ENERGY PERFORMANCE OF RELATIVELY SMALL SPORTS HALLS USED AS PUBLIC WARMING SHELTERS

by

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To provide a warm place for the most vulnerable citizens during the 2022/2023 energy crisis, some municipalities have set up public halls as warming shelters. Thus, the present study analyzes the energy performance of a gymnasium in South-eastern Europe that is repurposed to be used as public warming hall. The study conducted 15 EnergyPlus simulations, covering five states of gymnasium occupancy and three heating, ventilation and air conditioning scenarios. Two scenarios were designed to reduce the possibility of viral disease transmission, in the case public health emergency occurs. The study indicates that gymnasiums with natural ventilation consume more energy than they would with more advanced HVAC systems. This way, when occupancy increases, building energy consumption decreases (from 171-102 kWh per m^2). Contrary to that, in more advanced heating, ventilation and air conditioning scenarios, energy consumption slowly increases with the increase of occupancy. Due to the utilization of heat recovery and air re-circulation systems, these scenarios require approximately 60-80% less energy compared to the base scenario. The complex simulations performed in this study provided relatively simple formulas that can be extrapolated to determine hall energy performance for any hall occupancy. These formulas can be used by non-experts and applied to similar buildings in other locations.

Key words: *2022/2023 energy crisis, energy poverty, EnergyPlus software, public warming halls, warm hubs*

Introduction

Over the past two decades, European governments have implemented a number of policies (energy efficiency directive [1], energy performance of buildings directive [2], social climate fund regulation [3], renewable energy directive [4], *etc.*) aimed at increasing building energy efficiency and reducing overall CO_2 emissions. However, two-thirds of EU member states declined before adopted energy efficiency gains [5] the EU arguing that the adopted plan had negative social impacts that needed to be better managed and mitigated [6]. To find a compromise between adopted environmental responsibilities and social welfare, societies throughout Europe reduced CO_2 emissions attributable to buildings, but not through the expected increase in buildings energy efficiency, but by shifting from coal and oil to a less carbon-intensive heating fuel – natural gas, which now accounts for 31.7% of household energy consumption in the EU [7]. As a consequence, these societies became more reliant on energy imports [8], their income levels

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became increasingly influenced by the state of international relations, and a significant proportion of their low and middle income households became highly susceptible to the consequences of energy price volatility [6]. Although governments in EU member states adopted regulations aimed at mitigating energy poverty* [3], the measures adopted prove insufficient to eliminate the negative effects of unexpected large-scale energy crises, particularly if they result in national energy shortages when rising prices became one of the measures to rationalize citizens' behavior** [11]. In these circumstances, low and middle income groups who lack the financial resources to invest in energy efficiency, or those who rent their homes and thus are unable to make such choices, may respond by turning down the heat or reducing other household expenditures [12], exacerbating the negative effects of energy poverty. The negative effects of energy poverty, which threatens around 50 million households in the EU (2021) [13], are particularly visible in Southern and Eastern Europe [9] and non-EU member countries, where social welfare is less developed than in EU member states [14] while public and residential building there consume more heat than the EU average [15]. To mitigate the adverse effects of the global energy crisis during the 2022-2023 heating season, European governments implemented measures and launched a series of campaigns to rationalize energy consumption and reduce the social burden. The policies undertaken in this manner were predominantly mandatory for public institutions and predominantly recommended for the residential sector (depending on the country, the recommended room temperature in public buildings and offices during the heating season should range between 18-20°C (18 °C: Portugal [16], 19 °C: France [17], Germany [18], Italy (19-21°C) [19], Spain [20], and 20 °C: Switzerland [21]), hot water should not be heated to temperatures above 60 °C, electrical appliances should be turned off rather than left on standby, and so on). In addition, governments and NGO intend to provide warm shelters for socially vulnerable members of society who are unable to pay their bills during the coldest months of the year [22, 23]. In the event of an emergency, these citizens will be able to warm up in public warming halls*** (PWH). However, given that PWH operating costs may be relatively high [24], and that protective measures against the uncontrolled spread of viral diseases may limit PHW occupancy potential [25] one might wonder how these buildings will behave in terms of energy performance after a change in their purpose? One may also question whether the hall repurposing is justified in terms of energy savings and public safety more than additional financial support for the most vulnerable households? To answer these questions, the present study investigates the energy performance of an exemplary PWH under five occupancy scenarios that may occur in the event of a severe energy crisis, and three HVAC scenarios and that can be used in the event of public health emergencies as a precautionary measures [26]. The research was conducted for a region where the negative effects of energy poverty are particularly pronounced – a non-EU member state in Southeastern Europe. The study findings may contribute to the professional and scientific communities' decision-making, especially when it comes to balancing energy savings, social responsibility, and public health. In addition, the work contributes to the analysis of the possible uses of public halls in crisis situations from an engineering and management standpoint.

