ISEC 2024 – 3rd International Sustainable Energy Conference
Heat Pumping Technologies and System Integration
https://doi.org/10.52825/isec.v1i.1171

Published: 30 Apr. 2024

Techno-Economic Analysis of the Heating System Robustness

Elisa Venturi[1*], Georgios Dermentzis[1], Mara Magni[1], Fabian Ochs[1]

[1] University of Innsbruck, AT

*Correspondence: Elisa Venturi, elisa.venturi@uibk.ac.at

Abstract. A techno-economic analysis of different heating systems of a multi-apartment building is performed. The final energy savings and the economic benefit under different boundary conditions are investigated for a Passive House that has been realized and monitored in Innsbruck, Austria. Eight different system combinations are considered, varying the heat generation (direct electric (as-built), air/water heat pump (HP) and groundwater HP) as well as the size of the photovoltaic (PV) system. The systems are investigated with a building model with two different parameterizations: the pre-design stage and the model adapted to the monitored boundary conditions (BC: climate and user behaviour) and monitored energy consumption. The monitoring of the first two years of operation revealed a significantly higher space heating demand (29 kWh/(m^{2}a) compared to 8 kWh/(m^{2}a)). The most robust system (i.e. the system that performs best independent of the BC) for primary energy optimization is identified as an air-source heat pump with a 32 kWp photovoltaic system. This system also allows economic savings in case of high heating demand (adapted building model) and slightly higher costs in case of low heating demand (pre-design model). The groundwater-source HP is cost-effective only in scenarios with high heating demand due to significant investment and installation costs. Monthly primary energy factors are used to account for seasonal effects of the energy demand, providing an assessment of system efficiency that accounts for the so-called winter gap.

Keywords: Techno-Economic Analysis, Efficient Building, System Robustness

1. Introduction and aim of the study

The residential sector is worldwide the third sector for energy consumption, and in Europe it is the second one [1]. The entire European building sector contributes 36% to the world's final energy consumption [2], with space heating and water heating dominating energy consumption in the residential sector [2]. The same trend is verified in Austria, too [3]. Thus, efforts are essential to reduce energy consumption in this sector. The European Union enhances energy efficiency in the building sector through several initiatives such as the Energy Performance of Buildings Directive (EPBD) EU/2010/31 and the Energy Efficiency Directive EU/2023/1791, both revised in 2023 [4].

The Passive House standard is a well-known building standard, acknowledged for its efficiency in practical applications, as proven by several studies [5], [6]. Furthermore, residents' satisfaction is also confirmed [7].

Several studies reveal a discrepancy between the foreseen building performances and the monitoring data, often due to diverse inputs. A non-optimal functioning of the building system has to be considered (and expected) [8] for several reasons, among them the rebound effect, the user behaviour, deviating performance of the used materials and components compared to the design, and varying climate data. The challenge is not merely to predict a building's actual heating demand, as it depends on unpredictable boundary conditions [9], but rather to select the heating system that consistently performs efficiently across various scenarios (i.e. with different boundary conditions (BCs). Consequently, gathering monitoring data from real projects remains crucial, as the real performance offers insights into BC that cannot be accurately predicted (e.g. occupants' behaviour).

2. Case study and aim of the study

The building considered in this study is a small multi-apartment building built in Innsbruck, Austria (**Figure 1**). The building accommodates people for a temporary assisted living environment, i.e. specific user behaviour. The building was planned according to the Passive House standard with PHPP (Passive House Planning Package) to a space heating demand of 8 kWh/(m^2a). The reference area in PHPP is 1204.9 m^2.

Figure 1*: Outside view of the building*

The installed heating system is completely electric for space heating (SH) and domestic hot water (DHW). Each apartment is provided with electric radiators and an electric boiler (capacity of 50 litres) for the DHW preparation. In the common rooms, additional electric heaters and 3 large electric boilers (capacity of 120 litres) are installed. A large photovoltaic system of 32 kWp covers the south façade of the building and electric batteries (total capacity of 20 kWh) are installed in the basement. The concept is to keep the investment costs low, minimize the installation effort and neglect distribution losses while increasing the share of on-site renewable energy production. Monitoring data for the first two years of the building is available. Monitoring data show a particularly higher SH demand (29 kWh/(m^2a)) than designed (8 kWh/(m^2a)), while DHW demand and appliances demand is lower than the design. Electricity consumption for mechanical ventilation and photovoltaic energy production are similar to the design. A thorough comparison has been carried out and the influence of user behaviour has been investigated [10].

