INVESTIGATION OF DECARBONIZATION POTENTIAL IN GREEN BUILDING DESIGN TO ACCELERATE THE UTILIZATION OF RENEWABLE ENERGY SOURCES

by

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Original scientific paper
https://doi.org/10.2298/TSCI200324195H

The construction sector as one of the highest carbon emitters in the World has an international initiative for GHG reduction. Green building certifications demonstrate performance, efficiency and economy in the construction sector. The motivation of the research was to investigate whether Green certified buildings which fulfill the minimum energy standards do demonstrate high energy performance compared to energy efficient buildings and renewable systems. The hypothesis was to investigate that RES application could contribute to higher performance, against a typical efficient HVAC system (usually applied in commercial buildings) and a building aiming for Green certification, concerning mandatory energy efficiency requirement. The research scope was to investigate and evaluate various HVAC solutions using triple-criteria evaluation method for decarbonization: energy performance, carbon footprint, and operation cost to formulate systematic solutions in the design phase of projects for wide audience with preferable and applicable results.

Key words*: renewable energy, energy modelling, dynamic simulation, carbon footprint, EnergyPlus*

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 GHG emissions. The EU 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 RES sources in order to cut down the buildings carbon footprint. In order to achieve target goals and ensure high environmental standards and stable energy prices, Hungary needs to make substantial investments in available renewable energy sources. [1, 2]

The motivation of the research was to investigate whether Green certified buildings which fulfill the minimum energy standards do demonstrate high energy performance compared to various HVAC solutions including RES. The hypothesis was to investigate the contribution potential of RES application for higher overall performance, against a typical efficient and automated HVAC system and a building aiming for Green certification.

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The research scope was to investigate and evaluate various HVAC solutions using triple criteria evaluation method for decarbonization:
- overall energy performance, end-use and source-use energy,
- carbon footprint evaluation, and
- operational cost of building.

Applied research approach was detailed dynamic building performance simulation technique in order to evaluate the energy, environmental and economic performance of a typical office building for the climate conditions of Hungary. The dynamic simulations were performed according to the ANSI/ASHRAE 90.1 2010 standard [3] with DOE EnergyPlus software [4]. The integrated 3-D thermal-zone resolution method was used with OpenStudio software development kit and suite of applications [5] ASHRAE climate zones refer to worldwide locations. The European weather data for Budapest were used from the data packages of ASHRAE Climate Design Conditions [6] and EnergyPlus Weather Data by Region [7]. Local energy efficiency standard was also taken into account during the energy modelling process, TNM (v.24.) 7/2006 local regulation [8]

Integrated design process and dynamic energy simulation is widespread in the field of energy performance optimization and strategic preliminary design process. Dynamic simulation is used in determining hydrothermal properties of building assemblies, thermal comfort, HVAC system energy consumption, energy conservation techniques, *etc.* [9, 10]. Renewable energy supply is gaining more interest and importance due to the global decarbonization strategy [11-13]. Green building technologies is also a new and innovative topic in mechanical engineering research, which is essential for achieving international Green building certification [14-17]. Taken into consideration new technologies the energy performance testing methods with computational technologies is also emerging [18-21].

In one of our previous researches, we used multi-criteria optimization methodology to determine an optimal energy retrofit solution in case of adequate building envelope selection [22]. 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. Energetic and environmental performance assessment should be parallely analyzed [23, 24]. Smart building strategy is also a widespread topic for improving the energy performance, environmental awareness and occupant comfort in buildings [25-29]. Energy utilization from various sources such as geothermal heat energy and different mechanical systems were analysed in our previous researches [30, 31]. Hungary has numerous examples of Green certified buildings [32], but an overall analysis of building performance metrics does not exist among Green certified and nearly zero energy buildings. The research evaluates the overall energy performance, carbon footprint and operational costs of typical reference buildings and constructions designed and built according to the ASHRAE and local standards and regulations. The motivation behind the investigation was to inform the designers and engineers to incorporate a triple criteria analysis procedure starting from the early phases of design in order to prepare their designs for the global decarbonization strategy of the building sector.