* Energy-poor household is a household that has difficulty, or sometimes inability, to afford its basic energy requirements needed for indoor activities, such as heating, cooling, cooking, and lighting [9].

** According to the social-cognitive paradigm, external factors influence people behavior more than internal forces [10].

*** Public warming halls are relatively large indoor public spaces that can be multi-purpose, sport, exhibition, or concert halls.

Materials and methods

Subject of research

Public shelters play an important role in the daily lives of socially vulnerable members of society, such as homeless people or those suffering from the consequences of extreme poverty [27]. However, in the event of an emergency that disrupts the daily lives of many citizens, the social importance of these buildings increases significantly [28]. In this regard, the proper selection of buildings that can provide appropriate care for as many people as needed is an important task for local public and emergency services. Without knowing the exact number of those who will require the use of PWH in the events of energy crises, the optimal selection of buildings to be used as public shelters can be particularly challenging. In general, building selection can be done in two ways: centralized approach, which considers the use of the large municipal sports halls previously used for COVID-19 immunization and decentralized (or distributed) approach, which considers the use of smaller gymnasiums* scattered throughout the community. Aside from the challenge of organizing sufficient indoor spaces, a decentralized approach has several advantages over the centralized approach. For example, the average distance between citizens' homes and PWH is shorter, small PWH have smaller crowding potential (which reduces the risk of viral disease transmission), thermal comfort in relatively small PHW is better controlled than in large sports halls, and operating costs for relatively small PWH are significantly lower than costs for large sports halls, and when overall demand for PWH is low, it is easier to optimize the occupancy of multiple small PHW than one large sports hall, *etc.* Aside from that, almost all city municipalities have schools appropriated to municipal population size, and school gymnasiums are generally unoccupied during the coldest days of the year (winter break) when the need for PWH use is expected to be greatest. Thus, due to their accessibility and from a health, financial, and energy efficiency standpoint, gymnasiums can be considered ideal for a potential increase in the number of distributed PWH during the coldest months of the year.

Object of research – School gymnasium in the city of Kragujevac, Serbia

This study analyses the energy performance of a sports gymnasium in central Serbia** repurposed to be used as PWH. Details of the moderate continental climate of the studied location studied (EnergyPlus weather file for the city of Kragujevac) are presented in tab. 1.

Table 1. Climate details of the location

Month	Dry bulb [°C]	Dew point [°C]	Wet bulb [°C]	Humidity ratio [kgkg^{-1}]	Relative humidity [%]	Barometric pressure [kPa]	Enthalpy [kJ/kg]	Air density [kgm^{-3}]
October	9.80	6.22	7.90	0.0062	79.74	98.9	25.46	1.21
November	6.08	2.69	4.45	0.0049	79.80	98.9	18.459	1.22
December	1.13	–1.47	0.09	0.0036	83.50	98.9	10.18	1.25
January	–0.24	–3.44	–1.44	0.0031	79.92	98.9	7.463	1.26
February	0.88	–2.43	–0.46	0.0033	79.82	98.9	9.26	1.25
March	5.57	0.61	3.30	0.0042	72.06	98.9	16.08	1.23
April	12.79	7.01	9.61	0.0066	69.75	98.9	29.55	1.19

* A building designed for indoor sports, exercise, or physical education.

** In terms of natural gas, Republic of Serbia is highly reliant on imports from a single energy exporting country (89%) [29].

