The 21st International Conference on
Thermal Science and Engineering of Serbia
SimTerm 2024
Niš, Serbia, Oct 22-25 2024

doi: 10.5937/SimTerm24264S

Operational Optimization of Heating Systems with Air-Source Heat Pumps Based on Realistic Electricity Tariffs

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Abstract: Heat pumps are among the crucial technologies for increasing renewable energy utilization in the building sector. One of the main factors for adopting heat pumps is their economic attractiveness, which depends on several factors. Air-source heat pumps are especially challenging in this regard because their performance relates significantly to the outdoor conditions. Optimization of operational regimes can lead to lower running costs of heating systems with heat pumps. However, most research efforts in this area are based on relatively simple pricing rules. This paper presents an attempt to perform operation optimization of a heating systems based on a realistic electricity pricing policy, applicable to the households in Serbia. The approach uses the results of detailed building simulations and existing rules for charging electricity as the inputs. It applies mixed integer linear programming to obtain the operation regimes that minimize the operational cost of a heating system over one year. The paper shows the comparison of the obtained results and the results drawn from simplified electricity pricing rules. Finally, it discusses the importance, applicability, and limitations of the presented approach.

Keywords: heat pump, mixed integer linear programming, operational optimization, residential building.

1. Introduction

Heat pumps are a very important technology for adopting renewable energy sources for heating and cooling of buildings [1]. Economic attractiveness is one of the main factors for adopting heat pumps. Cost optimization of design and operation is a tool that improves the economy of the heat pumps and might motivate their adoption. Optimization of operation regimes is important for achieving satisfactory economic results:

- In the planning stage, as a part of integrated design and operation optimization,
- During the operation period, to reduce the running costs.

Pesola [2] demonstrated the importance of operation optimization for the integration of decentralized heat pumps with the existing centralized district heating systems and reduction of the operation cost. Li et al. [3] used the non-dominated sorting genetic algorithm II for multiobjective optimization of the system that combines a photovoltaic heat pump and thermal storage. Aguilera et al. [4] combined mixed integer linear programming (MILP) with demand forecasting to reduce the costs of large-scale heat pumps with thermal storage. Krützfeldt et al. [5] also used MILP for combined design and operation optimization of a heat pump system for a residential building.

However, in most cases, the authors threat electricity (and other) prices as predefined model inputs. In practice, electricity prices might depend on the consumption, and as such, cannot be the inputs to the optimization models.

This paper considers one such case. It uses MILP to find the cost-optimal operation regime of a household heating system with air-source heat pump (ASHP) and district heating network connection. The optimization results are applied to analyze the difference between the operation regimes that correspond to the realistic and simplified prices.

2. Methodology

This paper aims to optimize the operation of a heating system of a residential building. The heating system consists of ASHP and a district heating networks connection. The optimization problem is adjusted to consider realistic Serbian electricity pricing for households.

The tariff system is defined in a progressive manner that motivates electricity savings, which might be problematic in terms of choosing heat pumps over alternative technologies such as gas boilers. There are three pricing zones:

- Green zone, with the lowest price of electricity, available until the total monthly consumption exceeds 350 kWh, for the period of 30 days,
- Blue zone, available from the moment the monthly consumption reaches the threshold of 350 kWh, until it exceeds 1600 kWh, for the period of 30 days,
- Red zone, with the highest price of electricity, valid after the monthly consumption exceeds 1600 kWh, for the period of 30 days.

If the accounting period is different than 30 days, the thresholds are adjusted proportionally.

In addition, the pricing model also includes taxes and incentives.

There are two kinds of tariffs applicable to households:

- Unique tariff, with the same electricity price throughout the day,
- Dual tariff, with the day-time electricity price (valid for 16 hours per day) being four times larger than the night-time price (valid for the remaining eight hours per day).

The pricing rules described — in particular the existence of the green, blue, and red zone — show that the price of electricity in each moment depends on the amount of electricity already consumed. Since the electricity amount must be a decision variable, the prices cannot be inputs.

The optimal operation parameters, which define how much heat is obtained from the heat pump and district heating system at each time step, are determined by formulating and solving MILP problem. The time step used is 1 h and the optimization horizon is one year.