Materials and methodology

Three thermal zone models were developed for the triple criteria evaluation method, taking into consideration the energy efficiency, carbon footprint and operational cost evaluation in case of the following HVAC systems:

- *Baseline building* according to ASHRAE 90.1 2010 Appendix G with HVAC System 7 variable air volume (VAV) with reheat and fossil fuel heating source (natural gas).
- *Proposed building 1*, Packaged rooftop heat pump (PRHP) system according energy efficient building directive in Hungary, TNM (v.24.) 7/2006 local regulation.
- *Proposed building 2*, with application of renewable geothermal energy source using ground source heat pump (GSHP) system.

The energy performance analysis had the following focus:

- Multi-zone thermal modelling and energy performance simulation.
- Special focus on heating and cooling energy consumption.
- The HVAC system simulation and end-use energy determination.
- Total energy saving potential, carbon footprint and economic analysis.

Climate data

The climatic data was used from the Meteonorm [33] Swiss global database. In the dynamic simulation process hourly average values were applied using to following parameters: 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 [6] which are shown in tab. 1. The location and weather data were imported from EnergyPlus Weather data center [7], since the climate data needs to be converted into EPW extension file, importable into EnergyPlus for dynamic energy simulation. The imported weather data were design conditions from *Climate Design Data 2009 ASHRAE Handbook*. ASHRAE design conditions are generated for a period of 30 years suitable for the use of heating and cooling load calculations. [6]

Table 1. Weather file for Budapest from ASHRAE climate design conditions

Extreme annual design conditions				
Extreme max wet-bulb temperature [C]	Extreme annual dry-bulb temperature [°C]			
	Mean		Standard deviation	
	Min	Max	Min	Max
26.8	–16.0	34.9	3.2	1.9
Sizing runs according to ASHRAE 90.1 2010, Appendix G section G3.1.2.2.1. (system sizing runs shall be based on historical hourly weather data containing peak conditions)				
Coldest month	January	Heating system sizing 99.6% for heating design temperature		
Hottest month	July	Cooling system sizing 1% for cooling design temperature		

Simulation methodology and input data

Multi-zone thermal model 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 from surrounding buildings. A representations of a typical inbuilt area of a reference office building is shown in fig. 1 according to typical inbuilt parcel regulations with 5 stories and 3.5 m height per story. The thermal model con-

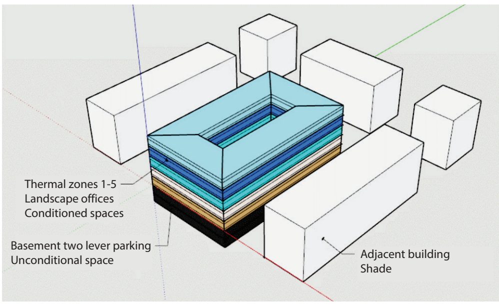

Figure 1. Thermal multi-zone model: axonometric view

sisting of five stories above ground and a two story underground parking was divided into five thermal zones. Each level forms a thermal zone except the parking which was excluded from the zoning calculation since garage heating and cooling is not provided. Demand control ventilation 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, electric equipment and lighting. The thermal zones design summary is shown in tab. 2.

Table 2. Thermal zone summary

Thermal zoning of landscape offices	Area [m^2]	Volume [m^3]	Above ground gross wall area [m^2]	Window glass area [m^2]	Lighting [Wm^{-2}]	People [m^2 per person]	Plug and process [Wm^{-2}]
Thermal zone 1 (1st floor)	1200	4200	840	420	10	17.70	7.6424
Thermal zone 2 (2nd floor)	1200	4200	840	420	10	17.70	7.6424
Thermal zone 3 (3rd floor)	1200	4200	840	420	10	17.70	7.6424
Thermal zone 4 (4th floor)	1200	4200	840	420	10	17.70	7.6424
Thermal zone 5 (5th floor)	1200	4200	840	420	10	17.70	7.6424
Total	6000	21000	4200	2100	10	17.70	7.6424

Input data of thermal models

The building constructions thermal properties and fenestration properties were determined according to the Hungarian Energy Efficiency Regulations (TNM energy efficiency regulation 7/2006 *Appendix 5* for construction thermal properties and *Appendix 6* for nearly zero energy performance buildings) [8]. The bearing structure was reinforced concrete, with exterior walls made from prefabricated empty cell porous concrete blocks, 30 cm thick with 1.14 W/mK thermal conductivity. On the exterior wall surface 15 cm of Expanded Polystyrene (EPS) thermal insulation was applied, 15 cm EPS for the vegetated roof and 10 cm EPS for the ground floor connected with the parking garage. The applied fenestration was steel framed double glazing system with argon gas filling and low-e layer. The overall thermal transmittance of the curtain-wall system, including glass with frame, was 1.4 W/m^{2}K. The envelope's thermal properties modeled in EnergyPlus are shown in tab. 3.

