

A heat pump strategy to meet the simultaneous heating and cooling needs of a multifunctional office and residential building

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Abstract - This paper discusses control solutions for the heating needs of a multifunctional office and residential building. The building is heated by district heating and heat pumps, whose different bivalent plants are analysed. To determine these bivalent operating states, optimisation calculations were performed in terms of primary energy consumption, operating costs and CO₂ emissions. In summary we can conclude the optimal operating mechanism.

Keywords: heat pumps, district heating, building heating, heating control, heating optimisation

Nomenclature

Sing	Description	Unit of measurement
A	floor area	m ²
C	cost of hourly thermal energy consumption	HUF/h
COP	coefficient of performance	1
E _{primary}	primary energy consumption	kWh/m ² h
E _{electric, hp}	electricity consumption of the heat pump	kWh/m ² h
E _{res.heat}	residential area's heating demand	kWh/m ² h
E _{off.heat}	office area's heating demand	kWh/m ² h
ε _{primary}	primary energy conversion factor	1
p	unit price of electricity	HUF/kWh
t	temperature	°C
m	CO ₂ emissions	kg
Q	heating power	kW
Indexes		
distr.	district-heating	
res. heat	residential area's heating	
e	external	
only distr.	only district heating	

Indexes	
alternating	alternating operation state
hp	heat pump
parallel	parallel operation state

I. INTRODUCTION

Today, minimising the energy use of the building stock is becoming increasingly important. The European Union aims to reduce its 1990 CO₂ emissions by 55% by 2030 and to achieve 100% carbon neutrality across the EU by 2050 under the European Green Deal, the Paris Agreement and the European Climate Law.

The fossil primary energy consumption of buildings can be reduced by the utilisation of renewable-based heat producers, such as solar thermal applications for heating and cooling, [1] fuel cells [2] and heat pumps [3]. However, the efficiency of these is not optimal in every operational point, therefore they need an optimised plan to co-operate with conventional heat producers, like boilers or district heating.

In the context of these considerations, in this paper I will investigate the options for optimising building operation by moving between the given system options - taking into account the entry and exit of heat producers and the optimal heat demand to be met by a heat producer.

II. DESCRIPTION OF THE BUILDING

The subject of the study is a multifunctional office and residential building. I will investigate the options for optimising building operation with this system, taking into account the entry and exit of heat generators and the optimal heat demand to be met by the heat generator.

The heating needs are met by district heating supplied by Főtáv, (the Budapest district heating company) and a heat pump on the roof, while the cooling needs are met by a chiller, also on the roof, and the heat pump just mentioned.

The building houses an office section and three almost identical residential towers. The residential part of the building has a floor area of 5126 m², while the office and common areas have a floor area of 4692 m². The expected annual thermal energy use of the building has been estimated

by the designer in accordance with TNM Regulation 7/2006, a Hungarian code of practice for the energy performance of buildings issued in 2006. They are as follows:

TABLE I: Estimated energy use of the building [4.]

Purpose of energy consumption	Required energy type	The building's yearly heating and cooling energy consumption
Heating (Residential)	District-heating and electricity	34,87 kWh/m ² /year
DHW (Residential)	District-heating and electricity	30,00 kWh/m ² /year
Cooling (Residential)	Cooling energy	19,75 kWh/m ² /year
Heating (Offices)	District-heating and electricity	40,52 kWh/m ² /year
Cooling (Offices)	Cooling energy	65,00 kWh/m ² /year
Free cooling winter cooling	Cooling energy	15,00 kWh/m ² /year

III. DESCRIPTION OF THE HEAT SUPPLY SYSTEM

The building's heating needs are met by an air-to-water heat pump and district heating supplied by the Főtv. The heat pump is not planned to operate below 5°C external temperature based on the design documentation but was not supported by any optimisation calculations. Below 5°C the whole complex the whole heating of the building will be supplied from then on by a secondary system supplied by Főtv. I will examine this bivalent point - set at 5°C in the plans - from a primary energy, economic and environmental point of view and optimise it on the basis of the data obtained. It is important to note, that this bivalent point is only a designer estimate.

The optimisation aspect will be the CO₂ emissions. The heat pump provides both heating and cooling but given that my field work focuses on the heating plant, I will not investigate the cooling plant.

Technical data of the heat pump in heating mode:

Heating capacity:	415 kW
• Heat output (heating):	40 °C
• Return temperature (heating):	35 °C
• Water-side flow rate:	19,88 l/s
• Ambient air temperature:	0 °C

For design reasons, the heating splitter can only be supplied by district heating, including the heating of office areas, common rooms and the air handler.

