TRIPLE-CRITERIA EVALUATION OF HVAC SYSTEM PERFORMANCES WITH DYNAMIC BUILDING SIMULATION

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ABSTRACT

The scope of the research was to investigate whether renewable energy source application could contribute to higher performance, against a typical efficient HVAC system considering mandatory energy requirements as usually applied in commercial buildings. Two HVAC solutions, an air-source heat pump and a ground source heat pump system was modelled, simulated and evaluated using triple-criteria evaluation method. The HVAC systems were evaluated from the aspect of energy use, environmental and economic performance. Results demonstrated that the ground source heat pump due to its higher initial investment will demonstrate approximately 28% higher performance in all categories compared to an air source system.

INTRODUCTION

A lot of effort regarding energy savings has been spent due to large environmental problems and limited fossil energy sources. According to the European Energy and Climate Change Policy and its targets for 2050, different options and solutions are explored in order to reduce greenhouse gas emissions. The EU's first step is to reduce the energy demand of buildings through compliance with envelopes thermal property regulations and afterwards the utilization of efficient HVAC systems and renewable energy sources in order to cut down the buildings carbon footprint. To achieve this target and ensure high environmental standards and stable energy prices, Hungary needs to make substantial investments in available renewable energy sources. (WEC 2019, NORT 2019)

The motivation of the research was to investigate whether energy efficient buildings which fulfill the minimum energy standards do demonstrate high energy performance. The hypothesis was to investigate and prove that renewable energy source application could contribute to higher performance, against a typical efficient HVAC system considering mandatory energy requirements.

The research scope was to investigate and evaluate HVAC solutions using triple-criteria method: energy use, carbon footprint and cost to formulate a systematic solution for wide audience with preferable and applicable results. Applied research methodology was dynamic building performance simulation in order to evaluate the energy, environmental and economic performance of a typical office building in temperate climate conditions of Hungary. The dynamic simulations were performed according to the ASHRAE 90.1 standards (ASHRAE 2017) with EnergyPlus software (EnergyPlus 2016). ASHRAE climate zones refer to worldwide locations. The European weather data for Budapest were used from the data packages of ASHRAE Climate Design Conditions (ASHRAE CDC 2016), EnergyPlus Weather Data by Region (EP Weather 2017) and Hun TNM 7/2006 directive (TNM 2019).

Integrated design process and dynamic energy simulation is widespread in the field of energy performance optimization and strategic planning of building energy efficiency. Dynamic simulation is used in determining construction properties, occupant comfort, HVAC system energy demands, energy conservation techniques etc. (Sijanec et al. 2016, Kmekova et al. 2015, Sacht et al. 2015). In one of our previous researches, we used multi-criteria optimization methodology to determine an optimal energy retrofit solution in case of adequate envelope glazing selection (Harmathy 2015). Our previous research demonstrated an optimized building envelope model using multi-criterion optimization methodology in order to determine efficient window to wall ratio and window geometry in the function of indoor visual comfort, followed by the assessment of envelope's influence on the annual energy demand. Optimal design methods for cooling systems considering cooling load analysis using simulation techniques is a topic of interest respectively (Gang et al. 2015). Energetic and environmental performance assessment can be parallel analyzed (Krstic-Furundzic et al. 2016). Extensions on the urban level were made respectively from the aspect of building envelope design for overall energy efficiency (Eui-Jong et al. 2014). Residential building refurbishment methods have been analyzed in multiple researches for different climate conditions (Dixon et al. 2010). Authors used two calculation methods for the energy consumption for heating: the quasi-steady-state method and the dynamic simulation method. The values obtained by measuring have proven that the difference in the energy consumption was 2.7% and 4.8% (Sumarac et al. 2010).