Table 2. Thermal characteristics of the analyzed PWH thermal envelope [30]

Construction	U [Wm^{-2}K^{-1}]
Floor	0.3
Wall	0.3
Roof	0.15
Window	1.5
Door	1.5

The net area and net volume of the exemplar PWH analyzed are 1130.04 m^2 (floor area 43.8 m × 25.8 m) and 10396.37 m^3 (average ceiling height: 9.2 m), respectively. The total area of the building's thermal envelope is 3479.3 m^2. The main entrance (external door: 2.2 m × 2.6 m) is located on the east facade. On the south facade there are 11 identical windows each measuring 3.5 m × 1.8 m, fig. 1(a). On the north façade, each of the 11 identical windows measures 3.5 m × 4.5 m, fig. 1(b). The properties of the building's thermal envelope are presented in tab. 2.

Occupancy scenarios

In terms of building occupancy, the study examines building energy performance under five equally increasing occupancy scenarios, ranging from 20-100%, fig. 1(c). The PHW full occupancy capacity (5 m^2 per occupant) was determined in accordance with health institution recommendations on how to prevent and suppress the infectious COVID-19 disease in indoor spaces (requiring a distance of at least 4 m^2/person) [31]. The criterion is consistent with COVID-19 indoor preventive measures in other countries, which require a distance of at least 1.5-2 m between individuals [32].

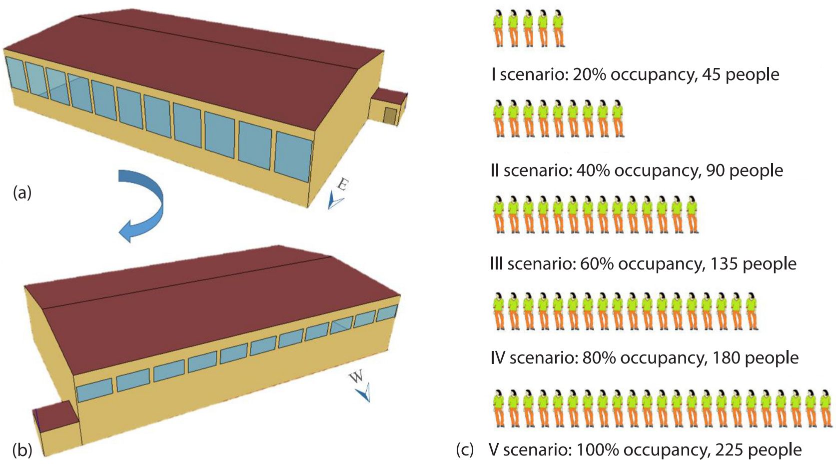


Figure 1. Building isometric views (a, b) and building occupancy scenarios (c)

Ventilation scenarios

The majority of existing sports gymnasiums have either natural, fig. 2(a) or supply-only forced ventilation. However, because these ventilation systems create air swirls while mixing outdoor and indoor air, it allows the spread of viral diseases, which can be especially problematic during public health emergencies. In this regard, balanced ventilation with an air supply placed at the bottom of the hall walls and air exhaust placed at the ceiling of the hall could direct the indoor air stream upwards. As a result, not only will the expired air and aerosols be exposed to the thermal convective plume*, which causes a clear upward air-flow near people's bodies,

* Thermal plumes caused by convective motion from localized heat sources, where hot fluid flows into a colder region above, are examples of nonlinear driven flow systems where buoyancy is steadily supplied [33].

but they will also be exposed to ventilation upward buoyancy forces**, figs. 2(b) and 2(c) [34]. Consequently, the lower hall zone will be less susceptible to disease contamination, making it a safer environment than when using natural or supply-only ventilation. Another precautionary measure would be the installation of a filter to purify the air recirculated in the hall. In that case, fig. 2(c), filtering in the return duct should have been completed before the exhaust air is mixed with fresh and re-injected into the hall. Assuming that the ventilation system can potentially spread contamination or pathogens, it becomes necessary to prevent this effect [35]. The use of high efficiency particulate absorbing filter in this regard is considered as effective since it removes at least 99.95% of particles with a diameter of 0.3 μm and larger fractions of the other sizes [32]. To analyze the energy performance of the exemplar PWH under the described conditions, this study considers three ventilation scenarios:

- natural ventilation (NV), fig. 2(a) – when there are no increased public health concerns due to the spread of viral diseases,
- forced balanced ventilation (FBV), fig. 2(b), and
- the FBV with filtered air re-circulation*** (FBV-FAR), fig. 2(c) – when there are increased public health concerns due to the spread of viral diseases.