The aim of the current study is to identify the most robust system within a range of boundary conditions. In this context "robust" is intended as the system that consistently performs optimally regardless of the boundary conditions, which lead to different energy demands. Thus, various systems, including three heating generations and four PV sizes, are modelled in a building model with two parametrization: one based on standard design conditions and one based on unexpected conditions. The study of different systems is carried out to identify the most efficient solution from both a technological and economic point of view. Decentralised and centralised concepts for SH and DHW production are compared (Figure 2) in combination with different sizes of PV systems (see Table 1). A thorough techno-economic analysis is performed, focusing on two Key Performance Indicators (KPIs): the primary energy and the investment and operation costs compared to the reference system. Moreover, the primary energy is calculated with 2 methods, with a constant conversion factor throughout the year and monthly conversion factors.

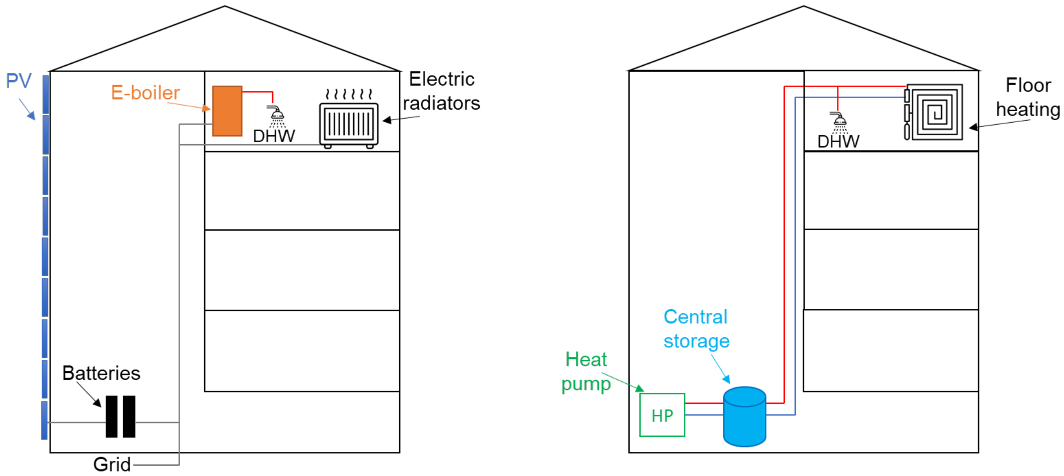


***Figure 2**: Concepts investigated in the current study*
Icons made by Freepik from www.flaticon.com.

3. Methodology

3.1 Heating systems

In the current study, eight system combinations of heat generation system and photovoltaic system (PV) are modelled. The heat generation systems are: 1) decentralised direct electric heaters (as-built), 2) centralized air-source heat pump (A/W HP) and 3) centralized groundwater-source heat pump (G/W HP). The photovoltaic sizes range from 0 to 70.9 kWp (which is the PV capacity achieved by covering also the East and West roofs with PV panels). The combinations are presented in Table 1. The reference system (REF) is the combination of direct electric heating system and no photovoltaic system. Case A represents the "as-built" building system.

***Table 1**: Description of the investigated systems (SH, DHW and PV technologies)*

Case	SH and DHW system description	PV system description
REF	Direct electric system	No PV system
A	Direct electric system	32.0 kWp – South façade
B	Direct electric system plus shower drain-water heat recovery	32.0 kWp – South façade
C	Direct electric system	70.9 kWp – South, East & West façade
D	Centralized A/W HP (4-pipe distribution system)	No PV system
E	Centralized G/W HP (4-pipe distribution system)	No PV system
F	Centralized air-source heat pump (4-pipe distribution system)	11.8 kWp – South façade
G	Centralized air-source heat pump (4-pipe distribution system)	32.0 kWp – South façade

In all the cases involving HP (Case D to G), the distribution system consists of a centralized 4-pipe system with fresh water stations in each apartment and common room (instead of the electric boilers). In these cases, the emission system is floor heating (FH).