Energy performance simulation, validation and results with discussion

A dynamic energy simulation is a complex mathematical approach, which requires numerous input parameters in order to create an environment approximated to natural conditions. The interpolation of detailed hourly climate data is mandatory in order to perform the simulation on annual basis in hourly time steps. The influence of each input parameter can be analyzed extensively which allows flexibility of the thermal model and its properties. The HVAC system

Table 3. Building envelope and fenestration properties

<table>
<tr><th colspan="4">Above grade envelope summary</th></tr>
<tr><td>Construction</td><td>Reflectance</td><td colspan="2">U-factor [Wm^{–2}K^{–1}]</td></tr>
<tr><td>Proposed exterior wall</td><td>0.08</td><td colspan="2">0.219</td></tr>
<tr><td>Proposed vegetated roof</td><td>0.30</td><td colspan="2">0.168</td></tr>
<tr><th colspan="4">Below grade envelope summary</th></tr>
<tr><td colspan="2">Construction F-factor ground floor [Wm^{–1}K^{–1}]
Acc. to ASHARE 90.1 2010 F-factor is the perimeter heat loss factor for slab-on-grade floors, ASHRAE Standard 90.1 specifies maximum F-factors for slab-on-grade or underground floors depending on space types and climate zones</td><td colspan="2">0.135</td></tr>
<tr><td colspan="2">Construction C-factor underground wall [Wm^{–2}K^{–1}]
Acc. to ASHARE 90.1 2010 C-factor (thermal conductance) is the time rate of steady-state heat flow through unit area of material or construction, induced by a unit temperature differnce between the body surfaces; assembly is without air film resistances</td><td colspan="2">0.490</td></tr>
<tr><th colspan="4">Exterior fenestration</th></tr>
<tr><td>Construction</td><td>Glass U-factor [Wm^{–2}K^{–1}]</td><td>Glass SHGC</td><td>Glass visible transmittance</td></tr>
<tr><td>Proposed exterior window with frame u-1.4</td><td>1.40</td><td>0.399</td><td>0.601</td></tr>
</table>

sizing for Baseline and Proposed 1 PRHP and Proposed 2 GSHP was performed according to the minimum indoor climate condition criteria for occupant thermal comfort. The validation of the HVAC systems sizing was determined according to the operative temperature oscillation ranges in the building, in order to have identical indoor climate conditions in all three scenarios. The calculation method for system sizing in EnergyPlus is validated and accredited by the US Department of Energy. The software has the capability to simulate multiple-zone interactions on both thermal and mechanical equipment level in the thermal model. It also models hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat setpoint, and HVAC system operation defined separately for the thermal zoning. The utilized calculation methods were the following [34]:

– *Building physics*. Conduction Transfer Function model was used within the heat balance model,
– *Mechanical system*. The loop and HVAC equipment sizing was performed according to the design weather data, external and internal gains and thermal comfort criteria.

Building default operation schedule and HVAC design parameters

The heating and cooling energy demands were calculated on an annual basis in hourly time steps, in total 8760 hours. The thermostat schedules were set according to the following date, time intervals and indoor air temperature levels as shown in tab. 4. The temperature schedules were assigned according to the default ASHRAE schedule set in EnergyPlus *Medium Office Heating Set-up* and *Medium Office Cooling Set-up*. The default schedule sets were identical in all thermal models. Throttling ranges during occupied hours were 2 °C.

Table 4. Thermostat schedules

Schedule	Date	Time	Indoor air temperature
Heating set-up schedule	October 1 – March 31	Monday to Friday 6-22 hours	21-23 °C
		Monday to Friday 22-6 hours	min 16 °C
		Weekend 0-24 hours	min 16 °C
Cooling set-up schedule	April 1 – September 30	Monday to Friday 6-22 hours	24-26 °C
		Monday to Friday 22-6 hours	max 28 °C
		Weekend 0-24 hours	max 28 °C

The simulation was performed according to the heat balance calculations method used in the EnergyPlus simulation engine. Detailed description of the heat balance model, calculation method of the heat losses and adaptive comfort model by the software developers is described in detail in the EnergyPlus Engineering [34]. The three thermal models, Baseline, Proposed 1 PRHP and Proposed 2 GSHP had identical interior lighting loads, plug loads, infiltration, outdoor air supply and occupancy. The identical load definitions can be seem in tab. 5.