The objective function to minimize is the total annual operational cost of electricity and district heating, expressed in Serbian Dinars (RSD), as defined in Eq. (1):

$$\min \sum_{i=1}^{m} \left(C_{e,\text{fix}}^{i} + C_{t,\text{fix}}^{i} + \sum_{j=1}^{n} c_{e,\text{G}}^{j} W_{e,\text{G}}^{j} + c_{e,\text{B}}^{j} W_{e,\text{B}}^{j} + c_{e,\text{R}}^{j} W_{e,\text{R}}^{j} + c_{t}^{j} Q_{t}^{j} \right) \tag{1}$$

where:

- i and j are the indices of a month and hour, respectively;
- m and n are the number of months considered and the number of hours in an observed month, respectively;
- $C_{e,\text{ fix}}^{i}$ and $C_{t,\text{ fix}}^{i}$ are the fixed monthly costs of electricity and district heating, respectively, in RSD; these quantities are the inputs into the optimization problem and affect only the value of the objective function, but not the optimal values of the decision variables;
- $c_{e,\text{G}}^{j}$, $c_{e,\text{B}}^{j}$, and $c_{e,\text{R}}^{j}$ are the prices of the electricity in the hour j, for the blue, green, and red zone, respectively; the prices are expressed in RSD/kWh and might depend only on the time of day, i.e. on j, so they are the inputs to the optimization problem;
- $W_{e,\text{G}}^{j}$, $W_{e,\text{B}}^{j}$, and $W_{e,\text{R}}^{j}$ are the non-negative continuous decision variables that represent the amounts of electricity consumed during the hour j, for the blue, green, and red zone, respectively, expressed in kWh;
- c_{t}^{j} is the price of the district heat in the hour j, expressed in RSD/kWh, which is an input to the optimization problem;
- Q_{t}^{j} is the non-negative continuous decision variable that represents the amount of heat taken from the district heating system during the hour j, expressed in kWh.

In addition to the afore-mentioned decision variables, the model also uses:

- $Q_{t,\text{HP}}^{j}$, which is the non-negative continuous decision variable that represents the amount of heat produced by the heat pump during the hour j, expressed in kWh;
- δ_{G}^{j}, δ_{B}^{j}, and δ_{R}^{j}, which are auxiliary binary decision variables that indicate whether the electricity is consumed in the blue, green, and red zone, respectively, during the hour j.

The model has a number of constraints. For brevity, they are omitted from this paper. The main categories of the constraints are:

- Constraints that bound the decision variables, i.e. grid electricity, district heat, and heat pump output amounts,
- Constraints that ensure the satisfaction of electricity and heat demand for each hour,
- Constraints related to the electricity pricing rules

The binary decision variables and constraints related to the electricity pricing make the model considerably more complex and harder to formulate and solve. This might lead to an outstanding increase in the computational time and resources needed to solve it.

This model covers a relatively simple energy supply system of a building that contains the connections to the electrical grid and district heating system, as well as ASHP. The model is applicable to all kinds of electrical heat pumps with a wide practical application. ASHP is chosen for the demonstration of the model because its coefficient of performance (COP) and capacity vary significantly with the environment conditions.

The model can be further extended to support:

- Cooling applications,
- Semi-continuous decision variables, as used in [6, 7],
- Other components such as heat and cool storage, boilers, or cogeneration, as described in [6, 7],
- Solar thermal and photovoltaic systems,
- Consideration of additional objectives, i.e. multiobjective optimization.

Furthermore, this model in its simplest variant can be decomposed over time into a series of smaller monthly models, which might result in the significant reduction of computational time required to obtain the optimal solution.

The model is implemented in the Python programming language by the first author of the paper. It uses the Gurobi Optimizer [8] as MILP backend.

3. Results and discussion

The described operation optimization approach is applied to a case of a single-family residential building with the heated floor area of 150 m². The demand is obtained with the EnergyPlus software [9], using the weather data provided as a typical meteorological year for the City of Niš, Serbia. ASHP properties are taken from manufacturer data and account for the dependence of the capacity and COP on the outdoor and indoor conditions. The optimization procedure is applied for the entire heating season, i.e. from October to April, which makes a total of 5088 hourly time steps.