3.2 Building models

The two building variants are implemented in PHPP [11]. The first one, called “Design Building”, corresponds to the design values with a space heating demand of 8 kWh/(m^2a)) and the second, called “Parametrized building” corresponds to the monitoring values with a space heating demand of 29 kWh/(m^2a). The “Parametrized building” model is created assuming the monitored boundary conditions (climate, internal temperature, internal gains) and the monitored energy consumption (SH, DHW, appliances and ventilation). The monthly energy demands and energy monthly self-consumptions are calculated in PHPP using the additional sheet developed within the framework of IEA SHC Task56 [12].

3.3 Economic assumptions

The economic analysis is carried out considering the costs for investment, installation, and maintenance for each system component as well as operation costs. Any surplus electric energy generated from renewables and not self-consumed is presumed to be sold to the grid. The economic evaluation utilizes the equivalent annual cost (EAC) method. Table 2 shows the economic assumptions and the assumed electricity prices.

***Table 2**: Economic assumption for the EAC method and electricity prices*

Time period	20 years
Interest ratio	3%
Electricity price	0.30 €/kWh
Annual increase rate of the electricity price	2%
Fed-in tariff	0.08 €/kWh

Table 3 provides the assumed specific costs for investment, installation, and maintenance associated with each system component as well as the corresponding expected lifetime.

***Table 3**: Economic assumptions for each component of the heating system and PV system*

Component	Investment costs	Installation costs	Maintenance costs	Lifetime
Electric radiant panels	0.2688*P[W] + 543.36 (**)	20% inv.	0 €/y	30 y
Electric boiler	0.4714*V[l] + 567.42 (**)	20% inv.	1.5% inv. €/y	30 y
Shower drain heat recovery	1307 €/system [13], (***)	20% inv.	0 €/y	40 y
A/W HP	2000 €/kW	157 €/kW [14], (***)	14 €/kW/y [14], (***)	15 y
G/W HP	1800 €/kW	3132 €/kW [14], (***)	20 €/kW/y [14], (***)	15 y
Central water storage	2500 €/system (*)	20% inv.	1.5% inv. €/y	12 y
Distribution system (insulated pipes)	1.8 €/m/mm [14], (***)	0.3 €/m/mm [14], (***)	0 €/y [14], (***)	30 y
Fresh water station	1500 €/system	0 € (included in inv. costs)	0 €/y	30 y
FH	100 €/m^2 (*)	0 € (included in inv. costs)	0 €/y	30 y
PV panels	1500 (*)	20% inv.	1.5% inv. €/y [14]	20 y

Electric battery	3800 € (*)	20% inv.	1.5% inv. €/y	20 y
Inverter (PV)	1600 € (*)	20% inv.	1.5% inv. €/y	20 y

(*): From market
(**): Curve fitting from market products
(***): Costs actualized to 2024 considering a 3% annual cost increase

3.4 KPIs

The KPIs for the current study are the additional primary energy (∆PE) and the additional total annual costs (∆C) compared to the reference system (REF).

The primary energy demand is calculated using the Austrian annual conversion factor (i.e. $f_{PE,AT}$ = 1.76 according to [15]) and the monthly conversion factors recommended in [16] (here referred as $f_{PE,10\text{-}10\text{-}10}$ and $f_{PE,10\text{-}30\text{-}30}$). The conversion factors are presented in Table 4. The use of monthly conversion allows for the consideration of energy demands in different periods of the year, i.e. seasonal effect. This approach is crucial to highlight differences between systems with potentially similar annual energy demand, but varying the seasonal needs. Therefore, it provides an assessment of system efficiency that accounts for the so-called winter gap.

Table 4*: Annual and monthly primary energy conversion factors*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$f_{PE,AT}$ [15]	1.76	1.76	1.76	1.76	1.76	1.76	1.76	1.76	1.76	1.76	1.76	1.76
$f_{PE,10\text{-}10\text{-}10}$ [16]	2.01	1.96	1.89	1.6	1.33	1.2	1.18	1.28	1.53	1.78	1.92	2.01
$f_{PE,10\text{-}30\text{-}30}$ [16]	1.53	1.42	1.23	0.5	0.08	0.08	0.08	0.08	0.33	0.98	1.33	1.54

4. Results

4.1 Energy demand

Figure 3 shows the electricity demand for Space Heating (SH), Domestic Hot Water (DHW), Ventilation and Auxiliaries (Vent+Aux), and Appliances (Appl) for all cases (REF to G, see Table 1) and the two building variants ("Design" and "Parametrized"). Additionally, the photovoltaic (PV) electricity production is represented with negative values.