IV. OPTIMISATION OF SYSTEM OPERATION

Three criteria are considered to determine the bivalence points, namely the energy, economic and environmental optimum, each of which is concerned with prioritising different considerations. At the end of the analysis, the optimal operating condition will be found by comparing these parameters. Bivalent systems are based on the use of more than one heat generator, one of which plays the main role, with an auxiliary heat source to enable operation at the highest possible efficiency. In the present study, alternating, parallel and district heating-only monovalent plants have been

investigated for all three optimum criteria. The calculations were based on hourly temperature data for a meteorological year and on data from the manufacturer on the COP values of the heat pump, which were extrapolated and interpolated over the whole temperature range. [4]

The formula used to calculate COP and the COP runoff obtained using it:

$$COP_i = IF(t_{e,i-1} - t_{e,i} = 0; COP_{i-1}; COP_{i-1} + \frac{COP_{10} - COP_{-10}}{(t_{e1} - t_{e2}) * 10} * (t_{e,i-1} - t_{e,i})) \quad (1)$$

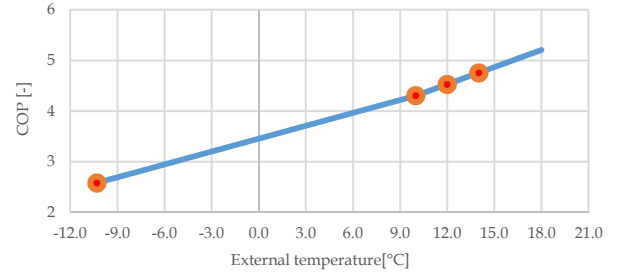


Fig. 1. Calculated COP values as a function of external temperature

A. Primary energy optimum

The first - and most important - analysis parameter is the energy optimum. Its importance is given by the regulatory system currently in place in Hungary and the fact that the other two methods of analysis are closely based on the results of the energy analysis. The regulation has made it mandatory to cover 25% of the total energy demand of newly constructed buildings with renewable energy sources. This criteria has been fulfilled since I extended the original bivalent point further to a lower temperature. I have solved most of my calculations using logic functions, an example of which is shown earlier in Fig. 1. The method of operation of the function "IF" is as follows:

IF(„claim under investigation”; „YES”; „NO”)

At the beginning of the function, the statement to be tested must be specified, for which a "YES" or a "NO" result can be obtained. After the function is run, it checks for each input whether the condition is satisfied or not and gives its output based on this. In the formula, the 'i'-th value represents the data currently being tested, the 'i-1' relative to it represents the index of the previous data. In alternating mode, I used the following formulae for my calculation. The first formula calculates the primary energy required to run the heat pump.

$$E_{electric, hp} = \frac{E_{res, heat}}{COP} * IF\left(\frac{\dot{Q}_{hp}}{\dot{Q}_{res, heat}} > 1; 1; 0\right) \quad (2)$$

In the second formula, I calculate the primary energy consumption of the district heating system. The value of the $e_{primary, distr.} = 0,745$ provided by Főtv. [7]

$$E_{primary, distr.} = \left(E_{off, heat} + E_{res, heat} * IF\left(\frac{\dot{Q}_{hp}}{\dot{Q}_{res, heat}} > 1; 0; 1\right) \right) e_{primary, distr.} \quad (3)$$

On the basis of this information, we can plot the following graph which represents the power consumption from primary energy both in case of the heat pump and the district heating.

The following graph will represent the results of these calculations in case of an alternating operational mode.

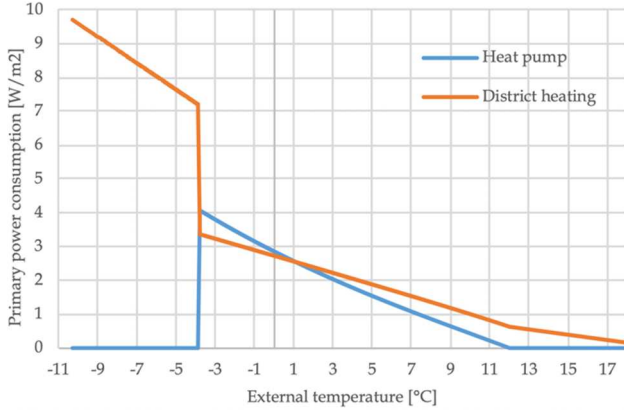


Fig. 2. Primary power consumption of the heat pump and the district heating in alternating mode

This graph represents the power demand of the building complex retrieved from primary usage. In the first section (18 °C – 12 °C) you can see that the heat pump is unable to work. This is due to a design error which I discovered in the heating system which severely hinders the potential use of the heat pump in its most favourable external temperature range. The second section (12 °C – -3,8 °C) shows parallel operating status even though we are in alternating mode. This anomaly is also due to the design errors made during the construction and beforehand.