Table 5. Internal loads and definitions report

Office – Open office (20 spaces and 5 thermal zones)		
Definition	Value	Unit
90.1-2010 – Office – Open office people definition	18	[m^2 per people]
90.1-2010 – Office – Open office electric equipment definition	7.64	[Wm^{-2}]
90.1-2010 – Office – Open office lights definition	10	[Wm^{-2}]
90.1-2010 – Office – Open office infiltration	0.007	[$m^3hour^{-1}m^{-2}$] per ext. surf. area
90.1-2010 – Office – Open office ventilation (outdoor air method sum)	8.5	[m^3 per hour] per person
90.1-2010 – Office – Open office ventilation (outdoor air method sum)	0.00947	[$m^3hour^{-1}m^{-2}$] per floor area

The HVAC design parameters

Design parameters of the three HVAC systems for the simulation determine the annual energy consumption, operation costs, and carbon footprint are shown in detail:

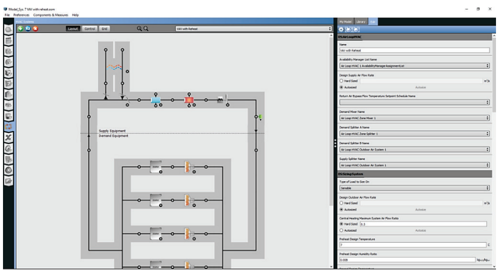

Figure 2. Baseline VAV system modelling interface in OpenStudio-EnergyPlus

Baseline HVAC was sized according to ASHRAE 90.1 2010 Appendix G with HVAC System 7 VAV consisting of hot, chilled and condenser water loops including the following sized components, as seen in tabs. 6-8: hot water source was natural gas boiler, cooling source was electric chiller with single speed cooling tower, variable speed pumps, air to air plate heat exchanger with 50% efficiency connected to the exhaust air loop. Figure 2 demonstrates the OpenStudio-EnergyPlus interface of the HVAC modelling protocol.

Table 6. Plant loop

	Maximum loop flow rate [m^{3}s^{-1}]	Plant loop volume [m^3]
Chilled water loop	0.02622	3.15
Condenser water loop	0.03706	4.45
Hot water loop	0.01071	1.29

Table 7. Specified HVAC components used in the energy simulation

	Design capacity [kW]	WFR [m^{3}s^{-1}]	Chilled WFR [m^{3}s^{-1}]	Condenser fluid flow rate [m^{3}s^{-1}]
Boiler hot water	485	0.01071	–	–
Chiller electric eir	734	–	0.02622	0.037067
	Design WFR [m^{3}s^{-1}]	Fan power [W]	Design AFR [m^{3}s^{-1}]	AFR [m^{3}s^{-1}]
Cooling tower	0.037067	9109.38	24.37	2.44

Table 8. Air loop HVAC summary

	Sum of air terminal max flow rate [m^{3}s^{-1}]	Adjusted heating design AFR [m^{3}s^{-1}]	Adjusted cooling design AFR [m^{3}s^{-1}]	Adjusted main design AFR [m^{3}s^{-1}]
VAV with reheat	25.67	8.15	25.67	25.67

Proposed HVAC 1 PRHP according to energy efficient building minimum requirements. The sizing of the system and components is presented in tabs. 9 and 10. The components of the HVAC system are the following: hot water source and cooling source is PRHP, air to air plate heat exchanger with 76% efficiency, and constant volume fans for outdoor air supply.