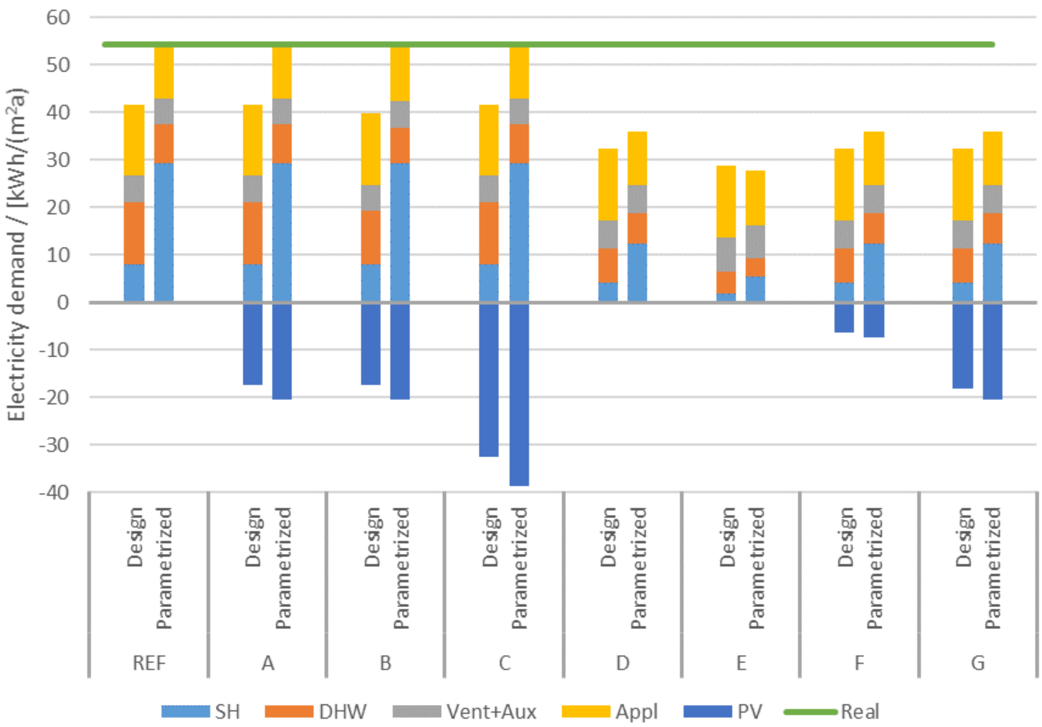


***Figure 3**: Electricity demand across the 8 systems (Table 1) and 2 building variants (“Design” and “Parametrized”). The green line illustrates the electricity demand in the real case (Case A, “Parametrized building”)*

The adoption of heat pumps leads to a reduction in the electricity demand for SH and DHW. While the largest share of energy demand in cases with direct electric heating is allocated to SH (e.g. 54% of the total energy consumption in the “Parametrized building”, case REF), this portion significantly diminishes in cases involving HPs, resulting in playing a similar role as appliances (e.g. SH: 35%, Appl: 32% of the total energy consumption in the “Parametrized building”, case D). Notably, Case E stands out as the only instance where the “Parametrized building” has lower electricity demand than the “Design building”. This reduction is attributed to the implementation of a groundwater HP, effectively decreasing the electricity demand for SH and DHW to the extent that the energy difference is now primarily driven by appliances (41% of the total energy consumption in the “Parametrized building”), which are higher in the “Design building” than in the “Parametrized building”.

4.2 Total annual cost

The total annual costs for the two building variants and eight systems are shown in Figure 4. The total annual costs are divided into investment and installation costs for heating system (HS) and for PV, maintenance costs for HS and for PV, and operation costs.