The results are obtained considering three tariff scenarios:

- Existing unique tariff,
- Existing dual tariff,
- Hypothetical simple tariff that uses always the same price, equal to the blue-zone price.

It is worth mentioning that the simple tariff does not have the zones, which means that the model is simpler, and the price of electricity is a constant and input to the optimization problem.

The results obtained for operation optimization in three scenarios clearly show that, for the current prices, ASHP is preferable over the district heating supply, except when the electricity is consumed in the red pricing zone. Figure 1 shows this conclusion.

Consequently, in both unique and dual tariff cases, the part of the heating demand covered by ASHP is constrained with the threshold value of the red zone. In other words, ASHP and all other electricity consumers are about to use at most 1600 kWh (in a month with 30 days). The rest of the heating demand is covered from the district heating system. In the case of the simple tariff, the price of the electricity is always the same and the entire demand can be satisfied with ASHP, if its capacity is sufficient. Figure 2 shows the demand coverage by ASHP and district heating system.

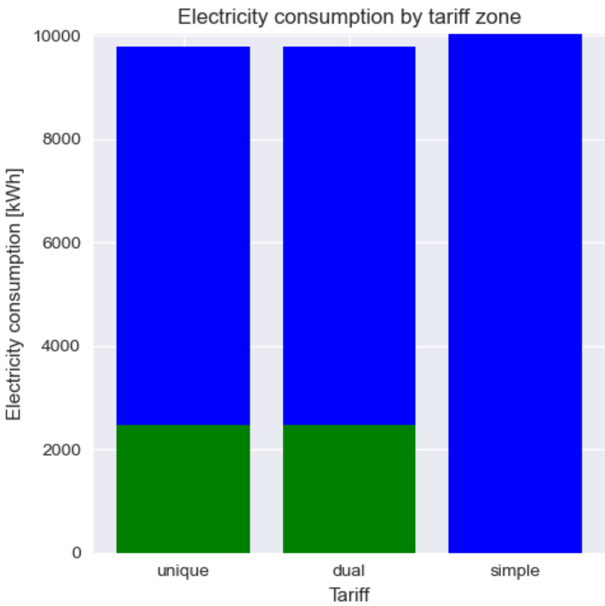

Figure 1. Electricity consumption in different tariff zones

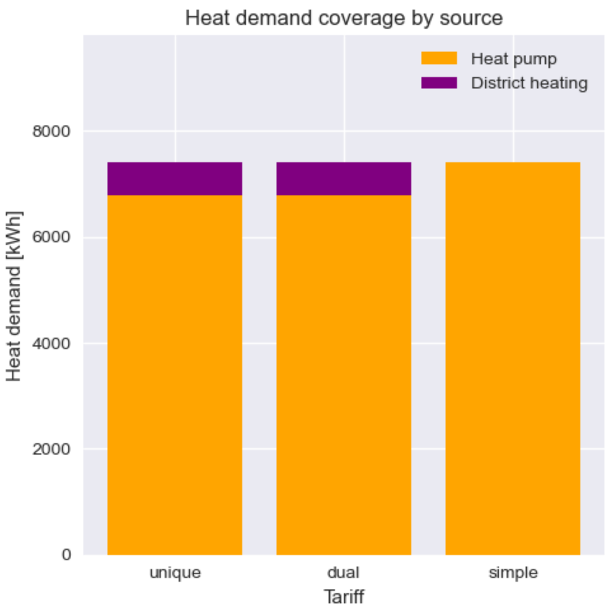

Figure 2. Heat demand covered by the heat pump and district heating system

The above consideration raises a very serious question whether and to what extent the existing electricity pricing rules obstruct a wider acceptance of heat pumps.

Figure 3 shows the histogram with the distribution of the heat demand coverage by source for various outdoor temperature values. An interesting observation is that the heat demand that corresponds to the outdoor temperatures above 0°C is provided entirely by ASHP, due to larger COP values.

Another important conclusion that cannot be seen from the figures is that the heat generated during nights comes from the heat pumps completely due to low prices of electricity.

Figure 4 compares the values of the objective function for all three scenarios. The operational cost of the system is the highest for the unique tariff, mostly because it does not benefit from the low night prices. The case of simple tariff underestimates the cost by over 30% just by neglecting the red zone prices.