Table 9. Cooling coil and heating coil DX – Single speed

Coil	Design size rate AFR [m^{3}s^{-1}]	Design size gross rated total cooling capacity [W]	Design size gross rated sensible heat ratio
Coil cooling *dx* single speed	25.67	637342.41	0.698083
Coil	Design size rated AFR [m3/s]	Design size gross rated heating capacity [W]	Resistive defrost heater capacity [W]
Coil heating *dx* single speed	25.67	637342.41	637342.41

Table 10. Air loop HVAC summary

	Sum of air terminal max flow rate [m^{3}s^{-1}]	Adjusted heating design AFR [m^{3}s^{-1}]	Adjusted cooling design AFR [m^{3}s^{-1}]	Adjusted main design AFR [m^{3}s^{-1}]
Packaged RT heat pump	25.67	8.15	25.67	25.67

Proposed HVAC 2 GSHP with application of renewable geothermal energy source for heating and cooling through GSHP 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 tabs. 11 and 12. The components of the GSHP HVAC system are the following: heating and cooling supply by ground source vertical heat exchanger, input data can be seen in tab. 13, variable speed pumps in water loop, additional cooling coil *DX* single speed, air to air plate heat exchanger with 76% efficiency and VAV fans for outdoor air supply.

Table 11. Cooling coil summary per thermal zone, water to air GSHP

	Design size rated AFR [m^3s^{-1}]	Total cooling capacity [W]	Sensible cooling capacity [W]	WFR [m^3s^{-1}]
Thermal zone 1	4.41	65358.43	55602.95	0.002829
Thermal zone 2	4.79	70667.97	60327.36	0.003059
Thermal zone 3	5.16	75777.73	64870.99	0.00328
Thermal zone 4	5.57	81607.94	70085.54	0.003532
Thermal zone 5	5.73	84099.91	72102.91	0.00364
	Design size rated AFR [m^3s^{-1}]	Design size gross rated total cooling capacity [W]	Design size gross rated sensible heat ratio	
Additional coil cooling dx single speed	2.63	65281	0.698083	

Table 12. Heating coil summary per thermal zone, water to air GSHP

	Design size rated AFR [m^3s^{-1}]	Design size rated heating capacity [W]	Design size rated water flow rate [m^3s^{-1}]
Thermal zone 1	4.41	65358.43	0.002829
Thermal zone 2	4.79	70667.97	0.003059
Thermal zone 3	5.16	75777.73	0.00328
Thermal zone 4	5.57	81607.94	0.003532
Thermal zone 5	5.73	84099.91	0.00364

Table 13. Ground source vertical heat exchanger summary

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

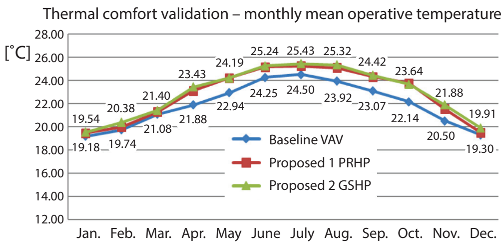

Figure 3. Monthly mean operative temperature comparison for thermal zone 3, 3rd floor offices

Results and energy performance evaluation

The validation of the thermal models was performed according to thermal comfort satisfaction, which was the mean operative temperature in a randomly selected zone, in this case third floor open plan office. The simulations for all three scenarios were performed on annual basis. In fig. 3 summarized monthly mean operative temperatures are presented for all three models. The highest deviation between the Baseline and Proposed 1-2 systems was maximum 1.5 °C in October which is acceptable and also within the thermal comfort ranges. All three HVAC systems qualify for indoor thermal comfort maintenance.

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 all three models.

End-use and source-use energy consumption

The dynamic energy performance simulations were performed on annual basis for the aforementioned climate database, building construction, thermal zones, internal gains and operation schedules. The total site energy consumptions are presented in tab. 14. where the highest consumption was determined for the Baseline system 7 VAV with 3806 GJ. The fossil fuel consumption is 1026 GJ equal to 285 MWh, which is 26816 m^3 of natural gas (1 m^3 natural gas is equal to 10.62 kWh). The typical HVAC PRHP system (Proposed 1) demonstrated 2430 GJ consumption due to its efficiency, which is 36% less. Finally the GSHP's energy consumption was 28% less compared to the PRHP and 54% less compared to the typical ASHRAE 90.1 2010 baseline office building. The end-uses per category can be seen in detail in tab. 15.