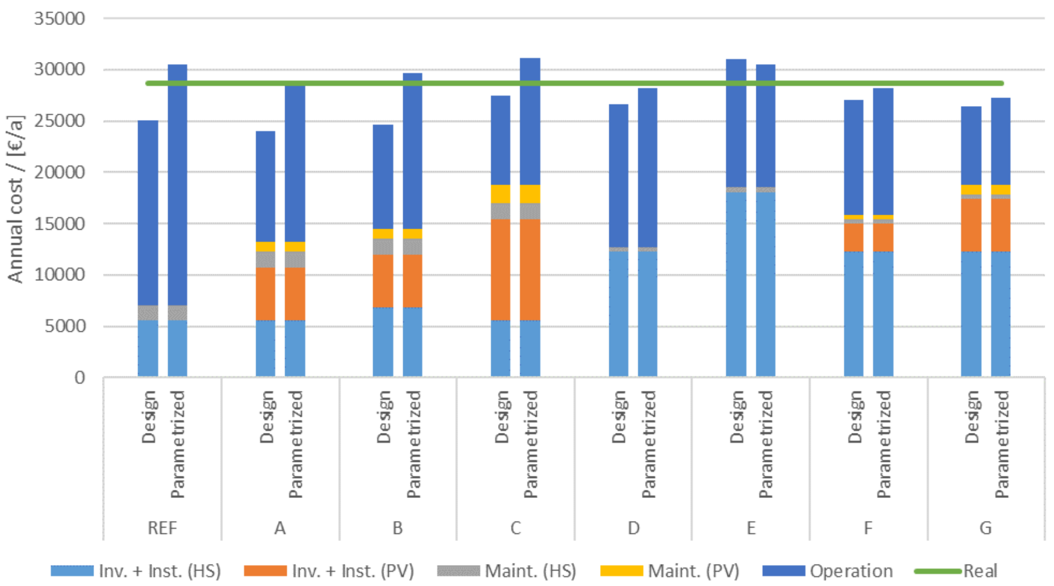


***Figure 4**: Total annual costs for the 8 systems (Table 1) and 2 building variants ("Design" and "Parametrized"). The green line represents the annual cost of the real case (Case A, "Parametrized building")*

In the "Design Building", all systems have higher total annual costs than the reference, except A and B. In contrast, in the "Parametrized Building", only Case C (i.e. direct electric system with the largest PV system) shows higher total costs than Case REF (+2%). Cases with HP (D to G) have higher investment costs for HS compared to the direct electric systems. When investment costs for PV are included, case D and F (with air-source HP) have lower investment costs than cases B and C (direct-electric). However, despite the possible higher investment costs, all cases with air-source HP (D, F, and G) show lower total annual costs than the real case indicated with the green line (Case A, "Parametrized building") due to reduced electricity demand (from -2% to -5%). Case E (groundwater HP) has higher total investment costs than the reference case (+224%). Because of the high initial investment and installation costs, the reduced electricity demand doesn't compensate for the total annual cost.

4.3 Primary energy savings and additional costs

The total required electricity, total primary energy demand (considering annual and monthly conversion factors), and annual costs for the reference case (REF) are summarised in Table 5:

***Table 5**: Total electric energy required, total primary energy demand and total annual costs for the reference case (Case REF)*

	Design Building	Parametrized Building
Total electric energy required [kWh/(m²a)]	41.7	54.4
Total primary energy ($f_{PE,AT}$) [kWh/(m²a)]	73.4	95.7
Total primary energy ($f_{PE,10\text{-}10\text{-}10}$) [kWh/(m²a)]	71.2	96.0
Total primary energy ($f_{PE,10\text{-}30\text{-}30}$) [kWh/(m²a)]	37.6	55.0
Total annual costs [€/(m²a)]	20.8	25.3

The results of the techno-economic analysis are presented in Figure 5. The primary energy calculation uses the Austrian conversion factor (constant). The blue area (left side of the plot) signifies primary energy savings (i.e. negative additional primary energy). The yellow area (lower part of the plot) denotes economic convenience (negative additional costs). Hence, the optimal system lies at the intersection of these two areas, located at the bottom-left corner of the plot.

