kW). The fixed cost of the nuclear district heating includes the costs of a 30 km transit pipeline. SH: Stand-alone heater; DH: District heating

The detailed comparison of the heating alternatives enables the selection of the optimal heat supply portfolios of the households, which are suitable to cover the seasonal heat demand profiles of the different building typological groups. Three portfolios were selected for each building typological group (Figure 6 and 7).

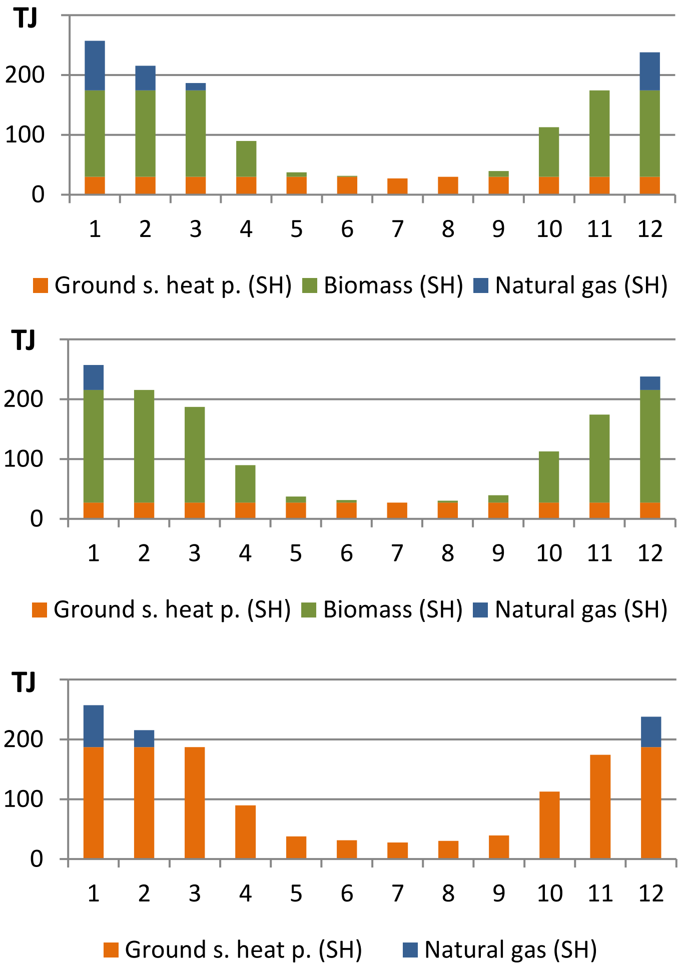

Figure 6

Optimal heat supply portfolios of single family houses for three cases: considering the fixed and variable costs only (top); including the carbon price additionally (middle) and finally, the external costs of environmental impacts (bottom)