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MATERIALS AND METHODOLOGY

Two multi-zone thermal models were developed for the investigation:

1. Proposed building 1, packaged rooftop heat pump (PRHP) according to energy efficient building minimum requirements, TNM 7/2006 local regulation and

2. Proposed building 2, with application of renewable geothermal energy source using ground source heat pump (GSHP).

Climate data

The climatic data was used from the Meteonorm (Meteonorm 2015) Swiss global database. The meteorological data package for Budapest contained more than 100,000 data. In the simulation process 30 year hourly averages were applied. In the dynamic simulation we used the following climatic data; air temperature, relative humidity, direct and indirect solar radiation, pressure, wind direction and wind speed. The weather data for Budapest were used from the data packages of ASHRAE Climate Design Conditions (ASHRAE CDC 2017).

Building representation

Budapest as most European cities has a central historic core developed mostly at the end of the 19th and first quarter of the 20th century. The design and construction of new buildings in the city core in many cases is a difficult architectural and engineering task, due to site, location, renewable energy supply and shading restrictions.

A representations of a typical inbuilt area of a reference office building according to the story number (5 stories) and height (3.5m per story), and inbuilt parcel regulations is shown in Figure 1.

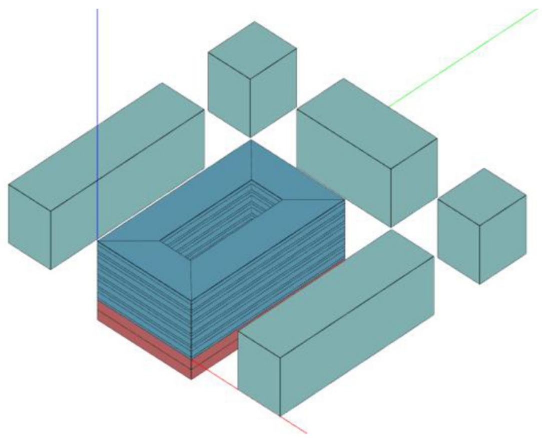

Figure 1: Thermal model, Axonometric view

The thermal model consisting of 5 stories and a two story underground parking was divided into 5 thermal zones. Each level forms a thermal zone. The parking was excluded from the zoning calculation since garage heating and cooling is not provided. Demand Control Ventilation (DCV) is mandatory in the parking garage for CO exhaust and jet fans in case of fire protection. In the research major energy consumers were analyzed, such as HVAC, equipment and lighting. The thermal zones design summary is shown in Table 1.

Table 1: Thermal zone summary

Thermal zone	Area [m^2]	Volume [m^3]	Window Area [m^2]
All zones from 1 to 5	1200	4200	420
Total	6000	21000	2100

Building construction

The building constructions thermal properties and fenestration properties were determined according to the Hungarian Energy Efficiency Regulations (TNM rendelet 7/2006 Appendix 5 and Appendix 6) (TNM 2019) The bearing construction was reinforced concrete skeleton, with exterior walls made from prefabricated empty cell concrete blocks, 30 cm and 1.14 W/mK thermal conductivity.

Expanded Polystyrene thermal insulation was applied, 15 cm for the outer layer of exterior wall, 15 cm EPS for the vegetated roof and 10 cm EPS for the ground floor connected with the garage.

The fenestration used was typical steel framed double glazing system with argon gas filling. The overall thermal transmittance of the fenestration system was 1.4 W/m2K. All construction assemblies are shown in Table 2.

Table 2: Building envelope and fenestration properties

Construction	Reflectance	U-value [W/m^{2}K]
Ext. Wall	0.08	0.212
Green roof	0.3	0.164
f-factor ground floor	-	0.135
c-factor undergr. wall	-	0.47
Construction	**U-value [W/m^{2}K]**	**Glass SHGC Light Trans.**
Ext. window with frame	1.4	0.399 0.601

ENERGY PERFORMANCE SIMULATION RESULTS

The heating and cooling energy demands and consumptions were calculated on an annual basis in hourly time steps, in total 8760 hours. The thermostat

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schedules were set according to the following date, time intervals and indoor air temperature levels as shown in Table 3. The temperature schedules were assigned according to the default ASHRAE schedule set in EnergyPlus "Medium Office Heating Setup" and "Medium Office Cooling Setup". the two models applied the default schedule sets.