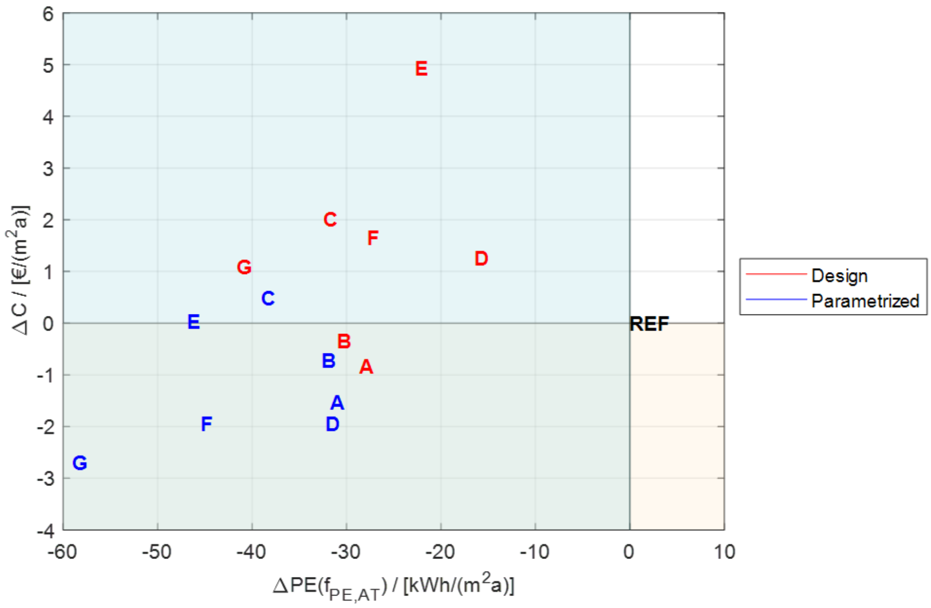
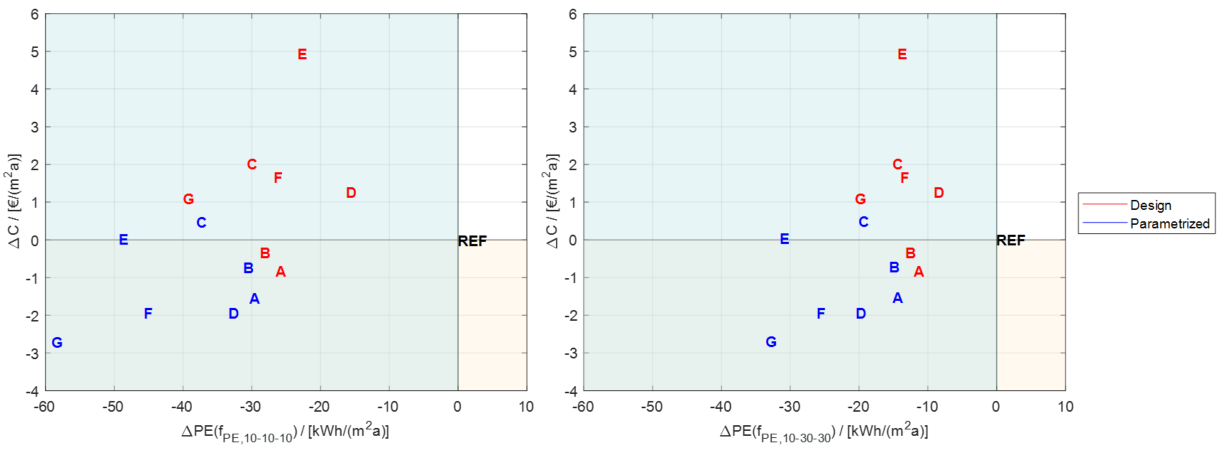


***Figure 5**: Additional costs and additional primary energy compared to Case REF. Primary energy evaluated with $f_{PE,AT}$*

In case of "Parametrized building", case G (A/W HP with 15.8 kWp PV system) is the most convenient system (i.e. highest economic and energy savings). Regardless of the heating demand (i.e. building variant), case G presents the highest primary energy savings. This solution is achievable with moderate additional costs in the "Design building" model (1.1 €/(m^{2}a)), while it allows economic savings of 2.7 €/(m^{2}a) in the "Parametrized building" model. Moreover, Figure 5 highlights a difference in the trend of primary energy savings between the two building variants. In the "Design building", direct electric systems (Cases A, B, and C) can lead to higher primary energy saving compared to HPs systems without PV (Cases D and E) or low PV peak power installed (case F). Contrarily, buildings with higher energy demand ("Parametrized building") achieve higher efficiency (and therefore primary energy savings) thanks to heat pumps integration.

Systems with direct electric heating and large PV installation (Case C) result in being uneconomical. The additional investment costs for the PV system are not compensated by the economic savings (i.e. energy self-consumption). Similarly, the system with groundwater HP (Case E) may not be cost-effective when the heating demand is low ("Design building").