The last section starts with a sudden drop in the heat pump power intake, which is the cause of the alternating operational mode: once the building's heating demand exceeds the heat pump's maximum heating power output, it switches off and the whole building is heated by the district heating from that point.

This is one example of the numerous graphs like this, which can not be shown due to the length requirements, but it gives a good idea of the structure of the summary graphs. The summary graphs are made up from these graphs where each operating mode's total power consumption is showed for example.

These calculations were also done for parallel operation, to which I did not include a diagram for reasons explained previously,

$$E_{electric, hp} = \frac{E_{res, heat}}{IF(COP > 3; COP; 3)} * \left(IF \left(t_k < -3; IF \left(\frac{\dot{Q}_{hp}}{\dot{Q}_{res, heat}} > 1; 1; \frac{\dot{Q}_{hp}}{\dot{Q}_{res, heat}} \right); 1 \right) \right) \quad (4)$$

$$E_{primary, distr} = E_{off, heat} * e_{primary, distr} + \left(E_{res, heat} * IF \left(\frac{\dot{Q}_{hp}}{\dot{Q}_{res, heat}} > 1; 0; \left(1 - \frac{\dot{Q}_{hp}}{\dot{Q}_{res, heat}} \right) \right) \right) * e_{primary, distr} \quad (5)$$

and for monovalent operation heated by district heating only. The COP = 3 is a basic rule of thumb value for the heat pump industry, operation under this value is not recommended.

$$E_{primary, only dist.} = E_{primary, distr} + E_{electric, hp} * COP * e_{primary, distr.} \quad (6)$$

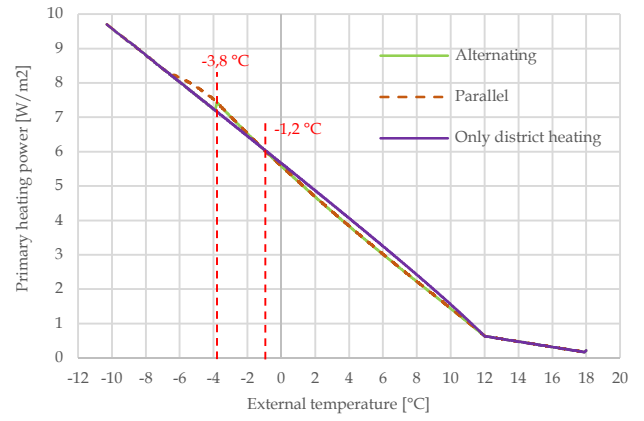


Fig. 3. Summed primary power consumption of the three operational modes as a function of external temperature

(Purple represents only district-heating, green represents the alternating, and the brown graph represents the parallel one). The figure shows that the bivalence point was -1.2°C, but I shifted the conversion temperature to -3.8°C to reduce the renewable fraction and thus CO₂ emissions. The energy data for the whole year can be used to determine which mode of operation was the most energy efficient.

- Alternating mode: 19.816 [kWh/m2a]
- Parallel operation: 20,391 [kWh/m2a]
- District heating only: 19.874 [kWh/m2a]

B. Economic analysis

The next point was the economic analysis. Although the most important element of the study for us was energy use, the economic role is very influential in today's market, with a clearly cost-based analysis in almost all areas of market competition.

Throughout the economic analysis the HUF - € conversion rate is 390 HUF/€. The optimum mode of operation will be the one with the lowest expenditure of money, and this will be determined. The table below shows the electricity tariffs used for my calculations:

		Variable cost		Fixed cost			
		Consumption dependent		Tie up dependent	Piece dependent		
Time-series	KÖF	0,0801	Euro/kWh	28,49	Euro/kW/a	385,57	Euro/piece/a
	KÖF / KIF III	0,0843	Euro/kWh	29,94	Euro/kW/a	128,52	Euro/piece/a
	KIF III	0,0891	Euro/kWh	24,89	Euro/kW/a	128,52	Euro/piece/a
Profile	KIF I	0,0875	Euro/kWh	0,00	Euro/kW/a	3,71	Euro/piece/a