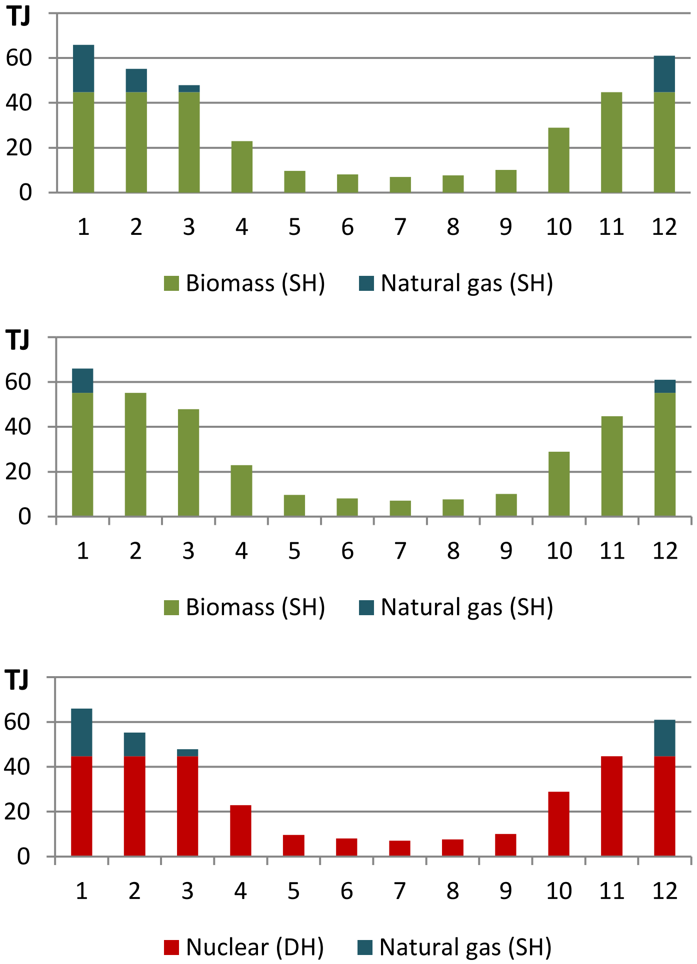

Figure 7

Optimal heat supply portfolios of medium-scale multi flat buildings for three cases: considering the fixed and variable costs only (top); includingthe carbon price additionally(middle) and finally, the external costs of environmental impacts (bottom)

In the first case, fixed and variable costs were considered only (neglecting carbon prices). In the second case, carbon prices were added, as well, and in the third case, also the external costs of the environmental impacts were taken into account. In cases of single family houses, the portfolios consist of three stand-alone heating technologies (biomass, ground source and natural gas-based heating). The base heat demand is supplied by ground source heat pumps while the peak load is covered by the natural gas based-heating; their ratio is different in the three scenarios. When considering a carbon price of 17 Euro/ton of CO_2 in the assessment, the installed peak load capacity of 64 MW of natural gas-based heating decreases to a half of its initial value; at the same time, the installed capacity of ground source heat pumps is constantly 23 MW in both cases (i.e. carbon prices neglected vs. included). In the third case, where the external costs of environmental impacts were considered, as well, the biomass capacity that was significant in the first two cases (112 MW without carbon prices and 146 MW with carbon prices) is not part of the energy mix; the role of the biomass combustion was replaced by 145 MW installed capacity of ground source heat pumps.

In case of the medium-scale multi flat buildings, the share of the stand-alone heater technologies is reduced because of the building structure; at the same time, the higher heat load density makes the district heating more attractive economically. The peak load is covered by natural gas-based heating of 17 MW installed capacity. Similarly to the single family houses, the installed capacity of natural gas based heating halves after considering the carbon price. Furthermore, 35 MW installed capacity of stand-alone biomass heating was replaced by the nuclear district heating after taking into account the external costs of environmental impacts in addition to the carbon price.

In the building typological group of the large-scale multi flat buildings, the feasible, competitive heating technologies are, with no exception, the district heating-based alternatives. In the first assessment, the 29 MW of nuclear base demand capacity was complemented by 14 MW installed capacity of natural gas-based heat in peak load. The installed capacity of the nuclear-based district heating increases to 31 MW after considering the carbon price, and it reaches 36 MW after taking into account the external costs of the environmental impacts, as well.

Conclusions

The aim of this study was to identify the potential costs and benefits of the development of the nuclear energy-based district heating. The main benefit of moving towards the district heating is expected from the carbon emission savings it can provide. Since a conservative approach was applied in our calculations with no exception, results can be considered as “a worst-case study”. At present conditions, Szekszárd is the only potential new location for nuclear-based heat consumption; however, the long payback period resulting from high capital costs and low carbon prices increases the risk of investment. Overall, we conclude that a governmental guarantee (assurance of nuclear heat in the long term) and the enlargement of the group of customers (by medium-scale multi flat buildings) could promote the investment. For single family houses, the low heat demand density is an obstacle to the development of the district heating, but the installation of heat pumps could contribute to reaching the carbon emission reduction targets. In the optimal heat supply portfolio calculation for households, the variable costs increase significantly when considering the external costs. Therefore, the alternatives of higher fixed costs could be competitive in the energy mix of the heat sector. The method presented in our study was finalized by conducting a partial sensitivity analysis to assess the influence of carbon prices. However, the sensitivity analysis could be extended to any other variable by a statistical approach [12] or by multiobjective optimization [2].