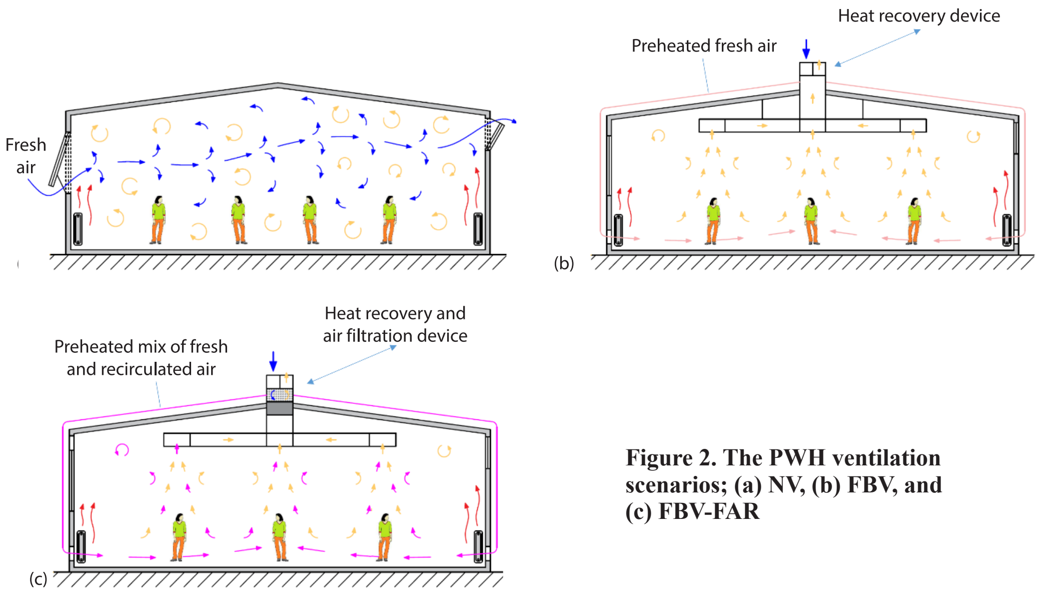


Figure 2. The PWH ventilation scenarios; (a) NV, (b) FBV, and (c) FBV-FAR

According to the Rulebook on energy efficiency in buildings [36], the study uses a constant number of building air changes (0.5 Lph) in the first ventilation scenario, regardless of the hall occupancy. This is due to the fact that it is difficult to accurately control air infiltration when using NV, so the rate of change is determined in respect to hall volume. In the other two scenarios, the number of air changes was determined in accordance to hall occupancy, floor area, and hall height, tab. 3, [32]. Figure 2 depicts illustrations of three ventilation scenarios.

** The buoyant force is the upward force exerted on any object in any fluid.

*** In the third ventilation scenario, fresh air from the supply is mixed with filtrated exhaust air in a one-to-one ratio before the mixture being injected into the building's interior.

Table 3. Building air change rates per different occupancy scenarios

Ventilation scenario		Occupancy scenario (number of people)				
		OS1 (45)	OS2 (90)	OS3 (135)	OS4 (180)	OS5 (225)
		Air changes [per hours]				
I		0.50				
II	III	0.75	0.78	0.82	0.84	0.86