Fig. 4. Electricity unit tariffs for early 2021, I used the KÖF/KIF III tariff [8]

For my calculations I used the KÖF/KIF III tariff (tariffs for medium and low voltage networks). The electricity tariff was thus taken as $p_{electricity} = 0,0843$ €/kWh. In calculating the unit cost of district heating, the gross district heating cost based on the heat metering option of the heat metering option is 6,65 €/GJ, and this is converted to the district heating price $p_{distr.} = 0,024$ €/kWh. In the alternative case, I calculated the operating costs as follows:

$$C_{electricity, alternating} = \left(\frac{E_{res, heat}}{COP} * IF \left(\frac{\dot{Q}_{hp}}{\dot{Q}_{res, heat}} > 1; 1; 0 \right) \right) * p_{electr.} * A_{total.} \quad (7)$$

$$C_{district,alternating} = \left(E_{off,heat} + E_{res,heat} * IF\left(\frac{\dot{Q}_{hp}}{\dot{Q}_{res,heat}} > 1; 0; 1\right) \right) * p_{district-heat} * A_{total} \quad (8)$$

While in the parallel case I used the following formulae:

$$C_{electricity,parallel} = \frac{E_{res,heat}}{IF(COP > 3; COP; 3)} * \left(IF\left(t_e < -3; HA\left(\frac{\dot{Q}_{hp}}{\dot{Q}_{res,heat}} > 1; 1; \frac{\dot{Q}_{hp}}{\dot{Q}_{res,heat}}\right); 1\right) \right) * p_{electric} * A_{tot} \quad (9)$$

$$C_{district,parallel} = E_{off,heat} + \left(E_{res,heat} * IF\left(\frac{\dot{Q}_{hp}}{\dot{Q}_{res,heat}} > 1; 0; \left(1 - \frac{\dot{Q}_{hp}}{\dot{Q}_{res,heat}}\right)\right) \right) * p_{distr.} * A_{total} \quad (10)$$

Finally, before summarising, I calculated the results for the monovalent district heating mode:

$$C_{distr.} = (E_{off,heating} + E_{res,heat}) * p_{distr.} * A_{total} \quad (11)$$

Or, summing up the results, I got the following chart.

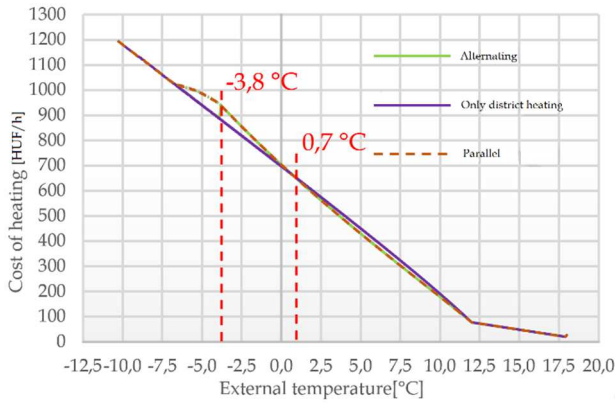


Fig. 5. Comparison of the cost per hour of operating modes

(Purple represents only district-heating, green represents the alternating, and the brown graph represents the parallel one). The figure shows that the bivalence point was 0.7°C, but I shifted the conversion temperature to -3.8°C to reduce the renewable fraction and thus CO₂ emissions. By summing up the costs for the whole year, we can tell which plant is optimal from an economic point of view:

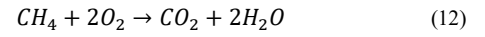
- Alternating mode: 6377,6 €
- Parallel operation: 6405,87 €
- District heating only: 6439,57 €

Although not by much, the alternating mode was more economically advantageous than the other two alternatives.