The primary energy demand calculated with monthly conversion factors is examined to highlight potential differences among systems with similar annual energy demand, but different distribution of energy demand throughout the year. Figure 6 shows the additional costs and additional primary energy evaluated using the monthly factors suggested in [16].



a) b)

***Figure 6**: Additional costs and additional primary energy compared to Case REF. Primary energy evaluated with $f_{PE,10\text{-}10\text{-}10}$ in 6a) and with $f_{PE,10\text{-}30\text{-}30}$ in 6b)*

The seasonal effect becomes evident in the comparison between systems with PV and more efficient systems in Figure 6b. For example, with annual factor and monthly factors "10-10-10", the Case C (direct electric with 71 kWp PV) shows higher primary energy savings than Case D (A/W HP without PV) in the "Parametrized building". However, with the monthly factors 10-30-30, the two cases have the same primary energy savings. This suggests that disregarding the seasonal effect, i.e. the so-called winter gap, would lead to the wrong conclusion that PV outperforms systems with better efficiency. When the seasonal performance is considered, the better efficiency of the system and PV perform the same (or better efficiency of the system may even slightly outperform PV). The same trend can be observed with Case E and Case A (and B) in the "Design building".

5. Conclusions and outlooks

The current study suggests a method to assess the robustness of different heating systems concerning primary energy savings and economic benefits under varying boundary conditions (i.e. climate and user behaviour) using a real case study of a multi-apartment building in Innsbruck (Austria) as an example. In this context "robust" is intended as the system that consistently performs optimally regardless of the boundary conditions, which lead to different energy demands. Eight system combinations are considered, varying the heat generation and size of the PV system with two different parameter sets for the building model: a pre-design model ("Design building") and a model adapted to the monitored boundary conditions and energy consumption ("Parametrized building").

Regarding primary energy optimization, the most robust system (i.e. performing best independent of the BC) is an air-source heat pump with a 32 kWp photovoltaic system (the south façade fully covered). The system also allows economic savings in the case of high heating demand ("Parametrized building"), being 11% more economical than the reference case and 5% more economical than the as-built case. In the case of low heating demand ("Design building"), it leads to slightly higher costs compared to the reference case (+5%) and as-built case (+10%). Thus, a centralized air-sourced HP system is suggested, as it guarantees primary energy savings at comparable or slightly higher costs to a decentralised direct-electric system with the same PV. In the likely case of a future implementation of relevant CO_2 taxes, this system would become even more economically favourable. Moreover, the air-source HP with a 4-pipe distribution system offers additional comfort benefits, such as the possibility of summer cooling. The groundwater-source HP is cost-effective only in cases with high heating demand due to the high investment and installation (i.e. well installation) costs.

The cost-effectiveness of the HP system is also influenced by equipment costs (e.g. fresh water stations). It is crucial to emphasize the significant uncertainty associated with cost assumptions, as they are highly dependent on specific cases (e.g., location, time, incentives, etc.).

The monthly primary energy factors (or alternatively CO_2-factors) provide a means to account for the seasonal effect of energy demand, i.e. the winter gap. For example, if two systems have the same annual energy demand but one has lower energy consumption during winter months (when the grid typically relies more on non-renewable sources), it is considered more efficient. With annual conversion factors, an inefficient system with a PV system might appear to outperform an efficient system without PV. However, when the seasonal effect is taken into consideration, the latter system may outperform the more inefficient system with PV.

The presented solution has been derived for a new building, but is equally applicable to renovation projects. Future studies are recommended to test and compare the proposed method with dynamic simulations. Additionally, the availability of a comprehensive database for costs and cost functions including an uncertainty analysis would enhance the accuracy of the study. To provide a more comprehensive assessment, the inclusion of a Life Cycle Assessment (LCA) for the components should also be considered in future work.

Data availability statement

Data will be made available on request.

Author contributions

Elisa Venturi: Methodology, Software, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualisation. **Georgios Dermentzis**: Methodology, Investigation, Writing - Review & Editing. **Mara Magni**: Writing - Review & Editing. **Fabian Ochs**: Conceptualization, Methodology, Writing - Review & Editing, Supervision.

Competing interests

The authors declare that they have no competing interests.

Acknowledgement

The authors would like to thank IIG (Innsbrucker Immobiliengesellschaft) for the collaboration. With the current work, we contribute to IEA SHC T66 Solar Energy Buildings.

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