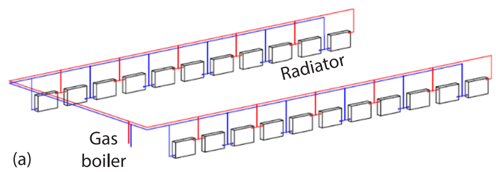
Heating scenarios

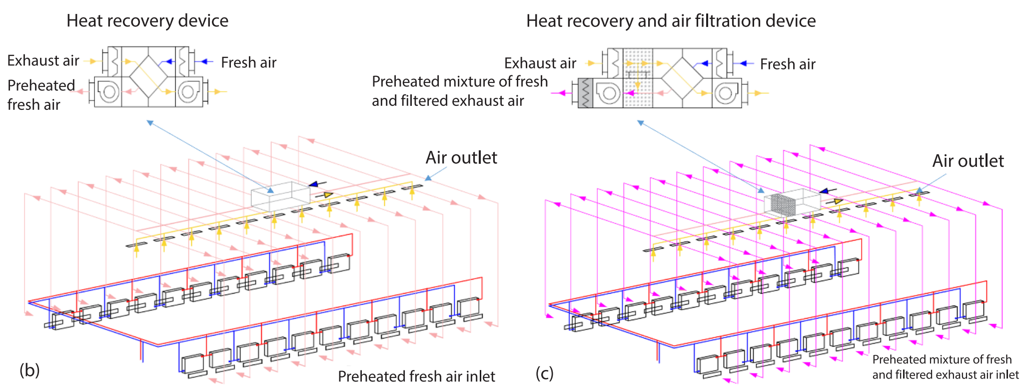
The analyzed PHW is equipped with a centralized heating system. The system heat generator (85 kW) is located in the technical room, next to the western facade wall. From there, the heat generated by gas combustion is distributed to 24 radiators equally parted on the north and south façades (dimensions 2800 mm × 900 mm × 100 mm). Following the order of adopted ventilation scenarios presented in section *Ventilation scenarios*, the study considers three heating scenarios:

– centralized heating with radiators (CHR), fig. 3(a),
– the CHR and exhaust air heat recovery (CHR-HR), fig. 3(b), and
– the CHR, exhaust air HR, and air re-circulation (CHR-HR-AR), fig. 3(c).

The first heating scenario, fig. 3(a) is most common in buildings of this type and is usually followed by NV, fig. 2(a). The second heating scenario, fig. 3(b), reduces the possibility of spreading viral diseases and moderately increases the energy efficiency of the buildings. Heat recovery becoming more popular in variety of HVAC applications [37] as such solutions are advantageous for enabling the maintenance of adequate indoor air quality, while improving the thermal performance of buildings [38]. To apply this principle in this study, fresh air (previously preheated in the ventilation chamber) is directed through the ventilation ducts to the openings at the bottom of the south and north PWH walls (behind the radiator), through which it is introduced into the building interior. The number of openings for air distribution corresponds to the number of radiators. In this way, the fresh air-flows over and around the radiators and is

Figure 3. The PHW heating scenarios; (a) CHR, (b) CHR-HR, and (c) CHR-HR-AR





heated to the ambient temperature (20 °C), fig. 2(b). The third heating scenario, fig. 3(c) uses the same heating principle as the second, supplemented by a FAR system.

The HVAC simulation scenarios

The HVAC simulation scenarios (HS) used in this study consider the respective coupling of heating and ventilation scenarios presented in sections *Ventilation scenarios* and *Heating scenarios*, tab. 4.

Table 4. The HVAC simulation scenarios

HVAC scenario	Ventilation	Heating
HS1	NV	CHR
HS2	FBV	CHR-HR
HS3	FBV-FAR	CHR-HR-AR

Simulation software

To analyze the energy performance of the exemplar building, for each of the three HVAC scenarios, tab. 4, and each of the five occupancy scenarios, fig. 1(c), the study used the EnergyPlus software package. This software, developed by Berkeley National Laboratory and the United States Army Construction Engineering Laboratory [39], is a useful tool for modelling the energy and environmental behavior of buildings. It enables the definition of complex HVAC system schedules, as well as schedules for lighting, internal energy devices, and building occupancy [40].

Results and discussion

Heat consumption

According to EnergyPlus simulations performed on models developed in accordance with sections of *Objesct of research – School gymnasium in the city of Kragujevac, Serbia to The HVAC simulation scenarios*, the first HVAC scenario requires more heat during the heating season than the other two HVAC scenarios, fig. 4.