C. CO₂ emissions

The focus is on CO₂ emissions during operation. Once the calculations have been carried out, it is decided which mode of operation has the lowest annual pollution. The pipeline gas consists of 97% methane [5], so for simplification I assumed pure methane and calculated further. As a first step, I wrote down a stoichiometric equation for the combustion of methane, and thus calculated the ratio $m(\text{CO}_2)/m(\text{CH}_4)$ of the amount of carbon dioxide produced to the amount of methane

consumed. In writing the equation, I assumed perfect combustion for methane.



$$16 \frac{\text{g}}{\text{mol}} + 2 * 32 \frac{\text{g}}{\text{mol}} \rightarrow 44 \frac{\text{g}}{\text{mol}} + 2 * 18 \frac{\text{g}}{\text{mol}}$$

$$16 \text{ g CO}_2 \rightarrow 44 \text{ g CO}_2$$

$$\frac{m_{\text{CO}_2}}{m_{\text{CH}_4}} = 2,75$$

Where:

- $\frac{m_{\text{CO}_2}}{m_{\text{CH}_4}}$ = CO₂ emissions from the combustion of 1 unit of methane, expressed as a mass fraction [kg(CO₂)/kg(CH₄)]

The pollution value per unit of energy released was calculated as follows:

$$m_{distr.} = \frac{m_{\text{CO}_2}}{F} * e_{distr.} * (1 + 0,1124) \quad (13)$$

If we do this, we get how many kg of CO₂ emissions were produced by 1 kWh of district heating. This result for me is $m_{\text{távhő}} = 0.1641 \text{ kg/kWh}$.

For the pollution of electricity production, I used data from the Hungarian energy mix, the CO₂ emissions per unit of energy were $m_{\text{electric}} = 0.386 \text{ kg/kWh}$. [6] In alternating mode, the following calculation method:

$$\dot{m}_{alternating} = (E_{distr,alternating} * \dot{m}_{distr.} + E_{electric,hp,altern.} * \dot{m}_{electric}) * A_{total} \quad (14)$$

while in parallel operation, I determined the specific CO₂ emissions using the following calculation method.

$$\dot{m}_{parallel} = (E_{distr,parallel} * \dot{m}_{distr.} + E_{electric,hp,parallel} * \dot{m}_{electric}) * A_{total} \quad (15)$$

Finally, I defined the monovalent district heating mode:

$$\dot{m}_{only distr.} = (E_{off,heat} + E_{res,heat}) * \dot{m}_{distr.} * A_{total} \quad (16)$$

If I plot the tested operating conditions as a function of the external temperature on a diagram, I obtain the following diagram:

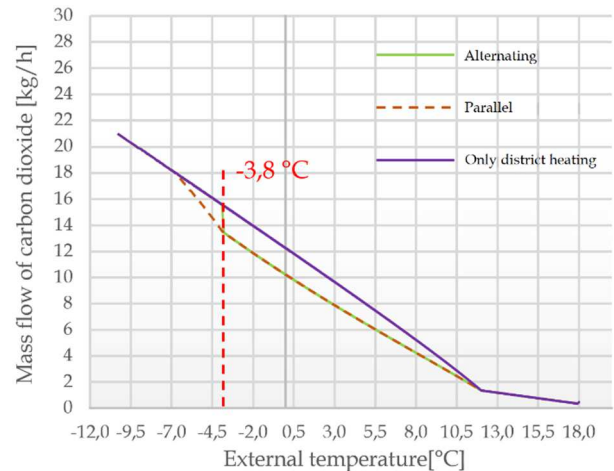


Fig. 6. Total CO₂ emissions depending on operating mode

(Purple represents only district-heating, green represents the alternating, and the brown graph represents the parallel one). The diagram can be divided into several parts: at high temperatures, the pollution of the building is almost negligible, since only the air handling system is running (up to 12°C). After that, the CO₂ emissions of the alternating and parallel plant will continue on the same straight line, but district heating will deviate from them in a higher emission direction.

By defining the areas under the functions, we can find out which case was the most environmentally friendly:

- Alternating mode: 37 762,6 kg
- **Parallel mode: 37 456,1 kg**
- District heating only: 44 098,4 kg

Of the two, alternating mode has lower CO₂ emissions than parallel mode.

V. Summary

After performing the calculations for the three optimisation criteria, we can compare the results. The alternating plant was better than the parallel plant in terms of primary energy use and economical operation but underperformed the parallel plant in terms of pollution.

The prolonged use of the heat pump gave the parallel plant the advantage in terms of CO₂ emissions, but also caused the additional primary energy consumption and increased operating costs. Since the primary optimisation factor in this study has been CO₂ emissions, we can conclude that the parallel mode is the optimal operational mode. The other factors have been calculated for extra information and their potential for comparison.

It is also important to note, that the design and construction solutions in the building in question make it impossible for the heating system to function optimally. Due to the limitations of

this article, I was not able to go into details, but it can be concluded from the above that it is not possible to optimise the system by control engineering and heating scheduling alone, physical modifications would be necessary. This aspect can explain the negligible differences in the different modes investigated by this study.

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