Table 3: Thermostat schedules

Schedule	Date	Time	Indoor air temp.
Heating setup	01.10. – 31.03.	Mon to Fri 6-22h	21°C – 23°C
Mon to Fri 22-6h		min. 16°C	
Weekend 0-24h		min. 16°C	
Cooling setup	31.03. – 30.09.	Mon to Fri 6-22h	24°C – 26°C
Mon to Fri 22-6h		max. 28°C	
Weekend 0-24h		max. 28°C	

The simulation was performed according to heat balance calculations method used in EnergyPlus software. The two models, had identical interior lighting loads, plug loads, infiltration, outdoor air supply and occupancy. The annual summary of all identical loads can be seem in Table 4.

Table 4: Internal loads and definitions report

Definition	Value	Unit
People	18	m^2/people
Equipment	7.64	W/m^2
Lights	10	W/m^2
Infiltration	0.007	$m^3/h\ /m^2$
Ventilation	8.5	m^3/h /person

HVAC modeling

Two HVAC systems were modeled for the simulation to determine the annual energy consumption, operation costs and carbon footprint:

– Proposed HVAC 1, Packaged rooftop heat pump (PRHP) according to energy efficient building minimum requirements. The sizing of the system and components is presented in Table 5 and 6. The components of the HVAC system are the following:

a. hot water source and cooling source in packaged rooftop heat pump,

b. air to air plate heat exchanger with 76% efficiency,

c. constant volume fans for outdoor air supply.

Table 5: Cooling and heating coil DX Single Speed

Coil	**Design Size Rated Air Flow Rate [m^3/s]**	**Total Cooling Capacity [W]**	**Gross Rated Sensible Heat Ratio**
Coil cooling dx	25.67	637342	0.698083

Coil	**Design Size Rated Air Flow Rate [m^3/s]**	**Gross Rated Heating Capacity [W]**	**Resistive Defrost Heater Capacity [W]**
Coil heating dx	25.67	352566	637342

Table 6: Air loop HVAC summary

	Sum of Max. Flow Rates [m^3/s]	**Heating Design Air Flow Rate [m^3/s]**	**Cooling Design Air Flow Rate [m^3/s]**
PRHP	25.67	8.15	25.67

– Proposed HVAC 2 ground source heat pump (GSHP) with application of renewable geothermal energy source for heating and cooling through ground source heat pump system. Water to air heat pump with single duct VAV fans with no reheat is supplying warm and cool air to the thermal zones. Parasitic electric coil heating is provided which is operating when outdoor conditions make it necessary. The sizing of the system and components is presented in Tables 7 and 8. The components of the GSHP HVAC system are the following:

a. heating and cooling supply by ground source vertical heat exchanger, input data can be seen in Table 9,

b. variable speed pumps in water loop,

c. additional cooling coil DX single speed,

d. air to air plate heat exchanger with 76% efficiency

e. VAV fans for outdoor air supply.

Table 7: Cooling coil summary per thermal zone, water to air GSHP

Thermal zone	**Air Flow Rate [m3/s]**	**Total Cooling Capacity [W]**	**Sensible Cooling Capacity [W]**	**Water Flow Rate [m3/s]**
Zone 1	4.41	65358	55602	0.00282
Zone 2	4.79	70667	60327	0.00305
Zone 3	5.16	75777	64870	0.00328
Zone 4	5.57	81607	70085	0.00353
Zone 5	5.73	84099	72102	0.00364

Table 8: Heating coil summary per thermal zone, water to air GSHP

Thermal zone	**Air Flow [m^3/s]**	**Heating Capacity [W]**	**Water Flow Rate [m^3/s]**
Zone 1	4.41	65358	0.00282
Zone 2	4.79	70667	0.00305
Zone 3	5.16	75777	0.00328
Zone 4	5.57	81607	0.00353
Zone 5	5.73	84099	0.00364