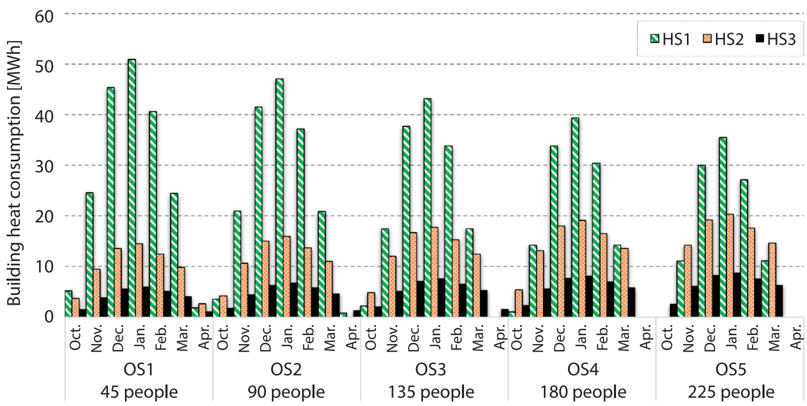


Figure 4. The PHW heat demand for various simulation scenarios

Aside from the lack of heat recovery and air re-circulation systems, the reason for significant differences in HS1 energy performance compared to HS2 and HS3 is that NV (HS1) air change rate is relatively difficult to control, so it is considered to be constant (0.5) regardless of hall occupancy [36]. As a consequence, HS2 and HS3 require 71% and 88% less heat than HS1 during the coldest months for OS1 and OS2, respectively. In general, the same order of HVAC scenarios heat demand applies to all occupancies considered, although the difference in consumption between HVAC scenarios decreases as hall occupancy increases. That being said, the difference decreases even further when considering the beginning and end months of a heating season, with HS1 being more efficient in October and April than HS2 and HS3 (OS2 and OS3). This is because the heating system treats more outside air in the forced ventilation scenario (HS2) than in the NV scenario (HS1), tab. 3. Furthermore, since the difference between outdoor and indoor temperatures is relatively small at the beginning and end of a heating season, utilization of heat recovery systems (HS2, HS3) do not make much difference in energy consumption compared to HS1, as is the case in the middle of the season (when the temperature difference between indoor and outdoor temperatures is relatively large). At the start and end of a heating season, heat gains from occupants meet hall demand in scenarios with medium to high occupancy (OS4, OS5). Therefore, in these months, OS4 and OS5 heat consumption is non-existent for all HVAC scenarios.

Electricity consumption

In addition heat output, the operation of FBV (HS2) and FBV-FAR (HS3) necessitates the use of electricity. In this context, HS2 electricity consumption ranges from 0.85 MWh at the start and end of a heating season (OS1) to 1.94 MWh in the middle months of a heating season (OS5). Due to the use of an air filtration unit, HS3 consumes approximately 30% more electricity than HS2, for all OS analyzed. More details in this regard, are presented in fig. 5. As shown in the heat matrices, fig. 5, an increase in occupancy leads to higher energy consumption for hall ventilation (HS2, HS3) and more energy for hall air filtration (HS3).

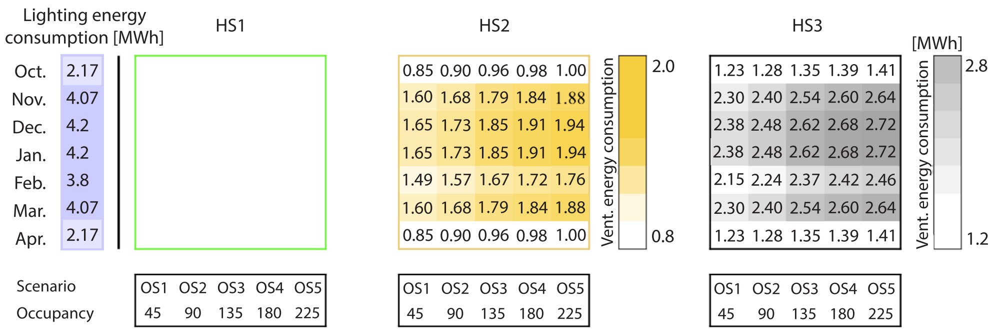


Figure 5. Monthly PWH HVAC energy consumption

Up to OS3, the average increase in HVAC systems electricity consumption is 5% per occupancy scenario, after which the trend decreases to approximately 3% for OS4 and approximately 1% for OS5. All HVAC scenarios consume the same amount of electricity used for PWH lighting.