Table 14. Annual total site energy per scenarios

Baseline – ASHRAE 90.1 2010 Appendix G, System 7 VAV with reheat and 50% air side heat recovery		
	Total energy [GJ]	Energy per conditioned building area [MJm^{-2}]
Site energy	3806.38	634.40
Proposed 1 – PRHP with 76% air side heat recovery		
	Total energy [GJ]	Energy per conditioned building area [MJm^{-2}]
Site energy	2430.43	405.07
Proposed 2 – GSHP with 76% air side heat recovery		
	Total energy [GJ]	Energy per conditioned building area [MJm^{-2}]
Site energy	1757.27	292.88

Table 15. End use energy performance summary of baseline and proposed buildings

End-use category	Baseline	Proposed 1	Proposed 2
	Electricity [GJ]	Electricity [GJ]	Electricity [GJ]
Heating	Gas 1026.29	50.91	48.30
Cooling	797.57	435.17	273.53
Interior lighting	584.32	584.32	584.32
Interior equipment	781.9	781.90	781.90
Fans	58.71	578.14	66.13
Pumps	336.47	–	3.09
Heat Rejection (cooling tower)	221.13	–	–
Total end uses	3806.38	2430.43	1757.27

The energy consumption of the HVAC systems' was analyzed and evaluated. Results presented that the monthly heating consumption of the Baseline VAV system was significantly higher compared to both Proposed systems. The VAV systems central air heater consumes more energy due to its constant operation in order to serve warm air to the zones. The control of the single air heater is central, thus a higher efficiency as for the proposed systems could not be achieved. The investment costs for this system are lower on the market, which usually is one of the major aspects for its selection. The VAV system's end-use natural gas consumption was also converted into [kWh] as shown on the graph which demonstrates a significantly high gas end-uses compared to other listed consumers. If only end-use energy consumption would be compared than probably the decision during the design process would be significantly influenced by the high end-use for heating. The Proposed HVAC 1 PRHP dedicated outdoor air system's (DOAS) monthly heating consumption is significantly lower compared to the Baseline VAV system, nevertheless the fans have ten times higher electricity consumption due to the fan-coil units and air source heat pump. The rated COP of the cooling coil DX was three and for heating coil DX was five by default, total fan efficiency was 0.7. Finally, Proposed HVAC 2 GSHP performed as the most efficient system from the aspect of end-use energy. 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 and 65% reduction compared to Baseline VAV system. Concerning the GSHP fans the consumption is close to the VAV systems end-use.

End-use source energy for the three systems was calculated according to the Hungarian source energy conversion factors which is 2.5 for electricity and 1 for gas [35] Due to the site to source conversion factor of the natural gas the baseline system demonstrated a lower source energy consumption compared to the Proposed 1 system by 11%. Proposed system 2 GSHP still remained with the highest performance, but its 54% lower site energy consumption according to baseline has fallen approximately 20% in source energy consumption, tab. 16.

Table 16. Total source-energy comparison

Baseline – ASHRAE 90.1 2010 Appendix G, System 7 VAV with reheat and 50% air side heat recovery				
	Total source gas [kWh]	Total source electricity [kWh]	Total source gas + electricity [kWh]	Energy per building area [kWhm^{-2}]
Site energy	285013	1218087	1503100	250
Proposed 1 – PRHP with 76% air side heat recovery			Proposed 2 – GSHP with 76% air side heat recovery	
	Total source electricity [kWh]	Energy per building area [kWhm^{-2}]	Total source electricity [kWh]	Energy per building area [kWhm^{-2}]
Site energy	1687800	281	1220330	203

Carbon footprint and economic evaluation

The carbon emission of Basline and Proposed systems operation was calculated on annual basis according to the aforementioned Hungarian carbon emission factors. It was concluded that Proposed system 1 DOAS PRHP resulted in highest carbon emission of 616 CO_2 tons per year. Basline VAV system has shown 18% less carbon emission and Proposed 2 GSHP with renewable energy source 28% less carbon emission compared to Proposed system 1 DOAS PRHP, and 11% less compared to Baseline VAV system. 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 side-effects could be really harmful. The investigation highlights the importance of taking into consideration the source energy and carbon emission during an overall analysis of the buildings environmental impact.

According to LEED v.4 Green building certification in the Energy and Atmosphere 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 [36]. 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 tab. 17 [37, 38] The findings demonstrated that Proposed system 1 PRHP has the highest annual energy cost for operation.