Acknowledgement

The research of the second author was supported in part by OTKA grant K 111797. Finally, we thank János Osán and Tibor Orbán for their comments that greatly improved the manuscript.

References

[1] Andrews D., Riekkola K. A., Tzimas E., Serpa J., Carlsson J., Garcia P. N., Papaioannou I. Background Report on EU-27 District Heating and Cooling Potentials, Barriers, Best Practice and Measures of Promotion JRC Report 2012

[2] Börcsök E., Gerse A., Fülöp J. Applying Multiobjective Optimization for the Heat Supply in the Residential Sector in Budapest, 12th IEEE International Symposium on Applied Computational Intelligence and Informatics, SACI 2018 May 17-19, Timisoara, Romania

[3] Börcsök E., Talamon A., Török Sz. Possibility of Nuclear Cogeneration Development in the Region of Paks, NENE, 2016 Sept. 5-8, Portoroz, Slovenia

[4] Börcsök E., Talamon A., Török Sz. Socio-Economic Aspects of Nuclear Cogeneration Development in the Region of Paks, IAEA Technical Meeting, 2016 Nov. 21-23, Wien, Austria

[5] Büki G., Metzing J., Orbán T. Local Energy Supply 2014 [in Hungarian]

[6] Cornuejols G., Thizy J. M. A Primal Approach to the Simple Plant Location Problem, Alg. Disc. Meth. Vol. 3, No. 4, December 1982

[7] Dantzig G. B. Linear Programming and Extension, Princeton University Press August 1963

[8] District Heat Price Regulation for Different Consumer Groups 50/2011. (IX.30) directive of Ministry of National Development [in Hungarian]

[9] Göblyös B. Energy Mix Optimization in District Heating Sector, PhD Dissertation, Óbuda University 2016 [in Hungarian]

[10] Kádár P. Application of Optimization Techniques in the Power System Control, Acta Polytechnica Hungarica, Vol. 10, No. 5, 2013

[11] Kádár P. Pros and Cons of the Renewable Energy Application, Acta Polytechnica Hungarica, Vol. 11, No. 4, 2014

[12] Kharitonov V. V., Criteria of Return on Investment in Nuclear Energy, Nuclear Energy and Technology, Vol. 3, pp. 176-182, 2017

[13] Hartmann B., Börcsök E., Oláhné Groma V., Osán J., Talamon A., Török Sz., Alföldy-Boruss M. Multi-Criteria Revision of the Hungarian Renewable Energy UtilizationAction Plan – Review of the aspect of economy, Renewable and Sustainable Energy Reviews, Vol. 80, pp. 1187-1200, 2017

[14] Macadam J., Davies G., Cox J., Woods P., Turton A. The Potential and Costs of District Heating Networks, A report to the Department of Energy and Climate Change Pöyry 2009

[15] Mayer-Spohn O, Besl M. Documentation of the Life Cycle Inventory Data in CASES, CASES – Cost Assessment for Sustainable Energy Markets, Deliverable No. D6.1, October 2007

[16] Methodology for the WEM Wholesale Electricity Price Module, OECD IEA Report 2012

[17] Nyers J. COP and Economic Analysis of the Heat Recovery from Waste Water using Heat Pumps, Acta Polytechnica Hungarica, Vol. 13, No. 5, 2016

[18] Report of sustainability 2012, MVM Group 2013

[19] Roshenthal E. R., Brooke A., Kendrick D., Meeraus A., Raman R., GAMS A User’s Guide.GAMS Development Corporation, Washington 1998

[20] World Energy Balances 2014 edition, OECD IEA Report, Paris 2014