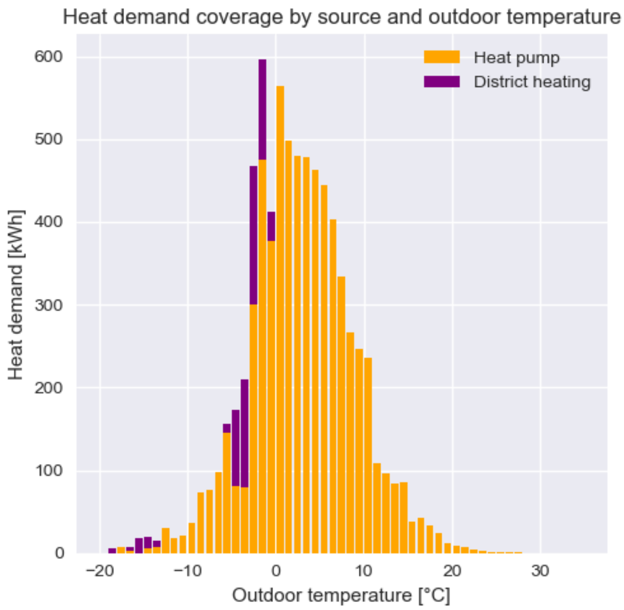

Figure 3. The distribution of the heat demand coverage by source for various outdoor temperature values

4. Conclusions

This paper presents operational optimization of a building heating system with a heat pump and district heating network connection. The most important aspect of the paper is using realistic electricity pricing rules that apply for Serbian households, which make the optimization problem more complex and computationally intensive. The cases with real prices are compared to a simplified case with a fixed price. It is concluded that the differences in the value of the objective function and the variables that define the operation regime can be significant.

It is necessary to underline that the obtained values of the objective function and operation parameters are highly dependent on the electricity and heat demand, properties of the components, and the prices.

The presented model covers a relatively simple energy system but can be extended to include other components and applications, more complex representation of decision variables, and multiobjective optimization.

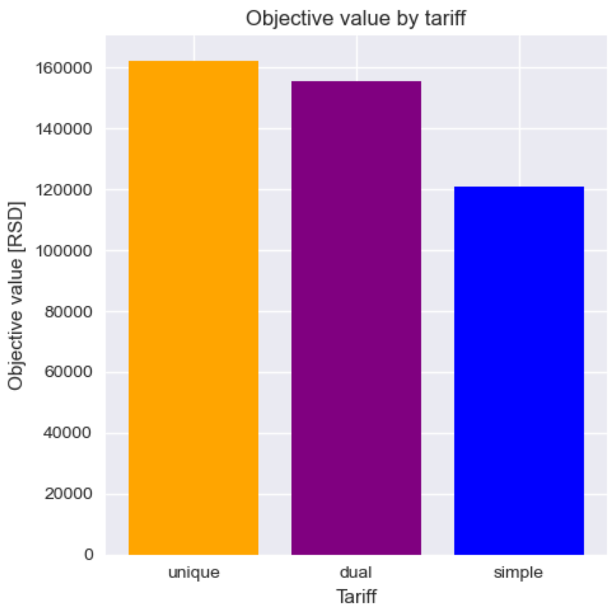

Figure 4. The values of the objective function for different tariffs

The main reasons that can justify the application of such an approach are:

- Operational regimes and objective values might differ significantly with realistic compared to simplified pricing.
- More accurate results of optimization problems can provide a better insight into the potential for cost reduction.
- More accurate results might also have the benefit of better understanding of desirable operation regimes.

However, detailed and accurate approaches might require more complex and computationally intensive mathematical models, which can be an obstacle to wider adoption of such an approach.

Finally, a very important limitation of this approach is that it is very complicated to be implemented directly. It requires the electricity and heating demand predictions until the end of the observed month, as well as all the parameters that impact the performance of heat pumps significantly. However, it might be possible to incorporate the obtained results into a machine learning models and extract rules to predict desirable operation of energy supply systems. This can be a guideline for future work.

Acknowledgment

This research was financially supported by the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia (Contract No. 451-451-03-65/2024-03).

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