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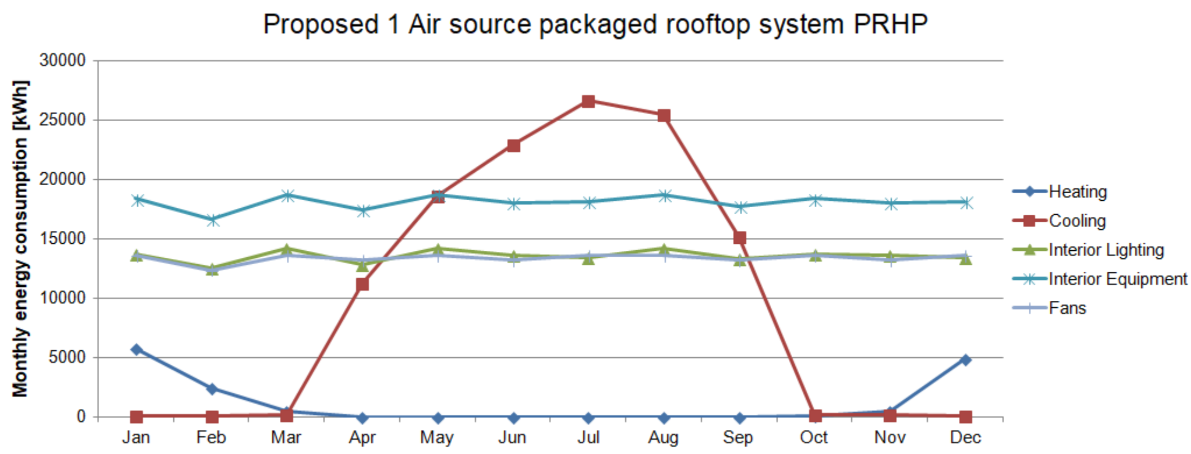

Figure 3: Energy use by category for PRHP system

Table 9: Ground source vertical heat exchanger

Number of bore holes	28
Bore hole length (pipe length)	120 m
Pipe radius	150 mm
Ground thermal heat capacity	2347 kJ/(m^{3}K)
Average ground temperature	14 °C
Ground thermal conductivity	1.8 W/mK
Pipe thermal conductivity	0.4 W/mK

Indoor environmental quality determination for modeling validation

The validation of the thermal models was performed according to operative temperature assessment. In Figure 2 a randomly selected office space on the third floor is demonstrated.

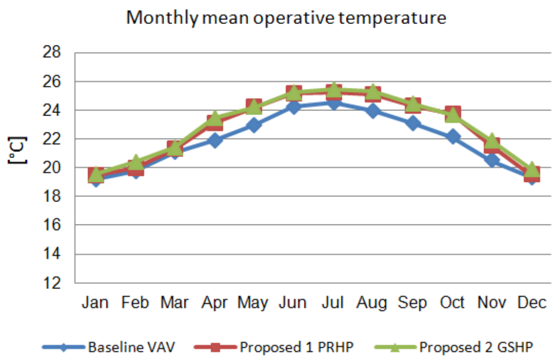

Figure 2: Validation using operative temperature

Results and energy performance evaluation

The calculation of annual heating and cooling energy consumption for the baseline and the two proposed HVAC systems was performed according to ASHRAE 90.1 2010 Standard. The input parameters of the occupants, equipment and lighting gains were used according to the energy design principles in case of the two models.

The comparison and evaluation of the HVAC systems overall performance is demonstrated according to three criteria:

1. End-use site and source energy consumption
2. Carbon footprint
3. Energy cost for building operation

The triple-criteria evaluation method demonstrates a more comprehensive overview of the design HVAC system selection during the preliminary design phase of office buildings since it will highlight system performances, cost efficiencies and environmental benefits. The economic calculations and carbon emissions were demonstrated for the Hungarian market using utility costs and power plant carbon emission factors from Budapest. The building performance can be demonstrated for any country using actual utility costs and energy production emissions factors due to the method's flexibility.