Indicators of energy consumption

Because PWH occupancy is expected to vary during the heating season, this study provides energy consumption indicators for five different occupancy scenarios. To obtain data comparable to other types of buildings, the study provides seasonal and monthly indicators of energy consumption (kWh per m^2 and kWh per occupant). The values take into account heat consumption (HS1) and combined heat and HVAC electricity consumption (HS2, HS3), fig. 6, in addition, study provides formulas able to describe the relationship between PWH HVAC scenarios, PHW occupancy, and PWH energy consumption, tab. 5. In the case of HS1, energy consumption per heated floor area decreases linearly as the number of occupants increases, from 170.8 kWh per m^2 for OS1 to 101.7 kWh per m^2 for OS5. For HS2, the indicator value increases along with the number of occupants (67 kWh per m^2 for OS1, to 86 kWh per m^2 for OS5), implying a strong polynomial dependence ($R^2 = 0.96$) between PWH energy consumption and PWH occupancy. In ascending order of occupancy scenarios, the increase in indicator values per scenario was 6%, 10%, and 7%, respectively, up to OS4. There were no differences in indicator values (kWh per m^2) between OS4 and OS5. In the case of HS3, similarly to HS2, the indicators show a strong polynomial dependence between PWH energy consumption and PWH occupancy ($R^2 = 0.98$). On average, HS3 requires 44% less energy per heated floor area than HS2, for each of the OS.

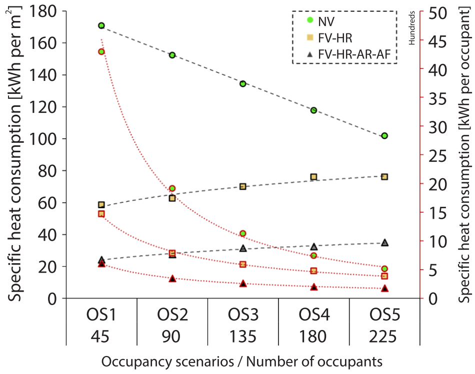


Figure 6. Seasonal indicators of PWH energy consumption

Table 5. Formulae for calculating energy consumption indicators for various PHW occupancy and PWH HVAC scenarios

Specific heat consumption [kWh per m^2]		
Heating scenario	Regression function	R^2
HS1	SHC = −17.265·(NO) + 187.16	0.999
HS2	SHC = 57.421(NO)0.1799	0.964
HS3	SHC = 23.998(NO)0.2288	0.984
Specific heat consumption [kWh per occupant]		
Heating scenario	Regression function	R^2
HS1	SHC = 4498(NO) – 1.31	0.995
HS2	SHC = 1441.9(NO) – 0.82	0.997
HS3	SHC = 602.64(NO) – 0.771	0.998

When it comes to energy consumption per occupant, each HS indicator decreases as PWH occupancy increases. The HS1 had the greatest decrease (kWh per occupant) from OS1 to OS5, at 88% (from 4.3 MWh per occupant to 511 kWh per occupant). Further on, the decrease was 73% for HS2 (from 1.48 MWh per occupant to 391.9 kWh per occupant) and 69% for HS3 (from 620 kWh per occupant to 190 kWh per occupant). Indicator values (kWh per occupant) have a strong functional dependence with PWH occupancy for all HVAC scenarios ($R^2 > 0.99$). In this regard, complex simulations performed in software requiring expert knowledge provided relatively simple formulas that can be easily extrapolated to determine PWH energy performance for any possible hall occupancy (except the case with no occupancy). Thus, the formulas can be utilized by non-experts in the field and applied to similar buildings in locations with similar climates.

Due to variations in PWH occupancy that can occur during the season, monthly indicators of energy consumption (kWh per occupant) provide more discrete details on PWH energy performance from an energy management and public administration standpoint [41]. In this regard, as expected, indicator values are highest in the coldest months of the heating season (December and January) for all HS.