Table 17. Annual operation costs summary

Baseline – ASHRAE 90.1 2010 Appendix G, System 7 VAV with reheat and 50% heat recovery on air side loop			
Energy type	Tariff	End-use energy	Annual cost [EUR]
Natural gas	0,008 EUR/MJ	1.026.000 MJ	8.208
Electricity	0,081 EUR/kWh	487.235 kWh	39.466
Proposed 1 – PRHP with 76% air side heat recovery			
Electricity	0,081 EUR/kWh	675.120 kWh	54.684
Proposed 2 – GSHP with 76% air side heat recovery			
Electricity	0,081 EUR/kWh	488.132 kWh	39.538

Triple-criterion evaluation wageing

A wageing method was applied in the evaluation process where points were introduced depending on the overall building performance. The highest performance, lowest carbon footprint and lowest operational cost was valued with 2, while the lowest performance, highest carbon footprint and highest operational cost was valued with 0. Since the energy performances were analysed from the end-use and source-use aspect the final value was determined as the average. The highest total indicator of six was demonstrated for the Proposed 2 GSHP system as seen in tab. 18.

Table 18. Triple-criterion performance evaluation

Criterion	Baseline VAV	Proposed 1 PRHP	Proposed 2 GSHP
Energy performance	End-use 0	End-use 1	End-use 2
	Source-use 1	Source-use 0	Source-use 2
Carbon footprint	1	0	2
Operation cost	1	0	2
Total value	2.5	0.5	6

Usually when assessing performance, only the end-use energy is taken into account whereas PRHP system demonstrates better performance according to the Baseline VAV. If we take into account the aforementioned triple-criterion the results will demonstrate an advantage of the Baseline VAV system with gas supply. System PRHP is efficient due to the air to air packaged heat pumps seasonal energy efficiency ratio (SEER), the negative property is actually the electricity production and supply inefficiency. Electricity in Hungary is produced from fossil fuels an nuclear power with an overall source energy conversion factor of 2.5. The building performance and its carbon footprint is deeply depends from the energy production and the power plants energy production technology and efficiency.

Conclusions

According to the results it is significant to evaluate the environmental performance of buildings within the frame of their energy performance. The end-use energy gives designers insufficient data for adequate decision making in the preliminary design stages. Soure-use energy and carbon footprint demonstrate the actual environmental impact of the design decisions and reflect on the building's lifecycle. The investigation demonstrated the differences in the site-use compared to source-use compared to carbon emission. It was concluded that engineers should preferably evaluate their decisions since not always high performance HVAC is the best solution. As an example if the heating source for the baseline building would be supplied from district energy system (purchased hot water) than the source energy's conversion factor would be 1.26. Electricity source energy conversion factor in Hungary is much higher 2.5.

It was also concluded that if only the HVAC system's energy performance is taken into consideration than the high annual energy reduction could mislead to inadequate conclusions, since the miscellaneous equipment consumption, artificial lighting and other process equipment usually account for minimum 50% of a contemporary office building's energy consumption. The aforementioned Baseline heating system's thermal efficiency was 0.8 (non-condensing boiler) and the electric water cooled chiller's seasonal energy efficiency ratio was 5.5. Proposed system 1 PRHP had a heating COP of 4 and a cooling COP of 3. Finally Proposed system 2 GSHP heating a COP was 4 and cooling COP 6.45. The efficiencies of the HVAC systems on a first view would demonstrate very high energy conservation differences, however if an overall energy analysis is performed for all consumers, with incorporated carbon footprint and operational costs than the final environmental impact of the building would not demonstrate such high performance. It is important to concentrate on the energy type and system efficiencies during the design phase to achieve high overall building performance. Ground source heat exchangers with high COP could be one of the advantageous solutions for better energy performance and lower environmental impact.

Further research will include the energy and economic analysis of various HVAC systems for office buildings. 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 thermal performance and investment costs of an on-going project. The decarbonization policy is an adequate direction for carbon footprint reduction in the building sector. Low carbon emitting buildings should be set as mandatory; nevertheless the energy production sector should apply the decarbonization strategy, respectively.

Acknowledgment

The research reported in this paper was supported by the Higher Education Excellence Program of the Ministry of Human Capacities in the frame of Artificial Intelligence research area of Budapest University of Technology and Economics (BME FIKP-MI/SC).

Nomenklature

WFR – water flow rate
DX – direct expansion
PRHP– packaged rooftop heat pump
AFR – air-flow rate
GSHP – ground source heat pump
VAV – variable air volume
SEER – seasonal energy efficiency ratio

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Paper submitted: March 24, 2020
Paper revised: May 2, 2020
Paper accepted: May 7, 2020