End-use site and source energy consumption

The dynamic energy performance simulations were performed on 8760 hour basis for the aforementioned climate database, building construction, thermal zones, internal gains and operation schedules. The total site energy consumptions are presented in Table 10. The typical HVAC PRHP system (Proposed 1) demonstrated 2430 GJ consumption due to its efficiency. Nevertheless the GSHP's energy consumption was 28% less compared to the PRHP. The end-uses per category can be seen in detail in Table 11.

Table 10: Annual total site energy per scenarios

Proposed 1 – Packaged rooftop heat pump (PRHP) according to energy efficient building minimum requirements and 76% heat recovery on air side loop	
Total Energy [GJ]	Energy use per prea [MJ/m^2]
2430.43	405.07
Proposed 2 – Energy efficient building with geothermal heat source GSHP and 76% heat recovery on air side loop	
Total Energy [GJ]	Energy use per area [MJ/m^2]
1757.27	292.88

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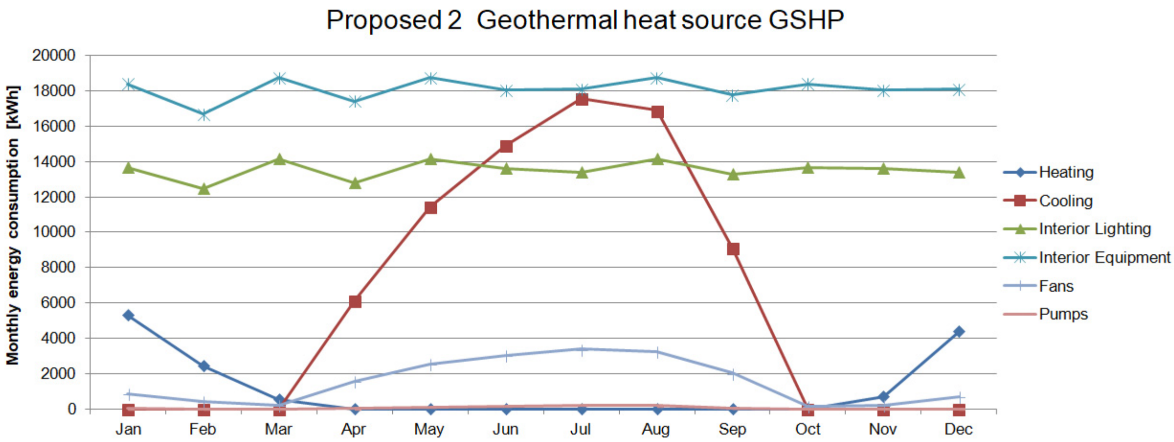

Figure 4: Energy use by category for PRHP system

Table 11: End use energy performance summary of Baseline and Proposed buildings

End-use category	**Proposed 1 Electricity [GJ]**	**Proposed 2 Electricity [GJ]**
Heating	50.91	48.30
Cooling	435.17	273.53
Lighting	584.32	584.32
Equipment	781.90	781.90
Fans	578.14	66.13
Pumps	0	3.09
Total End Uses	2430.43	1757.27

The energy consumption of the HVAC systems was analyzed in detail. The Proposed HVAC 1 PRHP DOAS system's monthly energy consumption can be seen in Figure 3. The heating consumption is significantly lower compared to the Baseline VAV system; nevertheless the fans have 10 times higher electricity consumption due to the fan-coil units and air source heat pump system. The rated COP of the cooling coil DX was 3 and for heating coil DX was 5 by default, total fan efficiency was 0.7.

Proposed HVAC 2 GSHP performed as to most efficient system from the aspect of end-use energy, Figure 4. The findings presented that the electricity consumption for heating is identical with the PRHP DOAS system. Cooling electricity consumption has shown 37% reduction compared to PRHP.

Source energy evaluation

End-use source energy for the three systems was calculated according to the hungarian source energy conversion factors (HEER TNM 2019).