According to heat matrices, fig. 7, the difference in these month indicator values ranges by approximately 67% when HS2 is compared to HS1, and by 48% when HS3 is compared to HS2. In the case of medium hall occupancy in January, the building consumes 320.2 kWh per occupant (HS1), 145.2 kWh per occupant (HS2), and 76 kWh per occupant (HS3). Assuming that medium occupancy is the most probable, using these indicators, one can examine PHW viability compared to other measures of social support such are financial aid for the most vulnerable members of society or the use of other types of buildings as PWH. Decisions adopted in this regard should also take into account climate specifics, the state of the building sector, details of the welfare system, the most commonly used heating fuel, and so on, implying that measures implemented in one society do not have to be effective or necessary to be considered in others. Regarding investments and HVAC scenarios, HS1 does not require any particular finances for gymnasium repurposing. On the other hand, gymnasium adaptation HS2 and HS3 requires investment in supplementary HVAC systems. The initial cost of utilizing this technology is relatively low. However, operational costs, particularly for electricity use in HS3 are relatively high, because the flow resistance of air filters is intense and thus additional energy is required to overcome the large pressure drop they create, which is especially evident at relatively high flow rates, fig. 5.

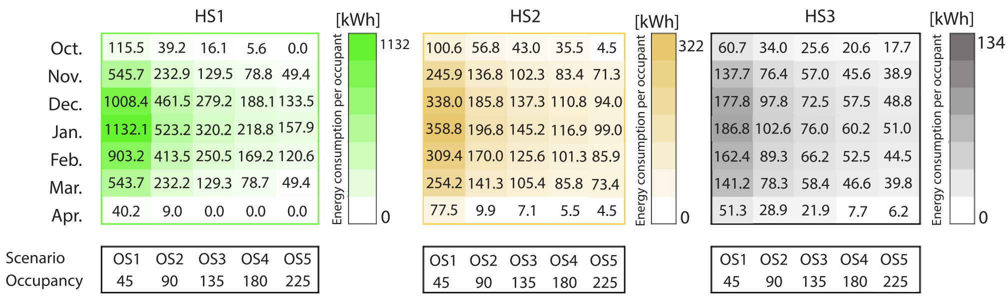


Figure 7. Monthly indicators of PHW energy consumption (kWh per occupant)

Conclusions

According to the simulations conducted in this study, HS1, while not requiring any investment in repurposing of a building used as PWH, has the highest energy demand of the HVAC scenarios considered. In average, seasonal heat consumption of HS1 was 57% higher than that of HS2, and 39% higher than that of HS3. When hall occupancy increases for 20% of full capacity (HS1), the heat consumption indicator (kWh per m^2) decreases linearly by 12%. In the other two HVAC scenarios, however, each increase in occupancy (OS) resulted in increased energy consumption. Nevertheless, the increase in hall heat consumption (kWh per m^2 per season) per ascending order of hall occupancy scenarios was unequal rather than similar. In detail, heat consumption increased by 6%, 11%, and 8% per OS in ascending order of occupancy scenarios for HS2 until the OS4. There was no discernible difference in hall heat consumption between OS4 and OS5. In the case of HS3, building heat consumption (kWh per m^2 per season) increased by 12%, 13%, 3%, and 8% in ascending order of OS, respectively. In terms of overall seasonal heat consumption, HS2 and HS3 were more energy efficient than HS1, but their use necessitates investment in hall repurposing, *i.e.* investment in supplementary

HVAC systems. Furthermore, the use of these systems necessitates the use of electricity (up to 2.7 MWh per month), which was not required in HS1.

Aside from that, the study provides indicators of energy consumption per occupant for each of the HVAC and occupancy scenarios considered. The indicator value decreases as the HVAC scenarios ascend in order. If the median occupancy scenario (OS3) is assumed to be the most probable, the indicator value for HS1 in the coldest month of a heating season would be 1132 kWh per occupant, 322 kWh per occupant for HS2, and 134 kWh per occupant for HS3. All of the analyzed PHW energy consumption indicators have a strong functional dependence on PHW occupancy, with coefficients of determination greater than 0.96. In this regard, the present study, based on relatively complex simulations, has resulted in relatively simple patterns that can be easily extrapolated for any possible hall occupancy and thus applied to similar buildings in moderate continental climates. Results obtained in this way, therefore, could aid professional and scientific communities' decision-making, especially when it comes to balancing energy savings, social responsibility, and public health.

Nomenclature

AR – air re-circulation
CHR – centralized heating with radiators
FAR – filtered air re-circulation
FBV – forced balanced ventilation
HR – heat recovery
HS – HVAC scenario
NO – number of occupants
NV – natural ventilation
OS – occupancy scenario
PWH – public warming hall
SHC – specific heat consumption

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