Proposed system 2 GSHP still remained with the highest performance with approximately 28% in source energy consumption Table 12.

Table 12: Annual total source energy per scenarios

Proposed 1 – PRHP with 76% HR on air side loop		**Proposed 2 –GSHP and 76% HR on air side loop**	
Total Source Electricity [kWh]	Energy Per Conditioned Area [kWh/m^2]	Total Source Electricity [kWh]	Energy Per Conditioned Area [kWh/m^2]
1687800	**281**	1220330	**203**

Carbon footprint evaluation

The carbon emission of the HVAC systems operation was calculated on annual basis according to the hungarian carbon emission factors, where proposed 1 PRHP resulted in higher CO2 emission of 616 tons/a, while Proposed 2 GSHP demonstrated 445 tons/a.

The results demonstrated that the end-use energy compared to the source energy and carbon emission demonstrated completely different results. If energy production and carbon footprint are not taken into account during the decision making process, the environmental sideeffects could be really harmful. The investigation highlights the importance of taking into consideration the source energy and carbon emission results during and overall analysis of the buildings environmental impact.

Economic evaluation

According to LEED v4 Green building certification in the Energy and Atmnosphere category credits for optimizing building energy performance reflect the economic improvement of the energy performance. The building operation is reflected through achievement of increasing levels of energy performance beyond the prerequisite standard to reduce environmental and economic harms associated with excessive energy use. (USGBC 2019)

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The economic analysis was performed according to the end-use consumption using Hungarian utility tariffs. The gas and electricity rates along with the total end-use energy are shown in Table 13. (Gas tariff 2019, Electricity tariff 2019) The flat-rate calculation method was used according to ASHRAE 90.1 2010 Appendix G.

Table 13: Annual energy cost comparioson

Proposed 1 – typical energy efficient building with packaged rooftop heat pump and 76% heat recovery on air side loop			
Electricity	0,081 EUR/kWh	675.120 kWh	54.684
Proposed 2 – Energy efficient building with geothermal heat source GSHP and 76% heat recovery on air side loop			
Electricity	0,081 EUR/kWh	488.132 kWh	39.538

The findings demonstrated that Proposed system 2 efficient PRHP has the highest annual energy cost for operation.

Results summary

The summary of results for both HVAC systems are shown in Table 14.

Table 14: Results summary on annual basis

System	**Primary energy consumption [kWh/m²/a]**	**Carbon emission [CO_2ton/a]**	**Operation energy cost [EUR]**
PRHP	281	616	54.684
GSHP	203	445	39.538
Reduction	28% in all categories, due to electricity supply for both heating and cooling		

The results demonstrate that the energy source depending weather it is aero thermal or ground thermal could significantly contribute to the efficiency of the overall energy consumption of the building. It can be concluded that the selection of the energy source such as aero thermal, ground or hydro thermal should be considered according to the climatic data, soil and location of the building if designers are seeking a de-centralised solution.

In case of Hungary the soil characteristics are adequate for geothermal energy utilization and the onsite drilling of boreholes is also cost efficient due to the soil characteristics and contents.

CONCLUSION

Findings demonstrated that the end-use energy gives designers insufficient data for adequate decision making in the preliminary design stages. HVAC solutions should be preferably evaluated from a wider aspect which combines multple-citeria in the design decision making phase.

According to the demonstrated building the geo-thermal energy utilization can contribute to 28% better performance compared to the air source heat pump system.

The overall recommendation is to evaluate during the preliminary design phase the possibilites of source energy selection with a triple-criteria evaluation to justify which is the most energy, environmental and cost efficient HVAC system for the region.

Further research will include the energy and economic analysis of various HVAC systems for office buildings containing a combination of fossil fuel and/or district energy utilization. The carbon footprint is highly important due to the environmental impact and decarbonization strategy when improving building performance. Materials and construction expenses will be taken into consideration according to the performance and investment aspect of an ongoing project.

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